HYDROLOGY OF THE FLORIDAN AQUIFER SYSTEM IN WEST-CENTRAL FLORIDA

REGIONAL AQUIFER-SYSTEM ANALYSIS

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1403–F

Hydrology of the Floridan Aquifer System in West-Central Florida

By PAUL D. RYDER

REGIONAL AQUIFER-SYSTEM ANALYSIS

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1403–F

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1985

UNITED STATES DEPARTMENT OF THE INTERIOR

Donald Paul Hodel, *Secretary*

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, *Director*

Library of Congress Cataloging in Publication Data
Ryder, Paul D.
Hydrology of the Floridan aquifer system in west-central Florida.
(Geological Survey Professional Paper ; 1403–F)
Bibliography: p. F60–F63
Supt. of Docs. No.: I 19.16:1403–F
1. Water, Underground—Florida. 2. Aquifers—Florida.
I. Title. II. Series.
QB1025.F6R93 1985 551.49 85-600254

For sale by the Branch of Distribution
U.S. Geological Survey
604 South Pickett Street
Alexandria, VA 22304

FOREWORD

THE REGIONAL AQUIFER-SYSTEM ANALYSIS PROGRAM

The Regional Aquifer-System Analysis (RASA) program was started in 1978 after 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 important components 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 often have been arbitrarily limited in the past. The broad objectives for each study are 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, to develop an understanding of the natural, undisturbed hydrologic system and of any changes brought about by human activities, as well as 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. 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 will continue in numerical sequence as the interpretive products of studies become available.

Dallas L. Peck
Director

CONTENTS

ILLUSTRATIONS

TABLES

ABBREVIATIONS AND CONVERSION FACTORS

Factors for converting inch-pound units to International System of Units (SI) and abbreviation of units

Inch-pound units *Multiply*	*By*	Metric units *To obtain*
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.509	square kilometer (km^2)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)

National Geodetic Vertical Datum of 1929 (NGVD of 1929).—A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called mean sea level. NGVD of 1929 is referred to as sea level in the text of this report.

REGIONAL AQUIFER-SYSTEM ANALYSIS

HYDROLOGY OF THE FLORIDAN AQUIFER SYSTEM IN WEST-CENTRAL FLORIDA

By Paul D. Ryder

ABSTRACT

A multilayered ground-water flow system exists in west-central Florida. The lowermost part, called the Floridan aquifer system, which in Florida consists of an Upper and Lower Floridan aquifer, is confined in most of the study area and consists of carbonate rocks ranging in age from Paleocene to Miocene. The Upper Floridan aquifer, about 500 to over 1,800 ft in thickness, is the chief source for large withdrawals and natural springflow in the study area—a 10,600-mi^2 area that approximately coincides with the management area of the Southwest Florida Water Management District. Predevelopment springflows within the study area averaged about 2,300 Mgal/d. By 1976, water-well development accounted for an additional average outflow of about 950 Mgal/d.

The shallow aquifers, including the permeable deposits of the intermediate aquifer and the surficial aquifer, are much less permeable than the Floridan aquifer system and are not present everywhere in the study area. Where they are present and have heads higher than those in the Floridan aquifer system, they provide recharge to the Floridan. Initial estimates of recharge to the Upper Floridan aquifer were based on water-balance calculations for surface-water basins; initial estimates of transmissivity were based on aquifer tests and flow-net analyses.

In the north, the Upper Floridan aquifer is at or near land surface. Transmissivity is high, ranging upward to over 1,000,000 ft^2/d. in the vicinity of high-yield springs. Recharge rates are relatively high, averaging 20 in. per year in some areas. Much of the recharge enters highly developed solution channels in about the upper 200 ft of the aquifer and flows relatively short distances before emerging as spring discharge.

In the south, the Upper Floridan aquifer is overlain by the less permeable intermediate aquifer and confining beds. Recharge to the Upper Floridan aquifer occurs as leakage from the surficial aquifer through thick confining beds. Discharge occurs principally as diffuse upward leakage as opposed to spring discharge. The thick confining beds in the south result in a flow system that is less vigorous than in the north.

A digital model was calibrated for the predevelopment era, wherein steady-state flow conditions were assumed (Ryder, 1982). Transmissivity and recharge rates were adjusted during calibration to make simulated values of heads and springflows approximate observed values. These values were changed only slightly for the 1976 conditions calibrated in this study. Recharge rates and transmissivity thus derived are similar to initial estimates. Calibrated transmissivities for the Upper Floridan aquifer range from less than 17,00 ft^2/d offshore where the aquifer thins to approximately 13,000,000 ft^2/d near large springs. Under prepumping conditions, simulated recharge to the system was about 2,500 Mgal/d. Of this amount, about 84 percent was discharged as springflow and about 16 percent was diffuse upward leakage, primarily along the coast.

Under 1976 steady-state conditions, total simulated recharge to the Upper Floridan aquifer was 3,200 Mgal/d; of this, 64 percent was discharged as springflow, 30 percent was discharged from wells, and 6 percent was discharged as diffuse upward leakage.

Major water-demand problem areas are the coastal zones from Pasco County southward to Charlotte County, where municipal demands for the year 2035 are projected to increase by about 380 Mgal/d over the 1975 rate. This additional water will have to be obtained mainly from large well fields located inland away from the Gulf and northward, where supplies are abundant. Additional supplies in the south will be derived mainly from increased downward leakage; in the north, they will be derived mainly from intercepted spring discharge.

A digital model simulation of two hypothetical well fields illustrates the large difference in the hydraulics of the flow system in the northern part of the study area compared to that in the south. The simulation also demonstrates the applicability of modeling techniques to water management and planning.

INTRODUCTION

FLORIDAN AQUIFER SYSTEM REGIONAL STUDY

In 1978, the U.S. Geological Survey began a four-year study of the Tertiary limestone aquifer system (hereinafter referred to as the Floridan aquifer system) of the southeastern United States. The purpose of the study, described in detail by Johnston (1978), was to provide a complete description of the hydrogeologic framework, geochemistry, and regional flow system of one of the major aquifer systems and major sources of ground water in the United States. In recent years, problems have developed in utilizing the aquifer, including declining water levels, saltwater intrusion in coastal areas, and inadequate supplies of fresh ground water locally.

The regional study encompasses all of Florida and extends into parts of Georgia, Alabama, and South Carolina—a total of about 90,000 mi^2 (fig. 1). The regional study was divided into subregional, or subproject, areas, as shown in figure 1.

To date (1983), a total of 15 publications—12 regional

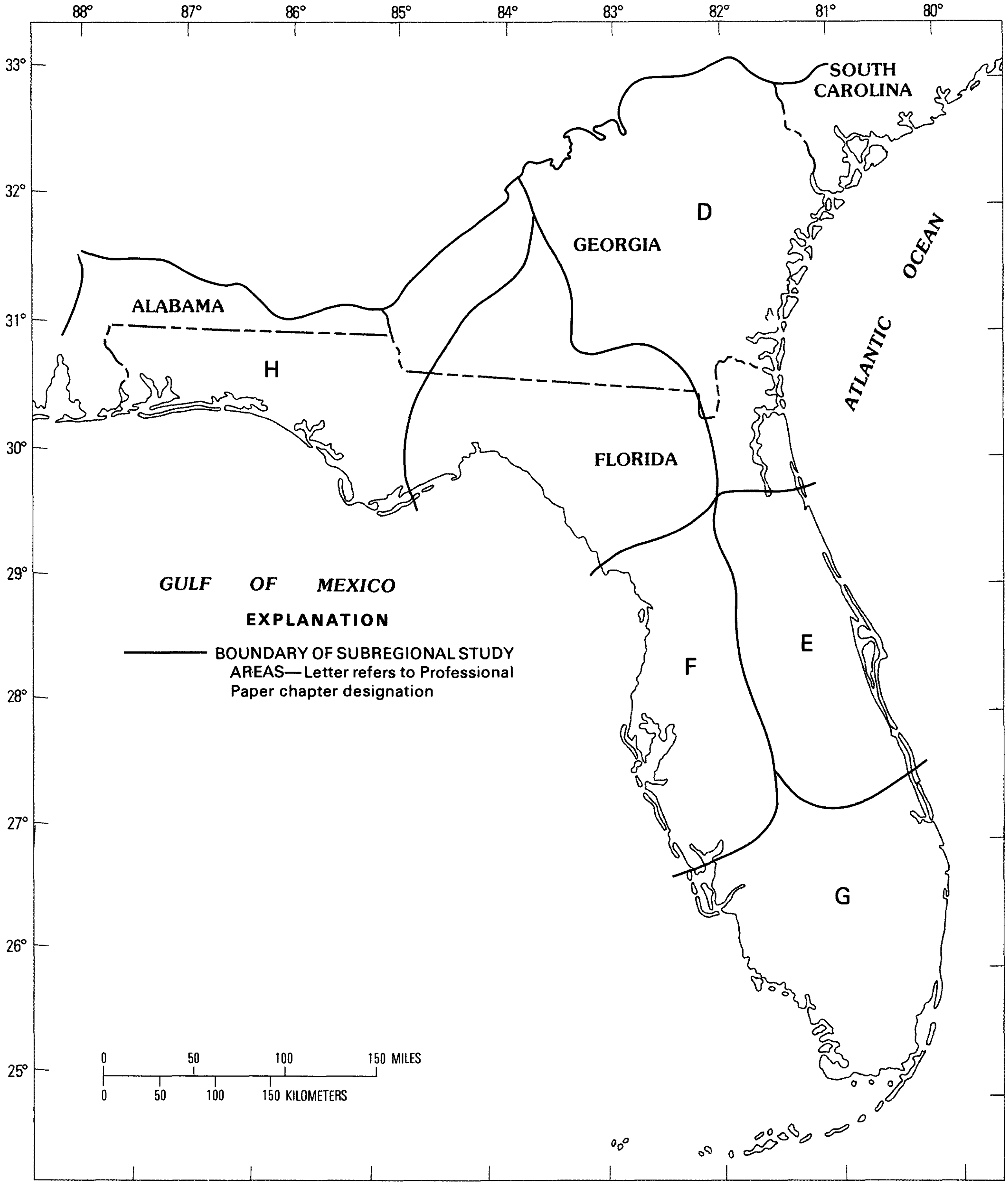


FIGURE 1.—Locations of subregional project areas with professional-paper chapter designation.

and 3 subregional in scope—have resulted from the study. Other activities associated with the study have led to additional published reports; these reports have been site-specific and are included in the "Selected References" section.

The 12 regional publications include: Maps of the potentiometric surface of the Upper Floridan aquifer (Johnston and others, 1980; 1981); maps that describe the thickness, base, and top of the Floridan aquifer system (Miller, 1982a; 1982b; 1982c) and the thickness and base of the Upper Floridan aquifer (Miller, 1982d; 1982e); water-chemistry maps that show sulfate, total hardness, chloride, and dissolved-solids concentrations for the Upper Florida aquifer (Sprinkle, 1982a; 1982b; 1982c; 1982d); and a report that describes the regional flow system prior to development (Bush, 1982). Three reports that describe the hydrogeology and predevelopment flow system in subregions D, E, and F (fig. 1) are, respectively: Tibbals (1981), Krause (1982), and Ryder (1982).

The regional analysis of the Floridan aquifer system is described in a Professional Paper 1403 series that consists of nine chapters as follow:

A. Summary of the hydrology of the Floridan aquifer system in Florida and in parts of Georgia, South Carolina, and Alabama
B. Hydrogeologic framework of the Floridan aquifer system in Florida and in parts of Georgia, South Carolina, and Alabama
C. Ground-water hydraulics, regional flow, and ground-water development of the Floridan aquifer system in Florida and in parts of Georgia, South Carolina, and Alabama
D. Hydrology of the Floridan aquifer system in southeast Georgia and adjacent parts of Florida, and South Carolina
E. Hydrology of the Floridan aquifer system in east-central Florida
F. Hydrology of the Floridan aquifer system in west-central Florida (this report)
G. Ground-water movement in the Floridan aquifer, south Florida
H. Hydrogeology and simulated effects of ground-water development in the Floridan aquifer system, southwest Georgia, northwest Florida, and southernmost Alabama
I. Geochemistry of the Floridan aquifer system in Florida and in parts of Georgia, South Carolina, and Alabama

WEST-CENTRAL FLORIDA SUBREGIONAL STUDY

PURPOSE AND SCOPE

The study that generated this report is one of a series that comprise the U.S. Geological Survey's Regional Aquifer-System Analysis program (RASA), a federally funded, nationwide effort to provide comprehensive descriptions of major aquifer systems in the United States. Specifically, the RASA projects are intended to define (1) the hydrology of the regional aquifers before significant development of ground water; (2) the changes or stresses on the aquifers caused by man; and (3) the hydrology of the aquifers as they exist today, including the effects of development.

The primary method of meeting these objectives was the development of a multilayered, digital ground-water flow model. The modeling section of this report and a preliminary report (Ryder, 1982) document the use of the model to simulate the regional flow system.

Results of this study will aid water managers and others by providing a description of the hydrogeologic framework and the associated ground-water flow system as well as a digital computer model that assesses the effects of large withdrawals of ground water.

DESCRIPTION OF THE AREA

The study area includes all or part of 18 counties in west-central Florida. The nearly 10,600-mi^2 area approximately coincides with the Southwest Florida Water Management District (fig. 2).

Topography in the southern half of the study area is characterized by a low-lying coastal plain that gradually rises toward the east, butting against sand-covered ridges that are about 200 ft above sea level. There are numerous lakes in the ridge areas. Surface-water drainage is relatively well developed; major streams include the Peace, Myakka, Manatee, Little Manatee, and Alafia Rivers.

The ridges trend in a north-northwesterly direction through northwestern Polk, eastern Pasco, east-central Hernando, and central Citrus Counties. Surficial sands and clays become relatively thin and discontinuous in the more northern areas. Locally, the sands and clays may support a perched water table or small lake, but generally limestone lies at or near land surface. Irregular karst topography occurs in northern areas with numerous sinkholes and poorly developed surface drainage. The coastal plain narrows toward the north, reaching its narrowest point in Citrus County. Eastward of the ridge, the topography becomes more subdued and has numerous swamps, lakes and shallow sinkholes. Major streams draining the northern area include the Hillsborough, Anclote, Pithlachascotee, Weeki Wachee, Chassahowitzka, Homosassa, Crystal, Withlacoochee, Oklawaha, and Waccasassa Rivers. Springs that discharge from the Upper Floridan aquifer account for a significant part of the mean annual discharge of many of these streams; for some streams, the discharges are virtually all springflow.

Records from 23 weather stations within and near the study area show that average rainfall for the period 1915 to 1976 ranged from 48 in./yr at Tampa to nearly 57 in./yr at Brooksville (Palmer and Bone, 1977, p. 6). More than half of the total rainfall occurs from June through September.

FIGURE 2.—Location of study area.

PREVIOUS INVESTIGATIONS

Numerous geological and hydrogeological investigations within or including the study area have led to published reports by the U.S. Geological Survey, the Florida Bureau of Geology (formerly the Florida Geological Survey), other State and Federal agencies, consulting firms, and others.

A regional report on the Tertiary limestone aquifer by Stringfield (1966) included a review of the literature and a comprehensive summary of the hydrogeology and geochemistry of the Floridan aquifer system. Wilson and Gerhart (1982) studied the Upper Floridan aquifer in an area of about 3,500 mi^2 in Manatee, Sarasota, Charlotte, De Soto, Hardee, and parts of Hillsborough and Polk Counties. They presented the results of a two-dimensional, single-layer, digital flow model. Grubb and Rutledge (1979) also used a two-dimensional, single-layer, digital flow model to evaluate the water-supply potential in an 870-mi^2 area known as the Green Swamp that includes parts of Polk, Pasco, Hernando, Sumter, and Lake Counties. Faulkner (1973a) discussed the hydrology of large springs associated with one of the world's most highly developed subsurface drainage systems in Marion County. A comprehensive study of the water resources of the Southwest Florida Water Management District (U.S. Army Corps of Engineers, 1980) focused on the problems of water-resource development and management. Other reports and investigators are listed in the section "Floridan Aquifer System Regional Study" and are referred to in subsequent sections of the present report.

HYDROGEOLOGIC FRAMEWORK AND HYDRAULIC PROPERTIES

FLORIDAN AQUIFER SYSTEM

The Floridan aquifer system consists of a thick sequence of carbonate rocks of Tertiary age (table 1). Parker and others (1955, p. 189) originally defined the Floridan aquifer as including parts or all of the Avon Park and Lake City Limestones, Ocala Limestone, Suwannee Limestone, Tampa Limestone, and permeable parts of the Hawthorn Formation that are in hydrologic contact with the rest of the aquifer.

More recently, Miller (1984) provided a regional definition of the Floridan aquifer system presenting maps of the top, base, and thickness of the system and its component aquifers. Because distinct, regionally mappable, hydrogeologic units occur within the Floridan, the term "aquifer system" is preferred to simply "aquifer." Usage of "system" follows Poland and others (1972), who stated that an aquifer system "comprises two or more permeable beds separated at least locally by aquitards that impede ground-water movement but do not greatly affect the regional hydraulic continuity of the system." This definition describes the Floridan aquifer system throughout much of its area of occurrence.

The Floridan aquifer system is defined in this Professional Paper as a vertically continuous sequence of carbonate rocks of generally high permeability that are of Tertiary age, that are hydraulically connected in varying degrees, and whose permeability is several orders of magnitude greater than that of those rocks that bound the system above and below. As shown in table 1, the Floridan aquifer system includes units of late Paleocene to early Miocene age. Professional Paper 1403-B presents a detailed geologic description of the Floridan, its component aquifers and confining units, and their relation to stratigraphic units. The Eocene and Paleocene stratigraphic units were revised in Chapter B, but the revisions are not used in the present report. (See footnote 2 in table 1.) The original definitions of stratigraphic units by Parker and others (1955) are used.

The Floridan aquifer system generally consists of an upper and lower aquifer separated by a less permeable unit of highly variable properties (table 2). In the northern part of the study area, there is little permeability contrast within the system, and the Floridan is effectively one continuous aquifer. Throughout most of the study area, the Floridan consists of two aquifers: the thick Upper Floridan aquifer containing freshwater (except along the coast) and separated by a "tight" confining unit from the Lower Floridan aquifer, which generally contains saltwater. In most reports on the hydrology of west-central Florida, the term "Floridan aquifer" has been applied to the rocks herein referred to as the Upper Floridan aquifer.

The base of the Upper Floridan aquifer in west-central Florida is generally at the first occurrence of vertically persistent, intergranular evaporites. This base is equivalent to "middle confining unit" used regionally in Professional Papers 1403-A, 1403-B, and 1403-C. Hydraulic tests of rocks with intergranular evaporites indicate that they have extremely low permeabilities. The rocks below the "middle confining unit" have known or estimated low transmissivity; therefore, for all practical purposes, freshwater flow is limited to rocks above the section with intergranular evaporites in west-central Florida.

The hydrogeology of the Floridan aquifer system is discussed in detail in Professional Paper 1403-B and is briefly summarized here. Figure 3 shows locations of geologic sections depicted in figures 4,5,6, and 7. Section A-A' (fig. 4) shows the thinness or absence of the Alachua Formation, Tampa Limestone, and Suwannee Limestone. The Ocala Limestone generally forms the top of the

TABLE 1.—*Hydrogeologic framework*
[Modified from Wilson and Gerhart, 1982, table 1]

System	Series	Stratigraphic unit	General lithology	Major lithologic unit	Hydrogeologic unit
Quaternary	Holocene and Pleistocene	Surficial sand, terrace sand, phosphorite	Predominantly fine sand; interbedded clay, marl, shell, limestone, phosphorite	Sand	Surficial aquifer
Tertiary	Pliocene	Undifferentiated deposits[1]	Clayey and pebbly sand; clay, marl, shell, phosphatic	Clastic	INTERMEDIATE AQUIFER AND CONFINING BEDS: Confining bed
	Miocene	Hawthorn Formation	Dolomite, sand, clay, and limestone; silty, phosphatic	Carbonate and clastic	INTERMEDIATE AQUIFER AND CONFINING BEDS: Aquifer
		Tampa Limestone	Limestone, sandy, phosphatic, fossiliferous; sand and clay in lower part in some areas	Carbonate and clastic / Carbonate	INTERMEDIATE AQUIFER AND CONFINING BEDS: Confining bed / FLORIDAN AQUIFER SYSTEM
	Oligocene	Suwannee Limestone	Limestone, sandy limestone, fossiliferous	Carbonate	FLORIDAN AQUIFER SYSTEM: Upper Floridan aquifer
	Eocene	Ocala Limestone	Limestone, chalky, foraminiferal, dolomitic near bottom	Carbonate	FLORIDAN AQUIFER SYSTEM: Upper Floridan aquifer
		Avon Park Limestone[2]	Limestone and hard brown dolomite; intergranular evaporite in lower part in some areas	Carbonate / Carbonate with evaporites	Upper Floridan aquifer / Middle confining unit
		Lake City Limestone and Oldsmar Limestone[2]	Dolomite and limestone, with intergranular gypsum in most areas	Carbonate with evaporites	Lower Floridan aquifer
	Paleocene	Cedar Keys Limestone[2]	Dolomite and limestone with beds of anhydrite	Carbonate with evaporites	Lower confining unit

[1]Includes all or parts of Caloosahatchee Marl, Bone Valley Formation, Alachua Formation, and Tamiami Formation.

[2]Since this report was prepared, the Avon Park, Oldsmar, and Cedar Keys Limestones have been changed to the Avon Park, Oldsmar, and Cedar Keys Formations. The Lake City Limestone has been abandoned, and the rocks are included in the lower part of the Avon Park Formation (Miller, 1984).

Floridan aquifer system. In figure 4, the intergranular evaporites occur in the Avon Park and Lake City Limestones, undifferentiated. These deposits pinch out from west to east, and the base of the aquifer system becomes the top of evaporite beds in the Cedar Keys Limestone.

Section *B-B'* (fig. 5) trends approximately east-west through the central part of the study area. The contact at the Tampa Limestone and Hawthorn Formation generally forms the top of the Floridan aquifer system. The first occurrence of intergranular evaporites in the Avon Park and Lake City Limestones, undifferentiated, marks the base of the Upper Floridan aquifer.

Section *C-C'* (fig. 6 is in the extreme southern part of the study area. Formations overlying the top of the Floridan aquifer system (top of Suwannee Limestone) are relatively thick and contain thick confining beds. The first occurrence of intergranular evaporites marks the base of the Upper Floridan aquifer.

Section *D-D'* (fig. 7) is approximately north-south through the study area. The section shows a thinning of the Upper Floridan aquifer and the disappearance of overlying formations form south to north as progressively younger rocks pinch out.

In the central and southern areas, the Upper Floridan aquifer has pronounced vertical anisotropy. Permeabilities are relatively low in the Ocala Limestone and very high in fractured dolomitic zones within the Avon Park Limestone, as substantiated by flow-meter and specific-capacity tests.

TABLE 2.—*Aquifers and confining units of the Floridan aquifer system*

PROFESSIONAL PAPER 1403 CHAPTER	A, B, C, I	H		D		E	F	G	
	Regional Summaries	Florida Panhandle	SW Georgia NW Florida	South Carolina SE Georgia	NE Florida	East-Central Florida	West-Central Florida [1-2]	SW Florida [2]	SE Florida [2]
	(Upper confining unit)						Intermediate aquifers and confining beds		
FLORIDAN AQUIFER SYSTEM	Upper Floridan aquifer								
	Middle confining unit		Middle semi-confining unit		Middle semi-cofining unit		Middle confining unit		
	Lower Floridan aquifer								
	Lower confining unit				Fernandina permeable zone	Lower confining unit			

[1] Many reports on west central Florida use the term "Floridan aquifer" as synonomous with the Upper Floridan aquifer as shown

[2] In west central and south Florida, the upper confining unit may contain one or more intermediate aquifers

Wolansky and others (1980) have mapped the top of the highly permeable Avon Park dolomite zone in the study area (fig. 8). Despite the large permeability contrasts, aquifer-test results indicate that enough vertical interconnection exists between each formation to analyze the Upper Floridan aquifer as a single hydrologic unit on a regional basis.

North of Pasco County, where the Ocala Limestone is at or near land surface, the permeability of this formation increases substantially, as indicated by its cavernous nature, high recharge rates, and numerous large springs. The Avon Park Limestone crops out in the Levy County area (fig. 7). In the general area of Levy and Marion Counties, Faulkner (1973a, p. 72-77) suggested that the Avon Park Limestone may be considerably less permeable than the Ocala Limestone. As evidence, he cited the following: (1) Pronounced highs in the potentiometric surface in southeast Levy County and southwest Marion County, where the Avon Park Limestone is at or near land surface, are the result of relatively low permeability in the Avon Park: (2) Recrystallization during dolomitization of the Avon Park Limestone may not only have reduced effective intergranular porosity, but because dolomite is much less soluble than limestone, development of solution channels from circulating ground water must also have been reduced: (3) Dissolved-solids concentrations, sulfate concentrations, and temperature of water form Rainbow Springs in southwest Marion County and Silver Springs in central Marion County suggest that the water has traveled relatively short distances through a well-developed solution-channel system in the shallower part of the aquifer, as opposed to flow through the less permeable, underlying Avon Park Limestone where water is known to be more mineralized. Total thickness of the Upper Floridan aquifer in the north ranges from about 500 ft in Levy County to about 1,800 ft in Marion County. The altitude of the top of the Upper Floridan Aquifer is shown in figure 9, and the thickness of the Upper Floridan aquifer is shown in figure 10.

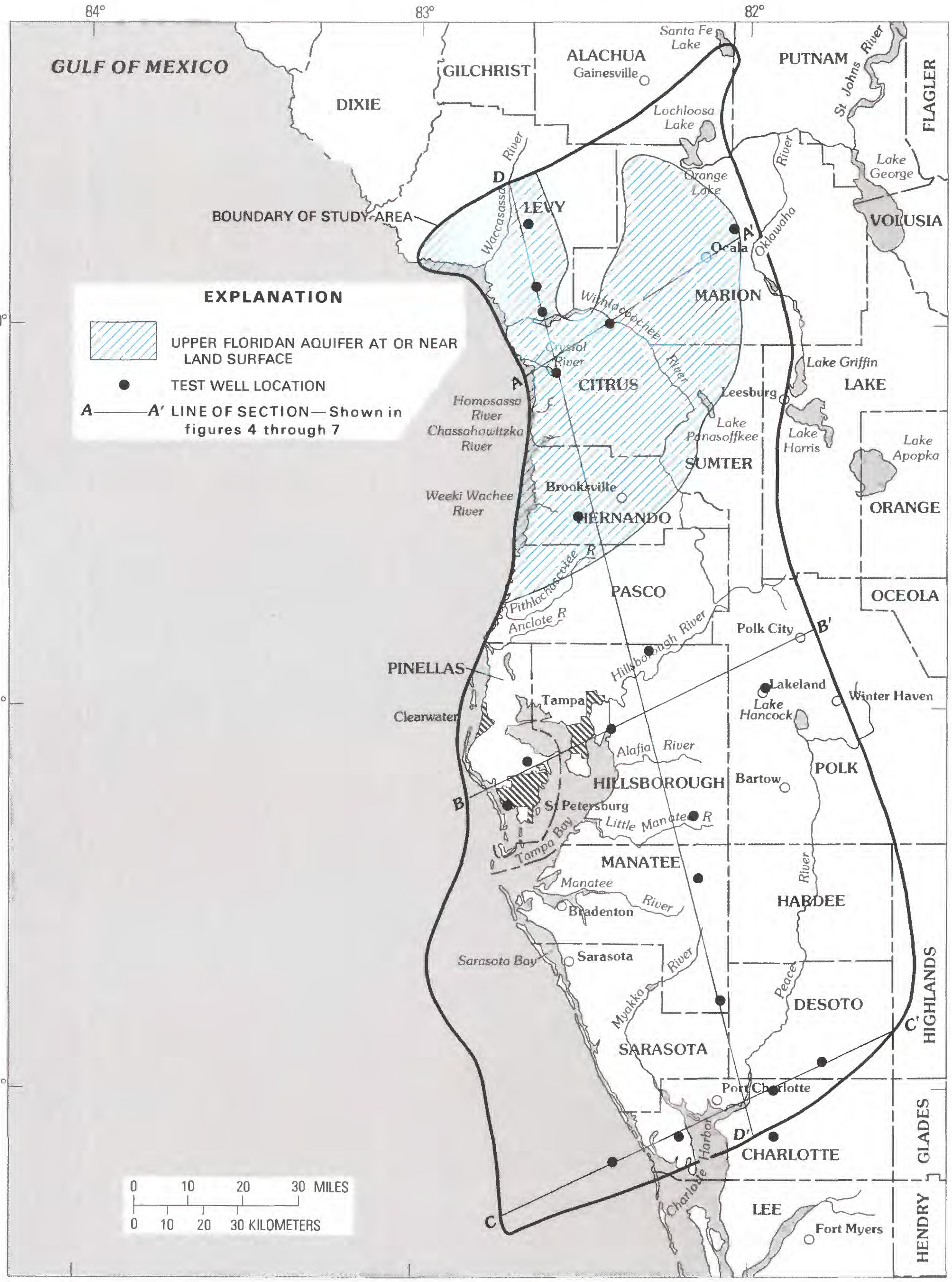


FIGURE 3.—Locations of geologic sections and area where the Upper Floridan aquifer is at or near land surface.

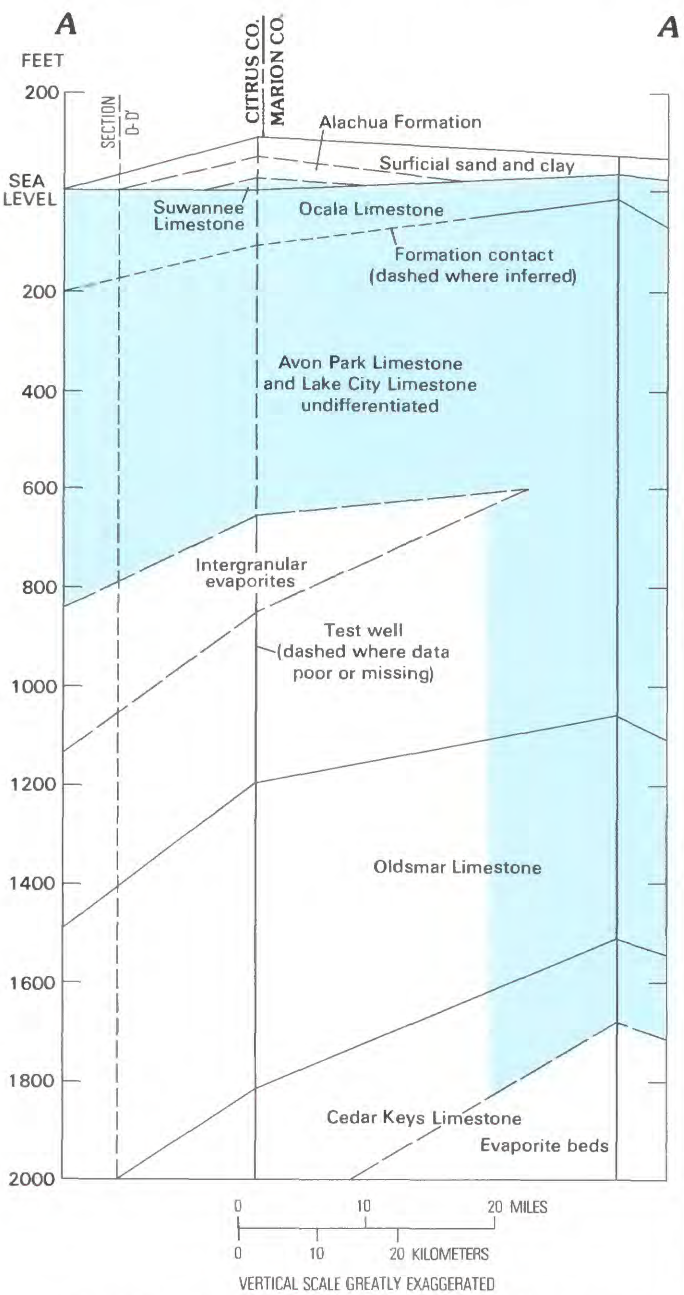


FIGURE 4.—Geologic section *A–A′* (J.A. Miller, written commun., 1981).

Plate 1 shows the transmissivity for the Upper Floridan aquifer determined form field tests (point values) and areal values derived form a calibrated digital model. (The model calibration is discussed in a later section of this report.) Nearly all wells associated with the field tests penetrated the more permeable zones of the aquifer; thus transmissivities should characterize the Upper Floridan. However, the interval continuing saline water (greater than 10,000 mg/L chloride concentration) is not considered to be part of the flow system in this report. Thus, transmissivities on plate 1 decrease progressively toward the Gulf as the freshwater section thins. In Pinellas and Sarasota Counties (where the upper, predominantly freshwater, part of the aquifer system is thin), the transmissivity is considerably lower than would be the case if the entire Upper Floridan aquifer, particularly the Avon Park dolomite zones, contained freshwater.

The transmissivity distribution derived from the calibrated model agrees reasonably well with field aquifer-test data (plate 1). Model-derived transmissivities range from 17,000 ft^2/d in the southwest, where the freshwater section of the aquifer system becomes progressively thinner seaward, to nearly 13,000,000ft^2/d near large springs in the north. Most transmissivities are in the range of 50,000 to 500,000ft^2/d. A model-sensitivity analysis (Ryder, 1982, p. 40) showed that the modeled estimate of transmissivity is more likely to be too low than too high.

Transmissivity in the southern two-thirds of the area is relatively uniform over large areas, and the range of transmissivity is not much greater than one order of magnitude. Development of large solution channels is relatively rare in the south and transmissivity correlates with total aquifer thickness better than any other hydrogeologic characteristic.

Hydrologic conditions in the north, particularly in the vicinity of large springs in Marion, Citrus, and Hernando Counties, are considerably different from those in the south. In these counties, solution channels in the Ocala Limestone apparently are highly developed. As discussed by Faulkner (1973a, p. 69–70), flow paths that converge into troughs in the potentiometric surface may indicate solution-channel systems that become increasingly well developed as large springs, such as Silver and Rainbow Springs, are approached. Because there is no increase in hydraulic gradient, a progressive increase in permeability is required to accommodate the increasing volume of flow that converges in the areas of discharge. Faulkner (1973a, p. 97) used a flow-net analysis to calculate an average transmissivity of about 2x10^{6}ft^2/d in the vicinity of Silver Springs. Thus, in areas that have large springs and low hydraulic gradients, transmissivity would be lowest at the divides of ground-water basins in which the springs are located and also be much lower in the interchannel zones than in the solution-channel zones. Transmissivities that were derived from the digital model are averages, representative of solution channels, interchannel zones, and the underlying, less permeable dolomite.

Distribution of the storage coefficient in areas where the Upper Floridan aquifer is confined was estimated by applying an average specific storage value of 1.0x10^{-6} times the aquifer thickness shown in figure 10. The specific storage value is an approximate value for most confined aquifers (Lohman, 1972, p. 8). This method for

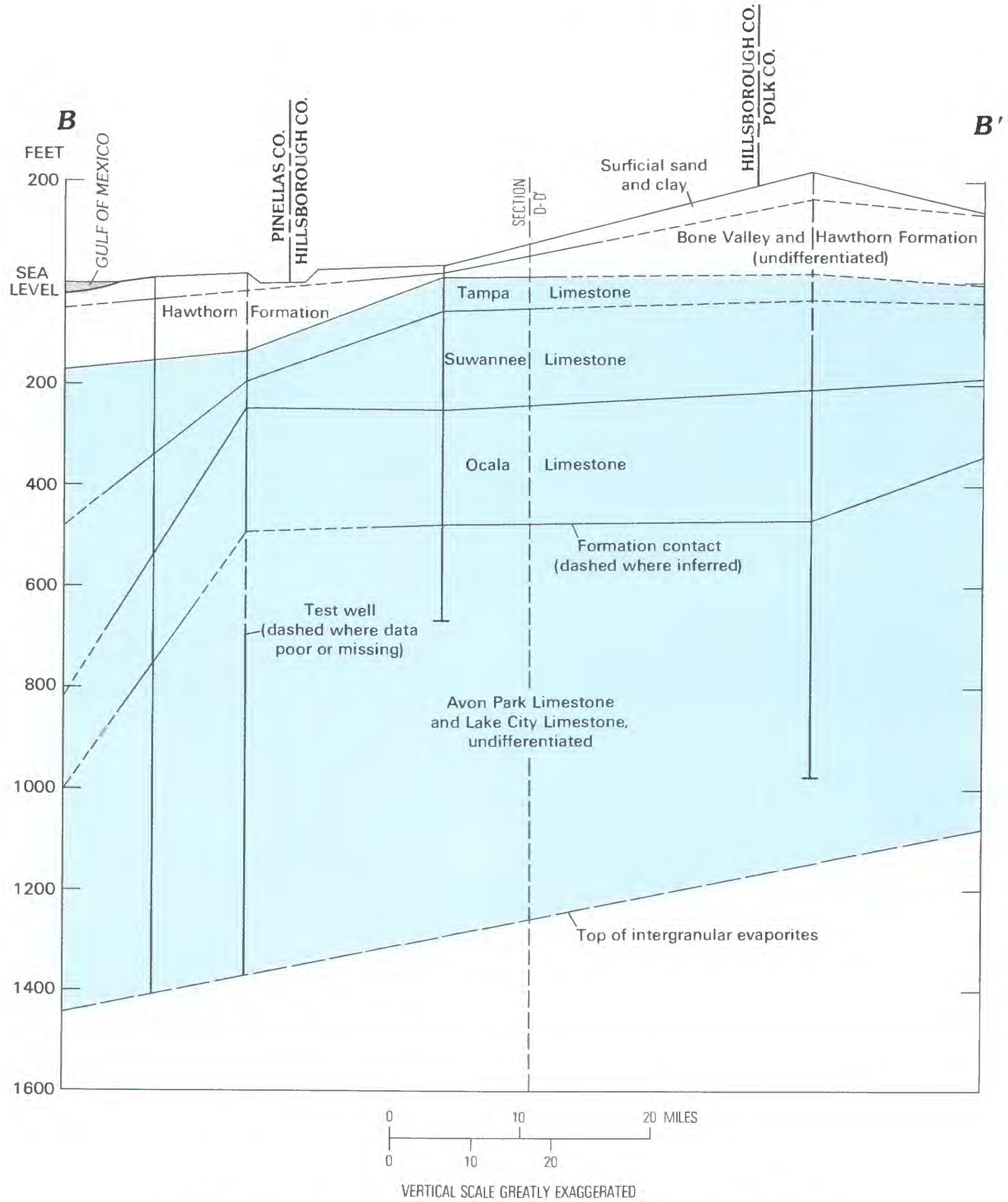


FIGURE 5.—Geologic section *B–B′* (J.A. Miller, written commun., 1981).

estimating storage coefficient was also used by Wilson and Gerhart (1982, p. 9) for the southern half of the study area. The method gives storage coefficient values that range from 5×10^{-4} to 1.8×10^{-3}; these values are fairly consistent with aquifer-test results.

INTERMEDIATE AQUIFER AND CONFINING BEDS

In a large area in the north, the Upper Floridan aquifer is at or near land surface (fig. 11) and can generally be described as unconfined, although local confining conditions do exist. However, for most of west-central Florida, the Upper Floridan aquifer is overlain by less permeable beds of the intermediate aquifer (defined by Franks, 1982) and confining beds that restrict movement of water (upward or downward) between the surficial aquifer and the Floridan. The intermediate aquifer and confining beds are equivalent to the "upper confining unit" used regionally in Professional Papers 1403-A, 1403-B, and 1403-C.

Within the intermediate aquifer and confining beds are deposits of sufficient permeability and sufficient

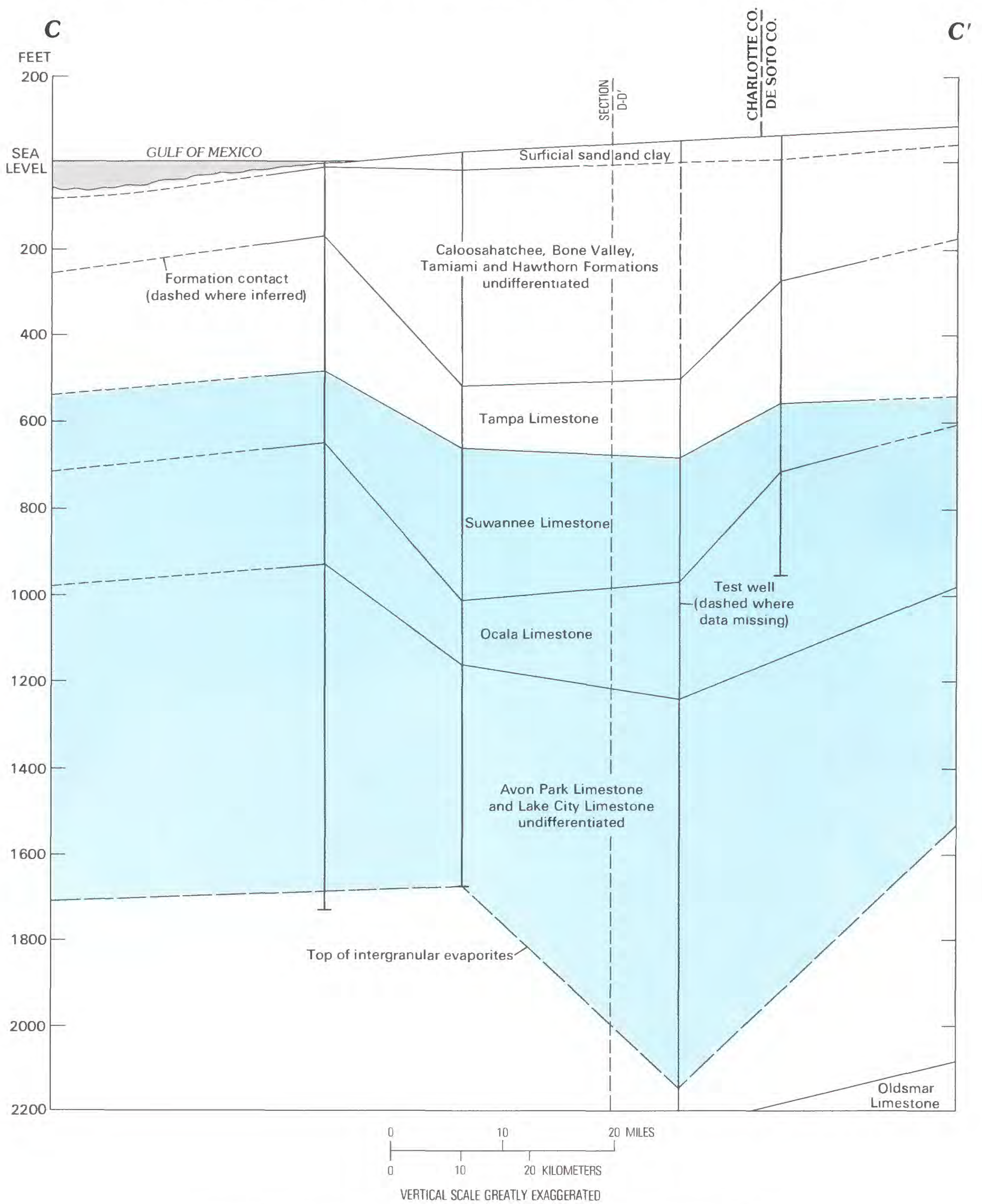


FIGURE 6.—Geologic section *C–C'* (J.A. Miller, written commun., 1981).

importance as a water supply in coastal areas to warrant inclusion as an aquifer layer in the digital model developed for this study. The intermediate aquifer and confining beds thus consist of three hydrogeologic units (table 1): (1) a confining bed in the lower part that lies directly on the Upper Floridan aquifer; (2) an aquifer that consists primarily of carbonate rocks within the Hawthorn Formation; and (3) a confining bed in the upper part that

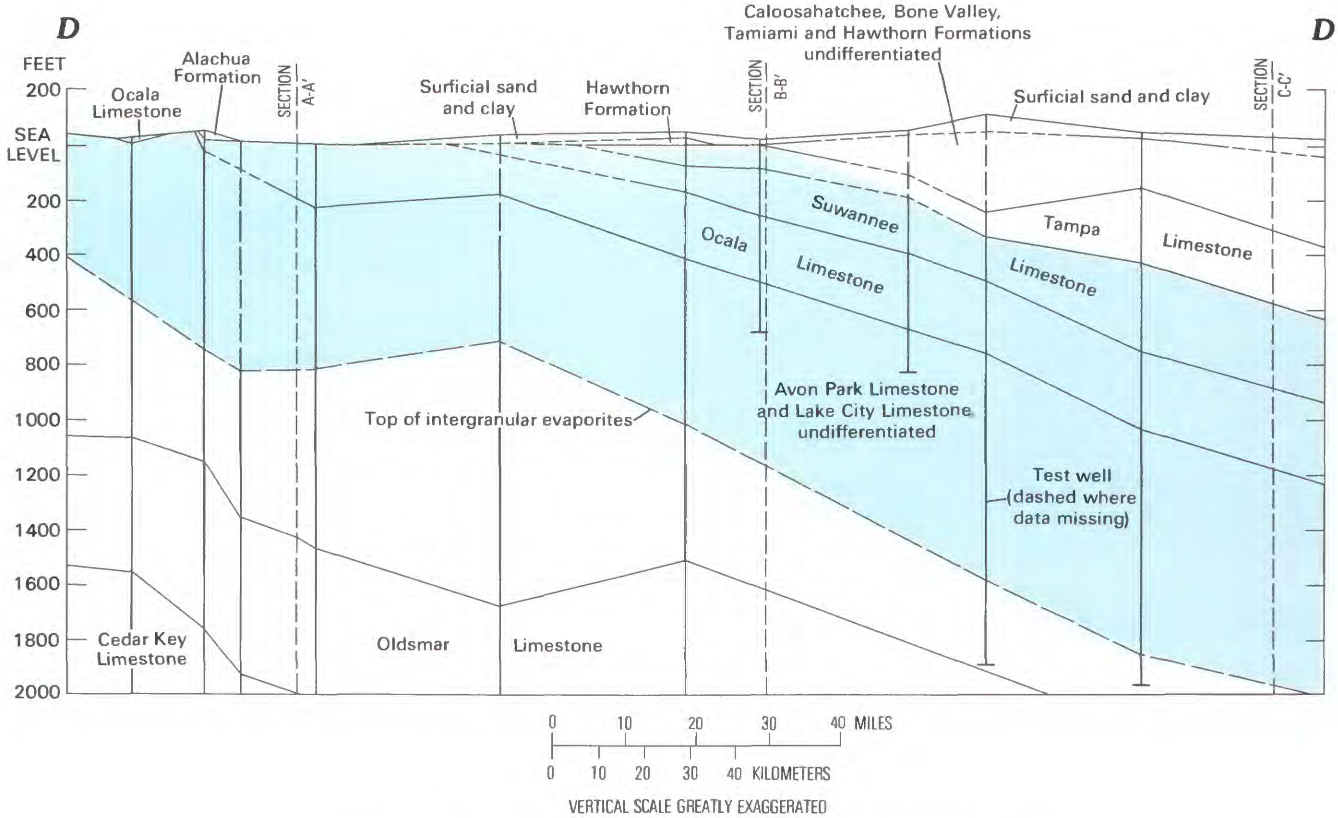


FIGURE 7.—Geologic section *D-D'* (J.A. Miller, written commun., 1981).

separates the water-bearing unit in the intermediate aquifer from the surficial aquifer.

The thickness of the lowermost intermediate confining bed for the northern area (fig. 11) was obtained from Buono and others (1979) and was estimated from geologic logs for the southern area. Figure 11 also shows leakance values (the ratio of vertical hydraulic conductivity of the confining bed to its thickness) for the confining bed as determined form aquifer tests and as derived from a calibrated digital model. Although only a few field leakance determinations are available, leakance values are reasonably similar to model-derived values. Leakance values range from $1\text{x}10^{-7}$ to $7\text{x}10^{-4}$ (ft/d)/ft.

The physical significance of the leakance values can be illustrated by examining the northern area, where values of leakance are generally greater than $1\text{x}10^{-4}$ft/d)/ft. For each foot of head difference between the surficial and Floridan aquifers in this area, at least 0.4 in./yr of recharge (or discharge) will flow through the confining bed.

The permeable deposits of the intermediate aquifer consist primarily of carbonate rocks within the Hawthorn Formation. They were formerly referred to as the secondary artesian aquifer (Stewart, 1966, p. 83). These permeable deposits are confined below by clay beds in the Tampa Limestone or, where the Tampa is part of the Upper Floridan aquifer, by less permeable material in the lower part of the Upper Floridan aquifer, by less permeable material in the lower part of the Hawthorn Formation. Geologic section *B-B'* (fig. 5) very nearly coincides with the northernmost extent of the permeable deposits of the intermediate aquifer. Toward the south, the deposits consist of permeable carbonates of the Tampa Limestone and the Hawthorn Formation. The permeable deposits thicken southward from less than 25 ft in Hillsborough and Polk Counties to about 400 ft in Charlotte County (fig. 12).

Transmissivities for the permeable deposits of the intermediate aquifer, as determined by field tests and as derived from the calibrated digital model, are shown in figure 13. Model-derived transmissivities are similar to values determined by aquifer tests, and range from nearly zero, where the deposits pinch out, to about 10,000 ft^2/d. Higher values coincide with the course of the Peace River, indicating that perhaps a more active flow system exists where ground water discharges to the river and secondary development of the carbonate rocks is enhanced.

Discontinuous clay beds may occur within the permeable deposits of the intermediate aquifer, particularly toward the coast. Where this occurs, the permeable zone

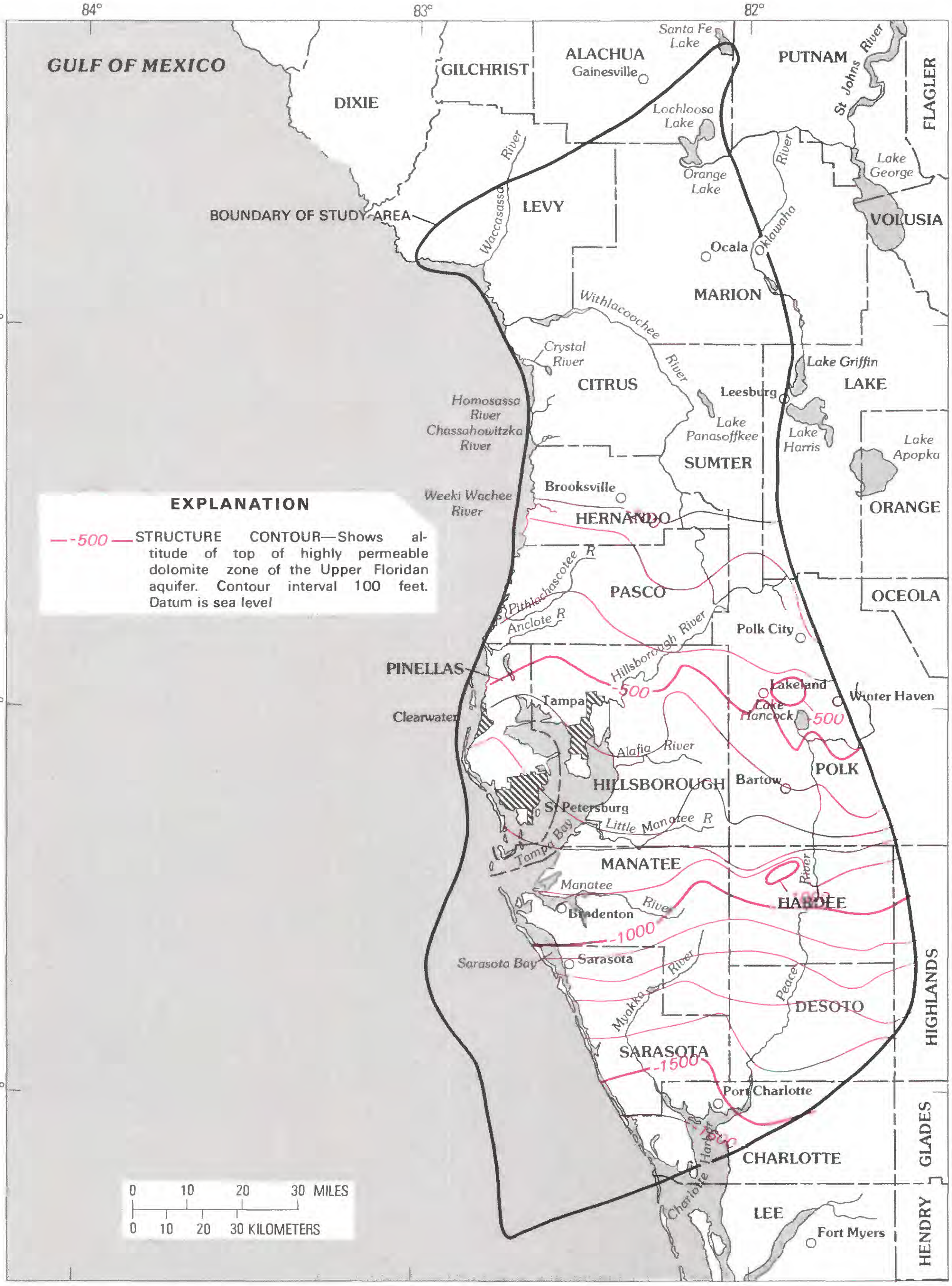


FIGURE 8.—Altitude of the top of the highly permeable dolomite zone of the Upper Floridan aquifer (Wolansky and others, 1980).

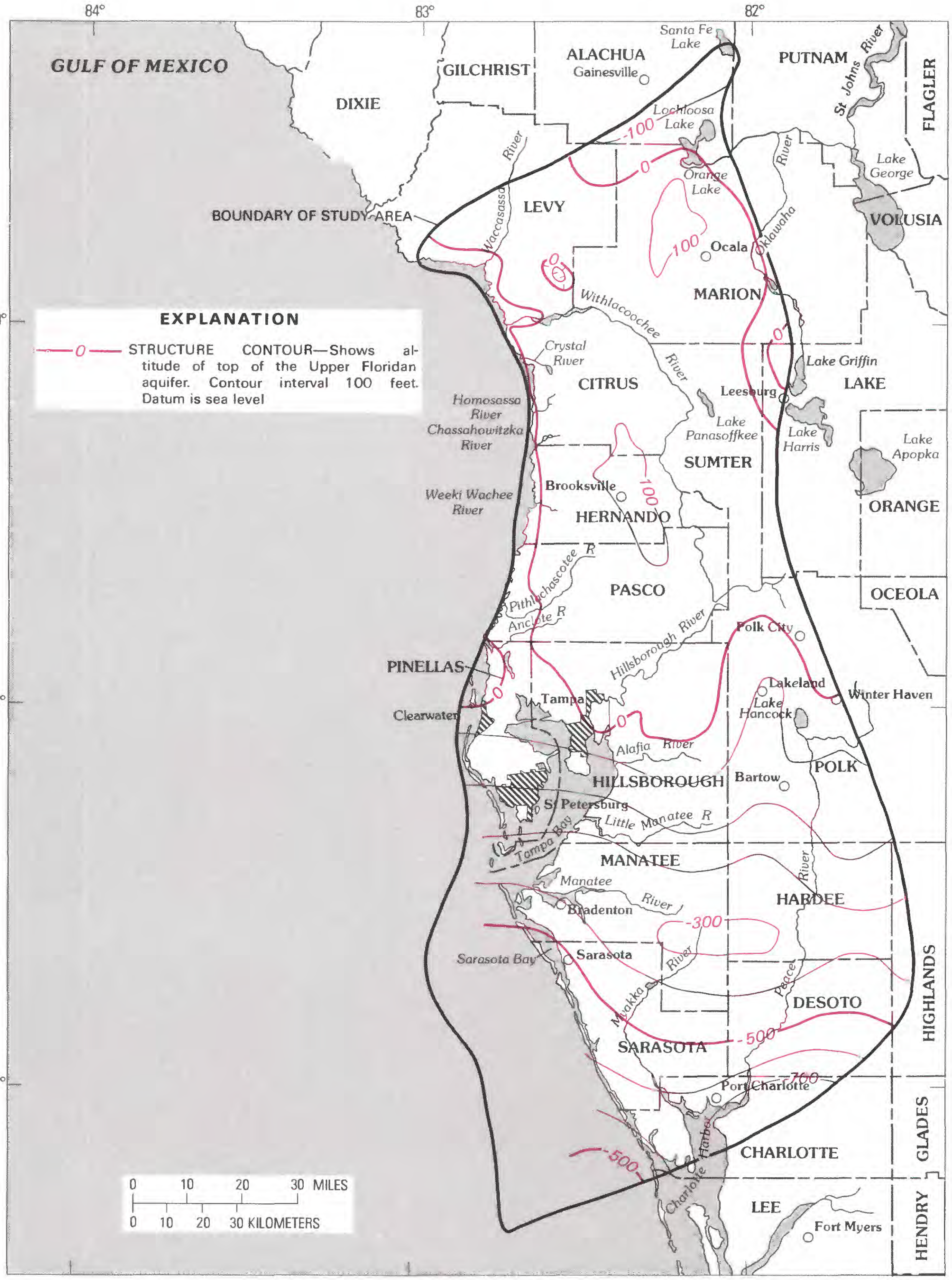


FIGURE 9.—Altitude of the top of the Upper Floridan aquifer (from Miller, 1982c).

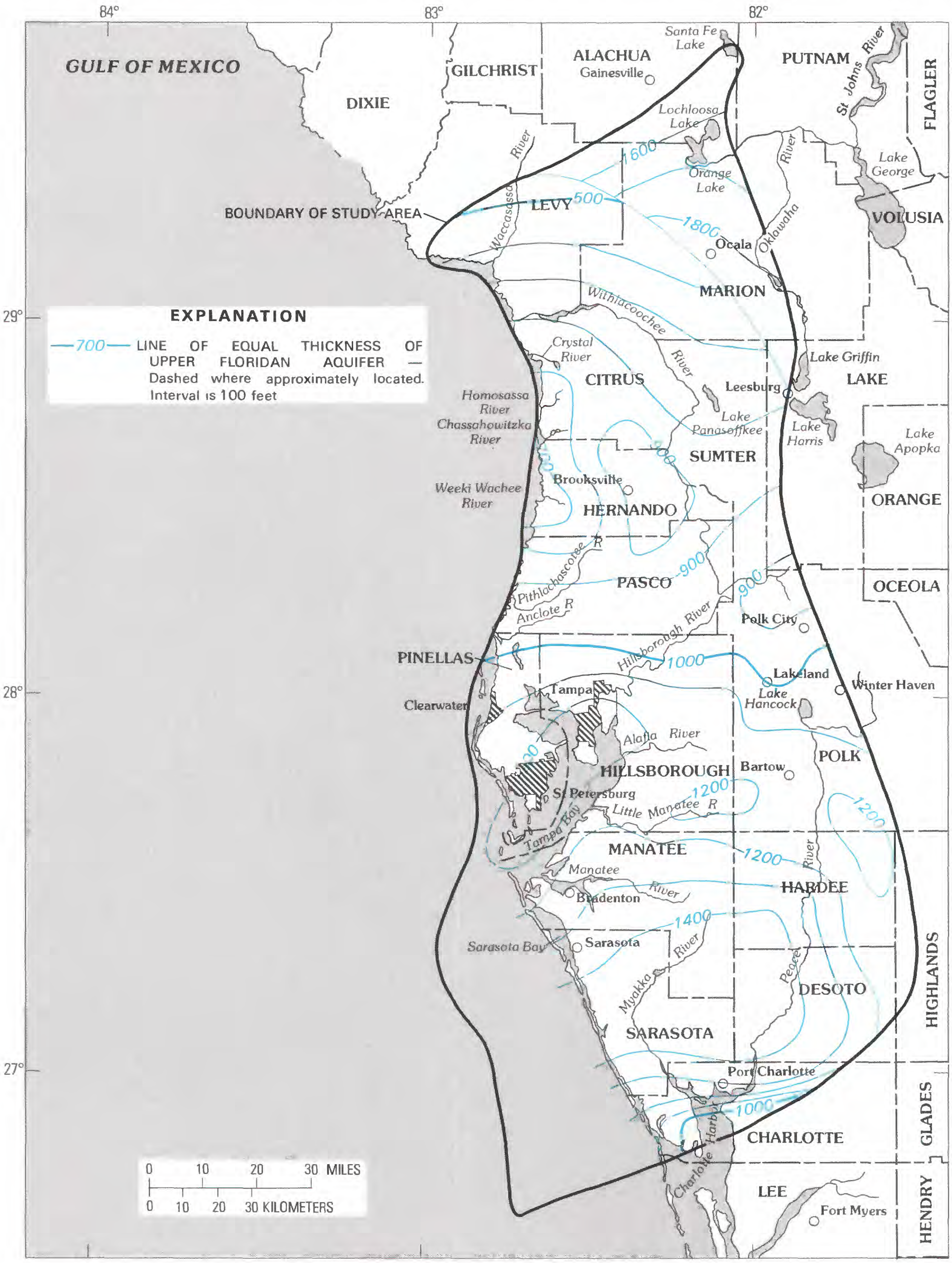


FIGURE 10.—Thickness of the Upper Floridan aquifer (modified from Miller, 1982d).

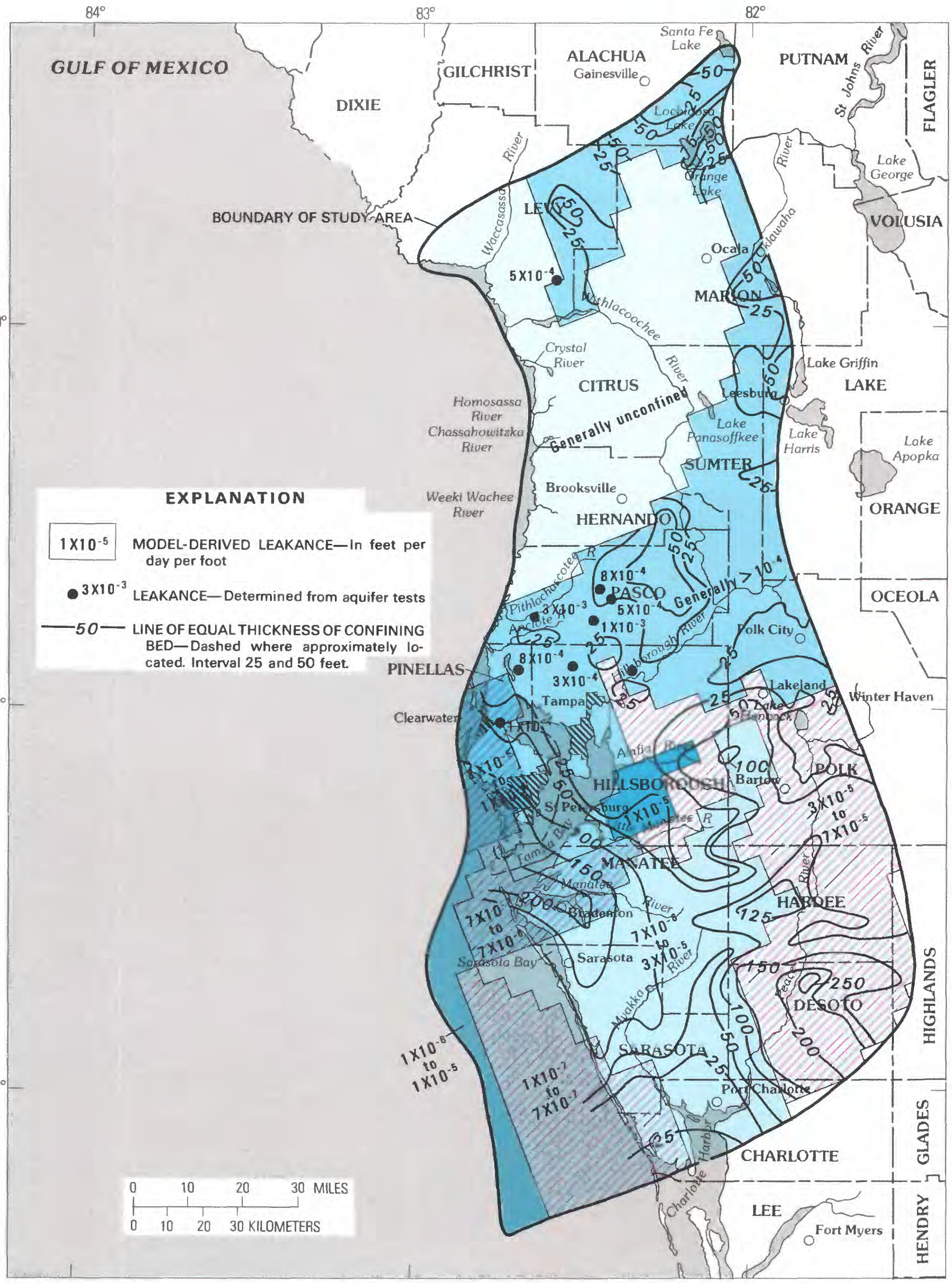


FIGURE 11.—Thickness and field and model-derived leakance of lowermost intermediate confining bed. (Aquifer-test references are in Ryder, 1982, table 2).

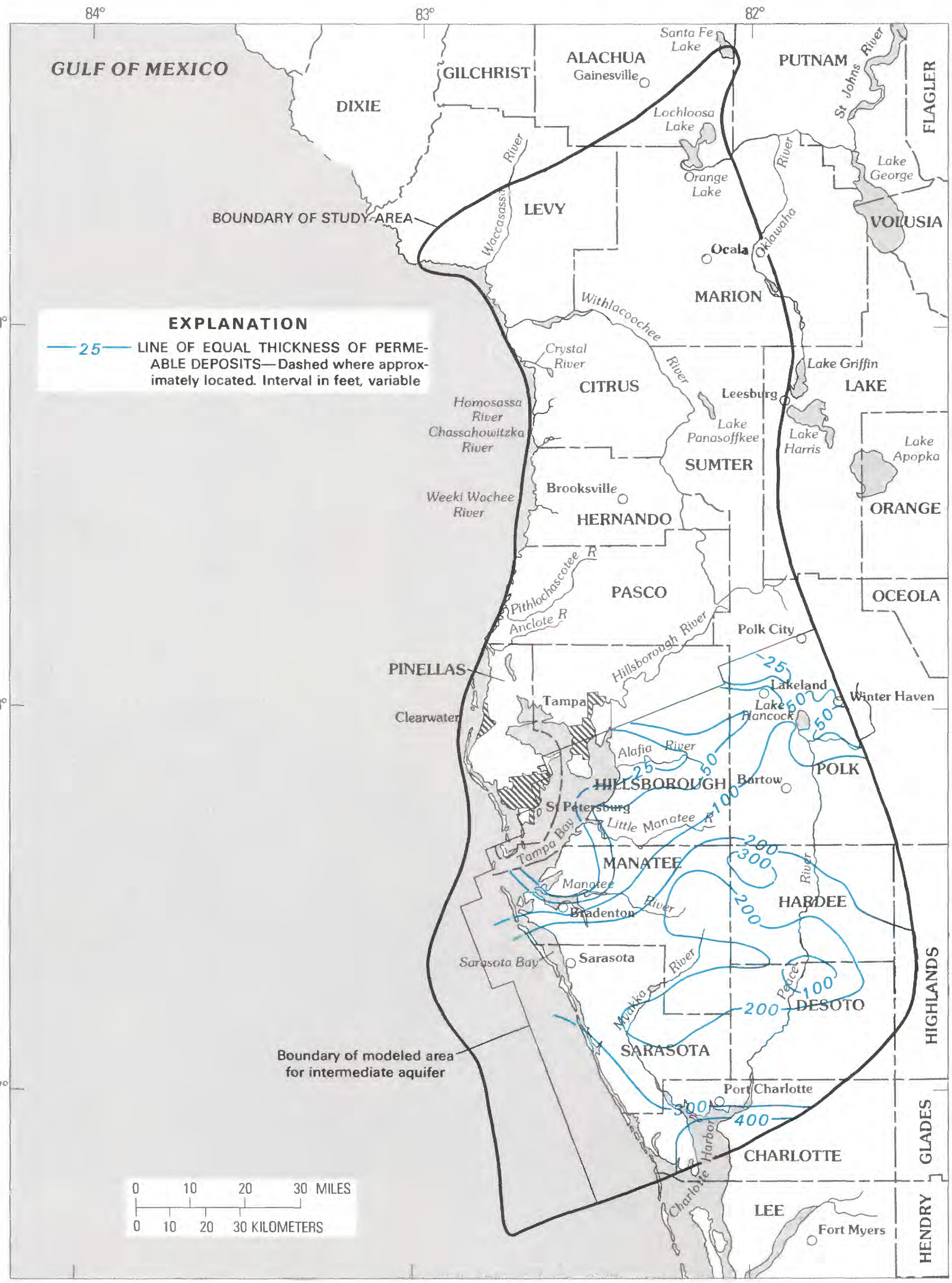


FIGURE 12.—Thickness of the permeable deposits of the intermediate aquifer.

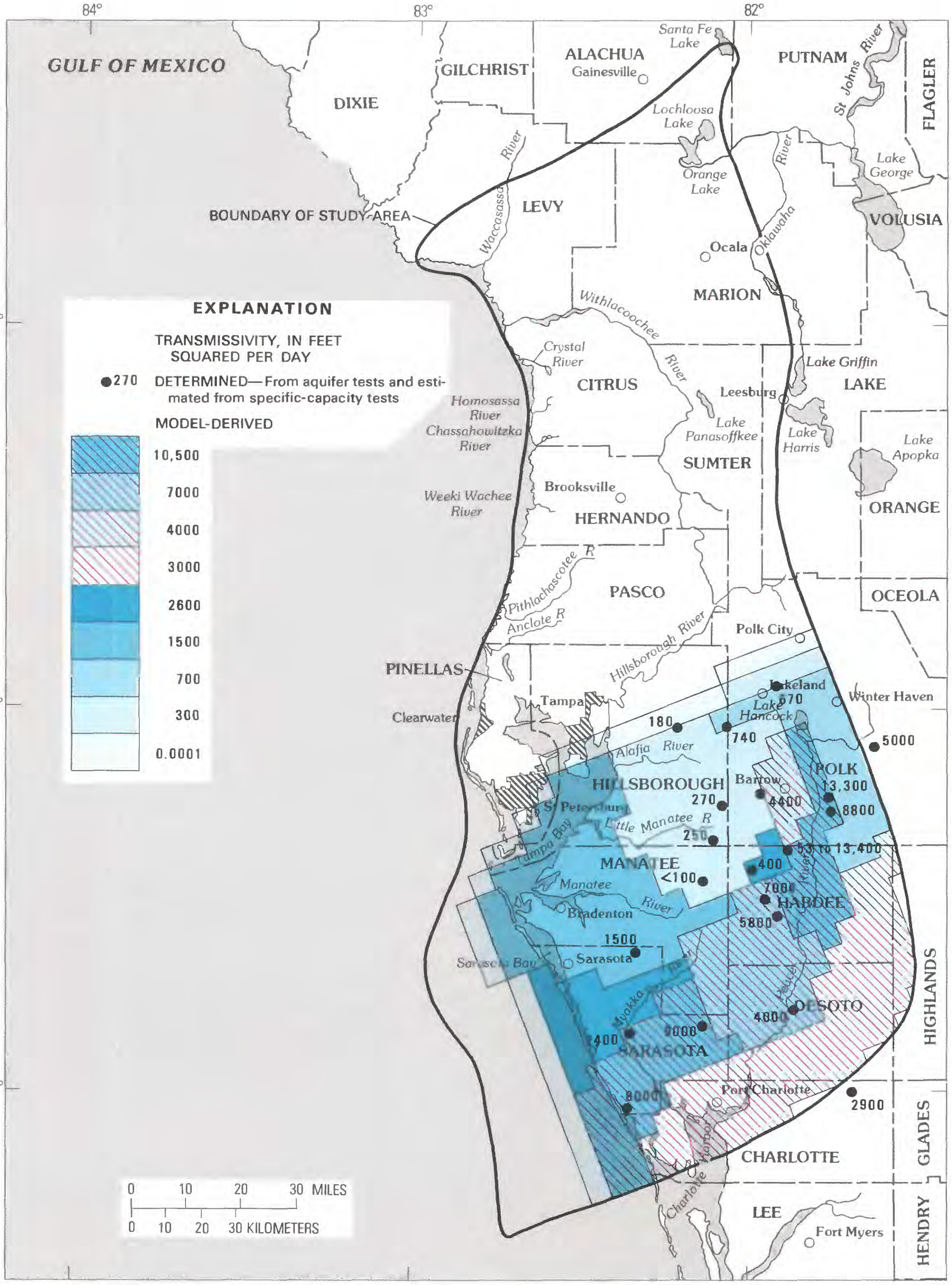


FIGURE 13.—Field and model-derived transmissivity of the permeable deposits of the intermediate aquifer. (Aquifer-test references are in Ryder, 1982, table 3.)

has been separated into several local artesian zones by some investigators. (See, for example, Joyner and Sutcliffe (1976).

The permeable deposits of the intermediate aquifer are confined above by less permeable material in the overlying formations or in the upper part of the Hawthorn Formation. The thickness of the overlying confining bed, as estimated form geologic logs, is shown in figure 14. Figure 14 also shows model-derived leakance values of the confining bed. Leakance ranges from 7×10^{-6} to 4×10^{-4} (ft/d)ft.

SURFICIAL AQUIFER

The surficial deposits generally consist of sand, clayey sand, shell, and shelly marl. The thickness of the deposits was mapped for most of the study area by Wolansky, Spechler, and Buono (1979). The thickness ranges from nearly zero in the north (fig. 3) to greater than 100 ft in southeastern Levy, eastern Sumter, eastern Hardee, and northeastern De Soto Counties.

The deposits are generally saturated to within a few feet of land surface in the south. North of Hillsborough and Polk Counties, the water table is progressively deeper below land surface. Here, the surficial deposits are thin and discontinuous over large areas.

The transmissivity of the surficial aquifer varies according to saturated thickness and lithology. R. M. Wolansky (U.S. Geological Survey, written commun., 1980) reported five values of transmissivity for the surficial aquifer—an average of 205 ft^2/d at two sites in northwest Hillsborough County; 1,800 ft^2/d in southeast Hillsborough County; 270 ft^2/d in northeast Sarasota County; and 880 ft^2/d in southwest De Soto County. Hutchinson (1978, p. 22) reported a transmissivity of 2,200 ft^2/d for a site in southern Polk County. Wilson (1977, p. 28) estimated an average transmissivity of about 1,100 ft^2/d for De Soto and Hardee Counties.

CHEMISTRY OF WATER IN THE FLORIDAN AQUIFER SYSTEM

Many reports have been published that deal with water quality in the Upper Floridan aquifer. As previously noted, detailed descriptions of water quality in the Upper Floridan aquifer are in Sprinkle (1982a; 1982b; 1982c; 1982d;). Chapter I of this Professional Paper (1403-I) provides a detailed discussion of the ground-water chemistry. The present report (Chapter F) presents a generalized summary of the areal occurrence of large potable water supplies in the Upper Floridan aquifer or the occurrence of water that does not need extensive treatment for most use categories.

THICKNESS OF POTABLE WATER

Three important parameters useful for defining potable water in the Floridan aquifer system are sulfate, chloride, and dissolved-solids concentrations. The U.S. Environmental Protection Agency (1979) has set the following maximum recommended concentrations of these parameters for drinking water: sulfate, 250 mg/L; chloride, 250 mg/L; and dissolved solids, 500 mg/L.

The sulfate and chloride criteria were used by Causey and Levy (1976) to map the thickness of potable water in the Floridan aquifer system. For west-central Florida, Causey and Levy showed the thickness of potable water ranging from zero along coastal areas and in most of Manatee, Sarasota, and De Soto Counties to more than 2,000-ft in parts of Lake, Sumter, and Polk Counties.

A 2,000-ft test well, located at Polk City in Polk County, was constructed as part of the RASA study to collect geologic and water-chemistry data for the Floridan aquifer system. According to A. S. Navoy (U.S. Geological Survey, written commun., 1982), the Upper Floridan aquifer at the site extended from 17 ft above sea level to 823 ft below sea level. Below the altitude at which intergranular anhydrite was first encountered (886 ft below sea level), the concentrations of dissolved solids increased from about 150 mg/L to 1,000–2,000-mg/L, concentrations of sulfate increased from a few milligrams per liter to 600–1,200-mg/L. Concentrations of dissolved solids and sulfate remained high in all subsequent samples to a total depth of 2,000 ft. Concentrations of chloride were consistently low, generally less than 10 mg/L.

The base of the Upper Floridan aquifer was previously defined as generally the first occurrence of vertically persistent, intergranular evaporites for most of west-central Florida. Numerous test holes have shown that water in the Lower Floridan below this base is highly mineralized, particularly in regard to sulfate concentrations. Thus, in west-central Florida, sulfate and dissolved-solids concentrations probably remain in excess of the potable limit from the first occurrence of intergranular evaporites to the evaporite beds in the Cedar Keys Limestone.

If this is true, then the thickness of potable water would not exceed the thickness of the Upper Floridan aquifer, as shown in figure 10. Probably the thickness of potable water, as mapped by Causey and Levy (1976), is much too great in northwestern Polk, northeastern Hillsborough, eastern Pasco, eastern Hernando, and Sumter Counties. However, additional detailed water-chemistry data from greater depths, as was collected at the Polk City test hole, are not available to support the above statements. Although logical, these statements regarding the thickness of potable water must remain speculative until sufficient data are collected.

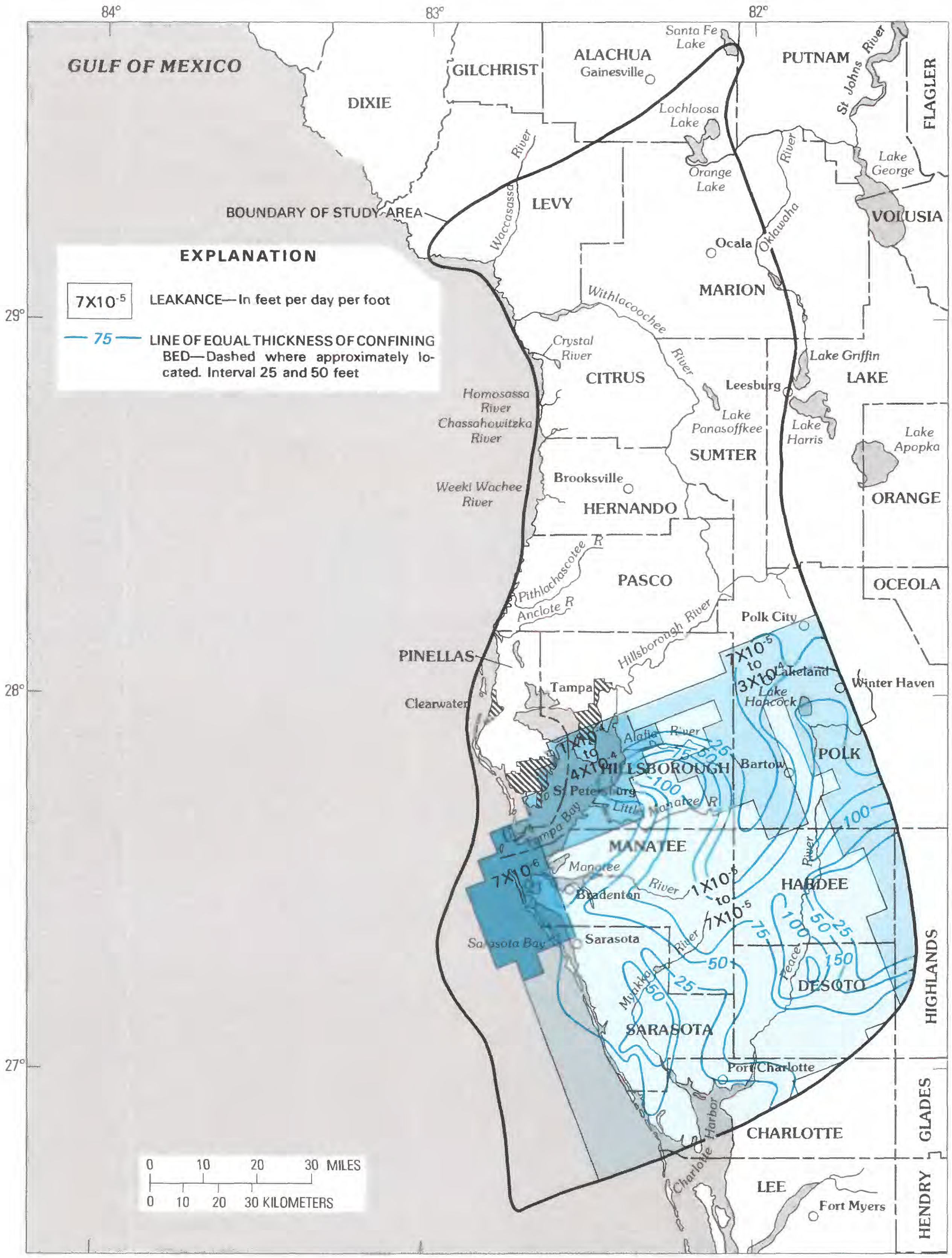


FIGURE 14.—Thickness and model-derived leakance of uppermost intermediate confining bed.

DISSOLVED-SOLIDS CONCENTRATION

Concentrations of dissolved solids are shown in figure 15. Preparation of this map was based on water samples that represented the entire thickness of the Upper Floridan aquifer. Samples from wells that were open to only part of the Upper Floridan aquifer, or open to both the Floridan and intermediate aquifers, were used as supplemental data were fully penetrating wells were nonexistent.

A composite water sample from a well that fully penetrates an aquifer is weighted naturally according to the permeability of the various contributing zones. Thus, the dissolved-solids concentrations shown in figure 15 are representative of water from the more permeable zones that are ordinarily tapped for large supplies. An exception to this, however, may be in Citrus and Hernando Counties where at least two large spring systems—Chassahowitzka and Weeki Wachee—discharge at a combined average rate of about 200 Mgal/d. Chemical analyses of water form these springs (Rosenau and others, 1977) showed dissolved-solids concentrations that are much lower than those indicated in figure 15. It is probable that the relatively shallow flow system, which consists of interconnected channels or conduits that collect and feed water to springs at high rates of flow, has water of significantly different quality than water from nearby wells that penetrate less permeable rocks to greater depths. This means that large quantities of potable water could be developed nearer to the coast in Citrus and Hernando Counties than is indicated in figure 15.

SALTWATER-FRESHWATER INTERFACE

Saltwater-freshwater relations are an important consideration in developing water supplies from the Upper Floridan aquifer along coastal margins and in the extreme southern part of the area. Although highly mineralized water underlies the Upper Floridan aquifer in inland areas, documented cases of significant upconing of salty water are not known even in areas where heavy pumping has caused several tens of feet of drawdown. A substantial increase in concentration of chloride was reported, however, from a well in the basal part of the Upper Floridan aquifer at Bartow in Polk County (R. M. Wolansky, U.S. Geological Survey, oral commun., 1981).

Geraghty and Miller, Inc., and Reynolds, Smith and Hills (1977, p. 2.16) concluded that saltwater contamination of the Upper Floridan aquifer due to man's activities has been a local phenomenon in some coastal areas and that intrusion is not a major threat regionally. Using chloride data collected during the 1960's and 1970's and assuming that major regional changes in chloride had not occurred during this period, Wilson (1982, fig. 7) mapped the distribution of saltwater and freshwater in the highly permeable dolomite zone of the Upper Floridan aquifer from Tampa Bay to Charlotte Harbor. Between the saltwater and freshwater is a broad transition zone in which chloride concentrations increase from 25 mg/L to 19,000 mg/L, the concentration in seawater (fig. 16). Areally, the transition zone ranges in width from about 2 mi. in Hillsborough County to about 30 mi in De Soto and Charlotte Counties. Wilson (1982, p. 11) used the predevelopment potentiometric surface of the Upper Floridan aquifer and the Ghyben-Herzberg formula (Domenico, 1972, p. 185) to calculate the theoretical trace of the saltwater-freshwater interface where it intersects the top of the transmissive dolomite (reproduced in fig. 16). Wilson suggested that the good agreement between the theoretical position and the mapped position of the seaward boundary of the transition zone may mean that the interface position reached equilibrium under predevelopment conditions but had not yet adjusted to changes caused by development. Wilson cautioned, however, that data needed to support such conclusions are lacking and that the good agreement may be merely coincidental.

Hickey (1981, p. 26 and fig. 15) mapped the saltwater-freshwater transition zone in the permeable dolomite in the Tampa Bay area. He also mapped chloride data for the upper part of the Upper Floridan aquifer. Other reports dealing with the saltwater-freshwater interface and chloride concentrations in the upper part of the Upper Floridan aquifer include: Reichenbaugh (1972) for coastal Pasco County; Mills and Ryder (1977) for coastal Citrus and Hernando Counties; and Causseaux and Fretwell (1982) for the coastline from Levy County to Charlotte County.

In Pasco, Hernando, and Citrus Counties, the presence of coastal springs and associated caverns and conduits that have direct connection with Gulf seawater greatly complicates the saltwater-freshwater distribution. Sinclair (1978) discussed the complex saltwater-freshwater relation in a spring-river system in coastal Hernando County.

REGIONAL FLOW SYSTEM

Regional flow in the Upper Floridan aquifer was investigated by simulating both predevelopment and modern-day conditions. A finite-difference, digital-flow model (Trescott, 1975; Trescott and Larson, 1976) was used to simulate the predevelopment flow system. A complete discussion of model theory, input data, and calibration procedure for the predevelopment flow system are included in a previous report by Ryder (1982).

The model was also used to simulate modern-day, steady-state pumping stresses. The calibration procedure, based on 1976 input data, is presented in the section

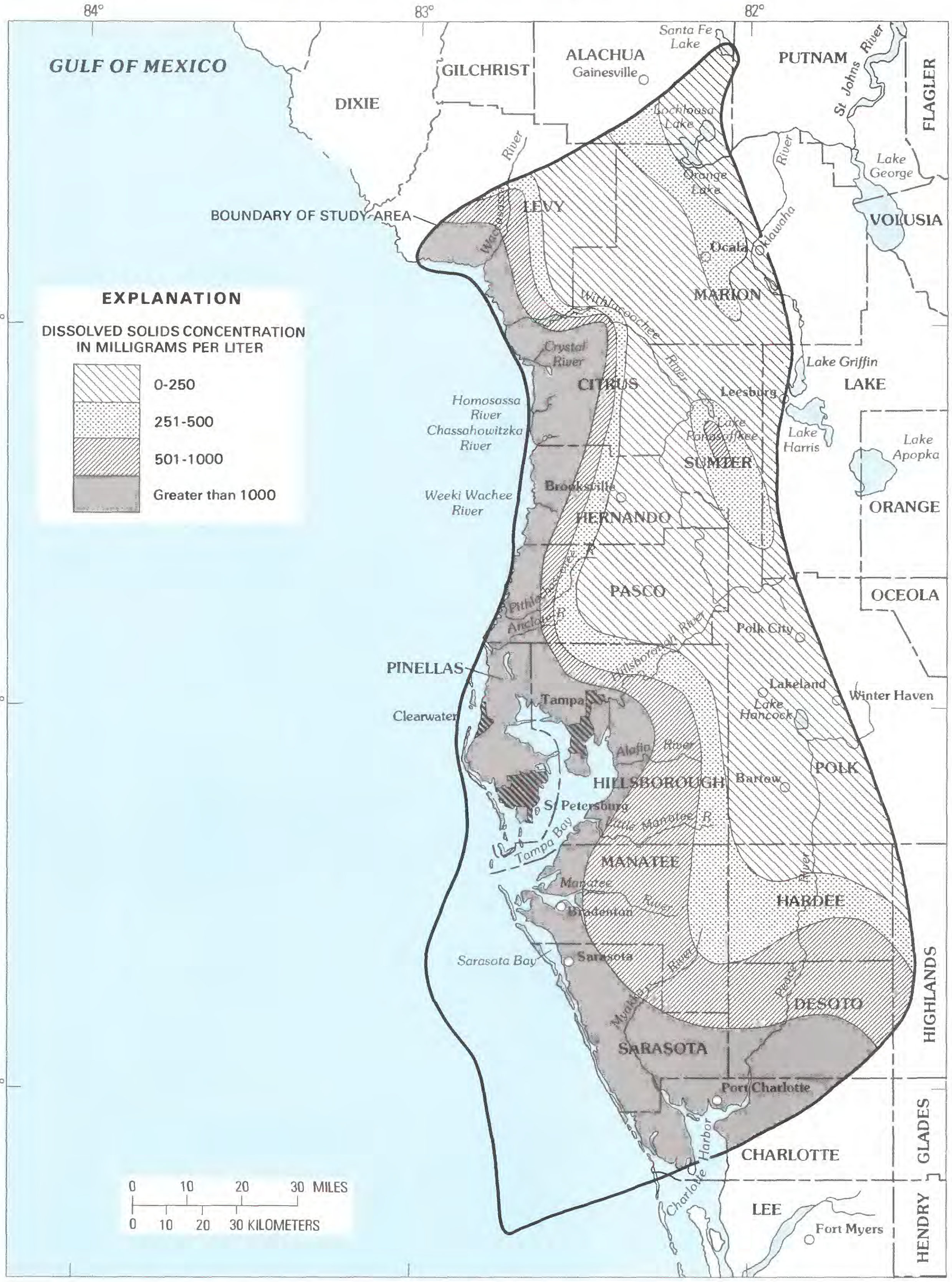


FIGURE 15.—Dissolved-solids concentration in water from the Upper Floridan aquifer (Sprinkle, 1982d).

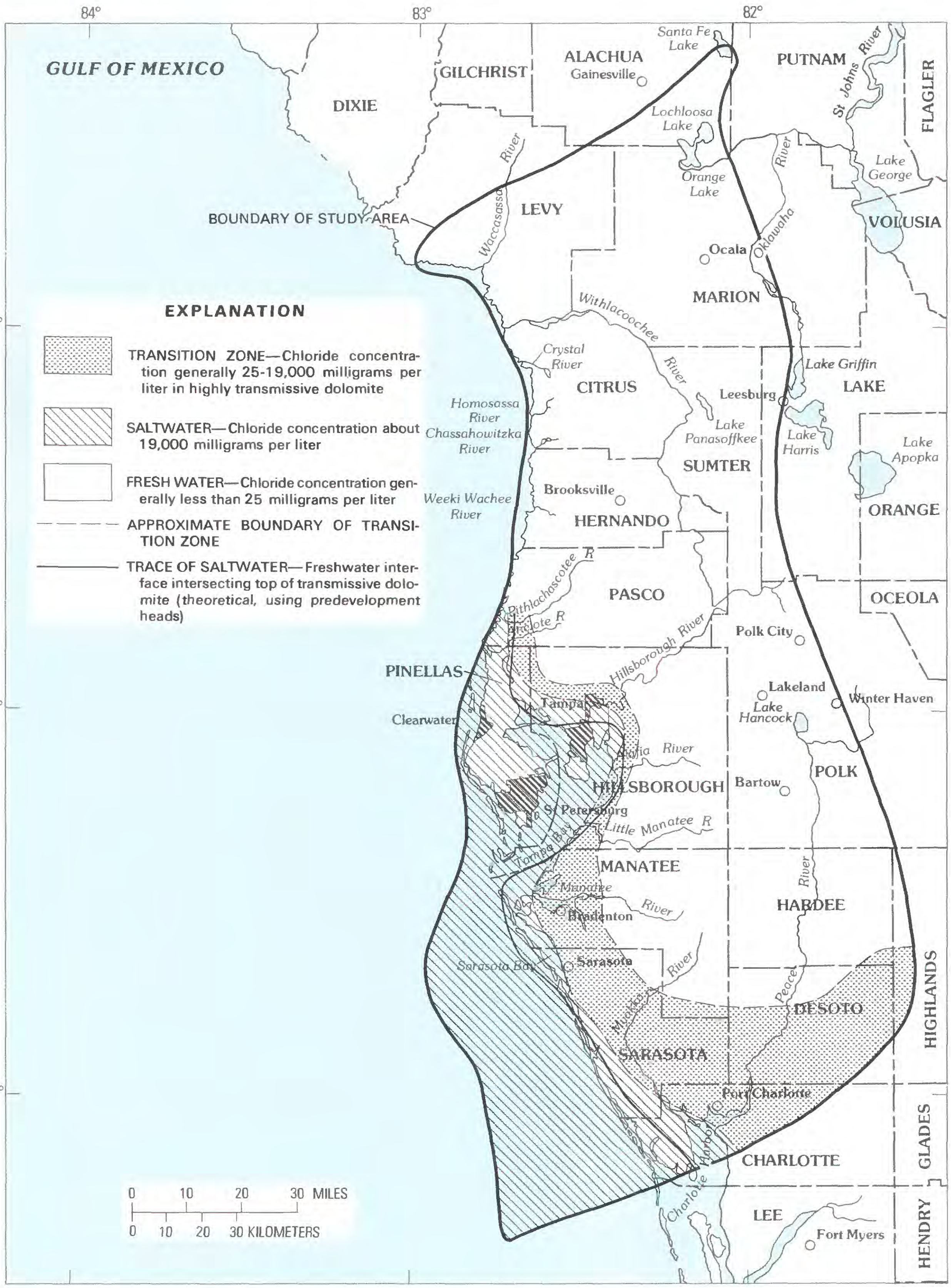


FIGURE 16.—Saltwater-freshwater transition zone in the highly permeable dolomite of the Upper Floridan aquifer (Hickey, 1981, fig. 15; Wilson, 1982, fig. 7)

"Digital model of 1976 flow system." Theoretical and technical details of the digital model are in the preliminary report by Ryder (1982).

Slight differences occur between the aquifer transmissivity and confining-bed leakance values reported in Ryder (1982). and those used to simulate steady-state pumping. Changes were made to provide a better calibration under pumping conditions. Rerunning the predevelopment model with the changed parameters produced essentially the same results as the initial predevelopment calibration.

PREDEVELOPMENT STEADY-STATE FLOW SYSTEM

CONCEPTUAL MODEL OF SYSTEM

The general direction of flow within the Upper Floridan aquifer and areas of recharge and upward leakage are shown by the predevelopment potentiometric surface (fig. 17). The configuration of the study area has been delineated along predevelopment, no-flow boundaries as follows: the landward boundary is the major north-south ground-water divide of the Florida Peninsula; the gulfward boundary is located where the aquifer becomes completely saline (thus defining the seaward extent of the freshwater-flow system); and the northern and southern boundaries follow flow lines form the divide to the coast.

A digital model was used to investigate the Floridan's regional flow system. For this purpose, the intermediate and Upper Floridan aquifers were discretized using the finite-difference grid shown in figure 38. Details of the model design, boundary designations, and assumptions are presented in Ryder (1982).

A generalized conceptual model of the predevelopment flow system is shown in figures 18, 19, and 20. The hydrogeologic sections are drawn along column 40, column 13, and row 20 of the grid in figure 38.

The hydrogeologic section in figure 18 shows the flow system along an east-west section in the northern part of the study area where unconfined conditions prevail. The unconfined or semiconfined conditions allow a relatively high rate of recharge to occur. Water enters the Upper Floridan aquifer, travels relatively short distances through well-developed solution channels, and discharges as large springs. Figure 18 shows that the aquifer base drops from about 600 ft below sea level to about 1,800 ft below sea level. However, as discussed previously ample evidence suggests very sluggish flow in the deeper zones compared to a vigorous shallow flow system.

The east-west hydrogeologic section in figure 19, which represents the southern part of the area, contrasts sharply with that in figure 18. Within most of the eastern one-half of the section, water flows downward from the surficial aquifer through a confining layer and into the intermediate aquifer. A relatively small amount of water returns to the surface in topographically low areas, such as the Peace River valley. The remainder of the water continues to flow downward through a confining bed and into the Upper Floridan aquifer where the flow is westward toward the Gulf. Locally, particularly in the lake region in the ridge area a few miles north of the eastern edge of the section, sinkholes may breach the overlying deposits and extend to the Floridan. The sinkholes may be occupied by lakes or by permeable sands and are sites for relatively high recharge to the Upper Floridan aquifer. Along the coastal margin and in the Gulf, there is a reversal of gradient, and water flows upward through the confining beds. No flow is assumed across the saltwater-freshwater interface.

Saltwater-freshwater interface positions in figures 18 and 19 were estimated by applying the Hubbert (1940) interface relation, which states that the depth below sea level to the base of freshwater is theoretically about 40 times the altitude of the freshwater head on the interface. Heads from the predevelopment potentiometric surface map or its offshore extension were used to establish the position of the interface. Because these heads were obtained from zones above the interface, a necessary assumption was that they were the same as those at the interface. This assumption is reasonable if lines of equal head in the section are nearly vertical. The interface, if shown without the vertical exaggeration of figures 18 and 19, would have a very low slope. The interface is the limiting flowline of the freshwater flow system; if it is nearly horizontal, then flow lines above the interface must be nearly horizontal, suggesting that lines of equal head are nearly vertical. The maximum seaward extent of the interface thus obtained was determined by extrapolating top-of-the-aquifer contours offshore to the point where the interface crossed the estimated top of the aquifer. In the southern half of the study area, a sharp decrease in aquifer transmissivity occurs where water in the highly permeable zone in the Avon Park Limestone goes from fresh to saline (assuming the saltwater zone is not part of the flow system). An areal trace of the saltwater-freshwater interface intersecting the top of the highly permeable zone is shown in figure 16.

In contrast to the hydrogeologic sections in figures 18 and 19, the north-south section in figure 20 is generally perpendicular to the flow paths within the aquifer systems. The flow is generally westward, out of the plane of the section, except for some local discharge areas near the top of the intermediate and Floridan aquifers. Figure 20 shows, from south to north: (1) thinning of the confining beds and a transition from confined to generally unconfined conditions in the Upper Floridan aquifer; (2) pinching out of the intermediate aquifer; (3) a decline in importance of the highly permeable zone in the Avon Park Limestone (solution channels in Ocala Limestone attain greater significance); and (4) thinning of the Upper Floridan aquifer.

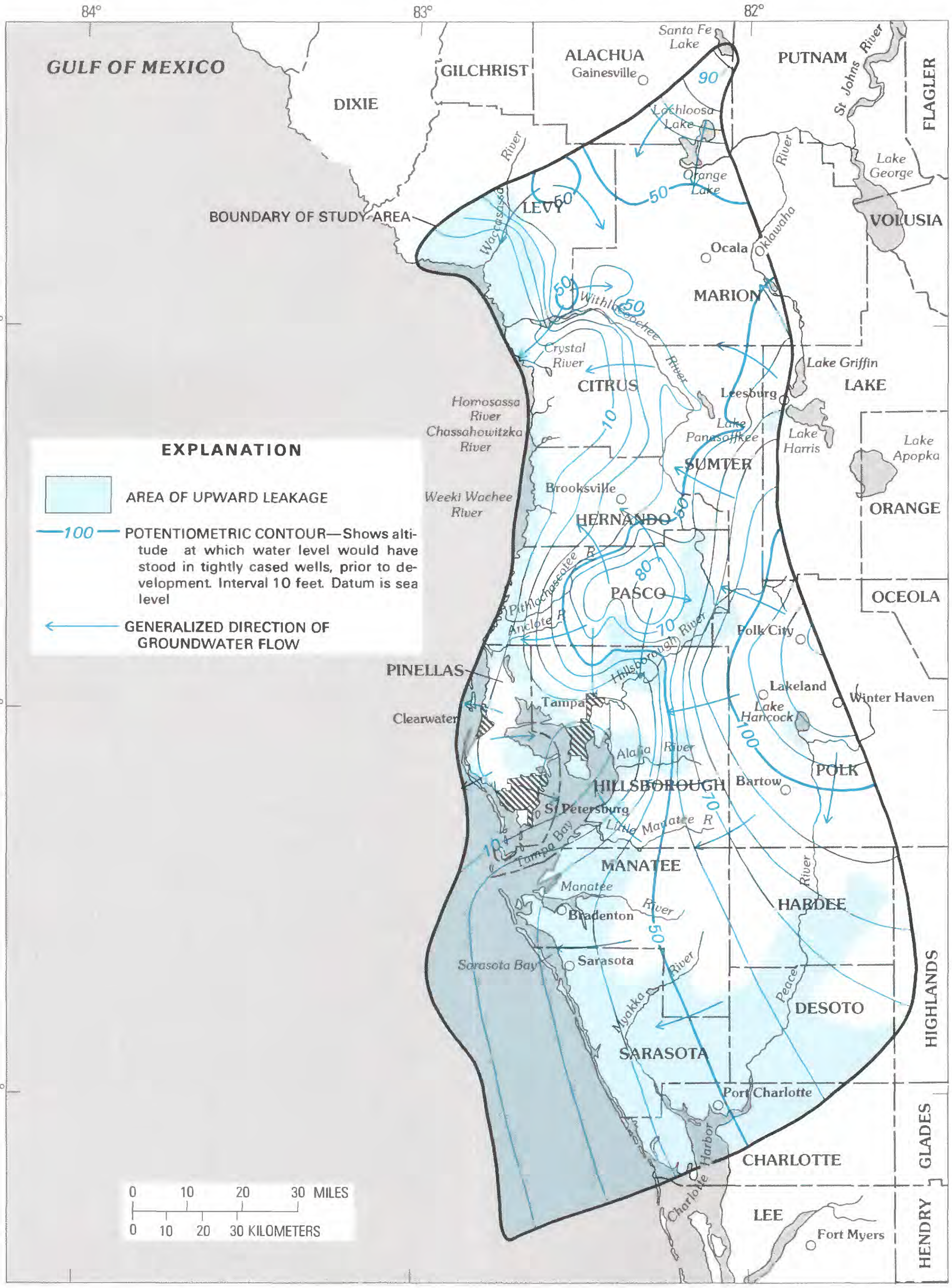


FIGURE 17.—Estimated potentiometric surface of the Upper Floridan aquifer prior to development (modified from Johnston and others, 1980).

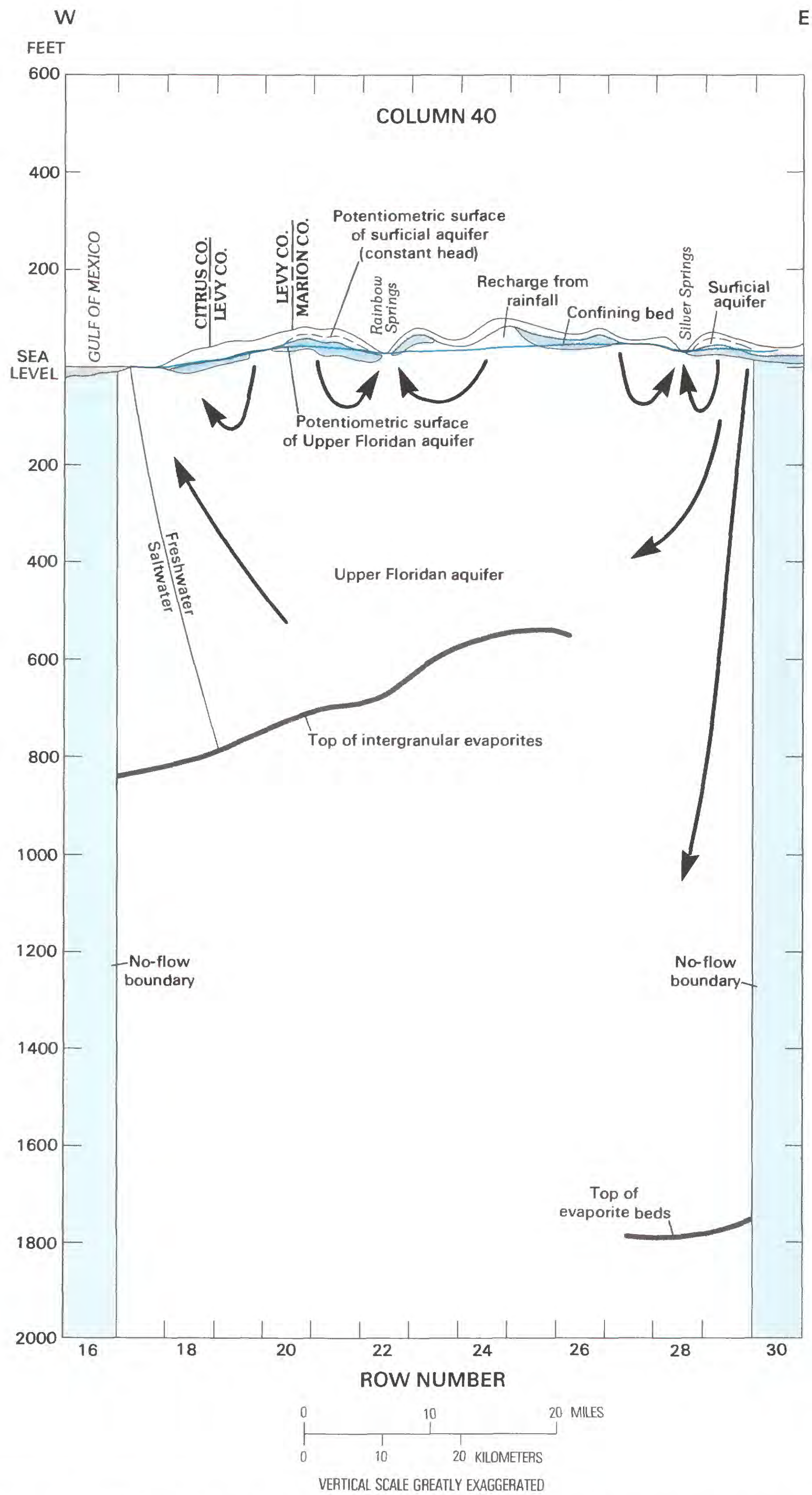


FIGURE 18.—Generalized hydrogeologic section along column 40 showing steady-state flow.

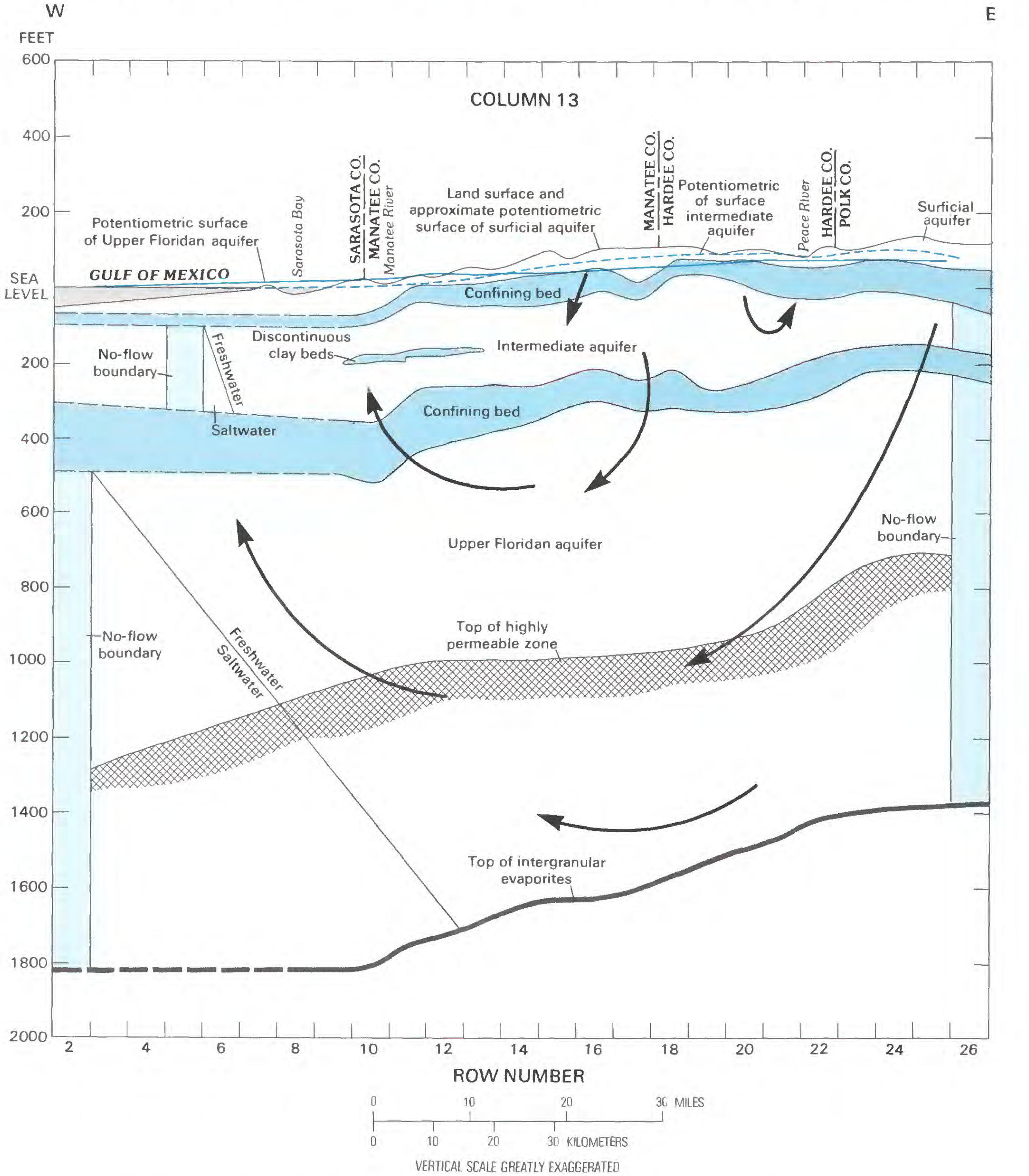


FIGURE 19.—Generalized hydrogeologic section along column 13 showing steady-state flow.

RECHARGE AND UPWARD LEAKAGE

Simulated values of recharge and upward leakage from the Upper Floridan aquifer (excluding spring discharge) are shown on plate 1. Higher recharge rates occur in the north where rates of 10 to 20 in./yr are common. Rates are moderate along the ridge area extending southward into Polk County, and decrease to generally 1 or 2 in./yr in the south where confining beds are thick.

High rates of diffuse upward leakage occur along the

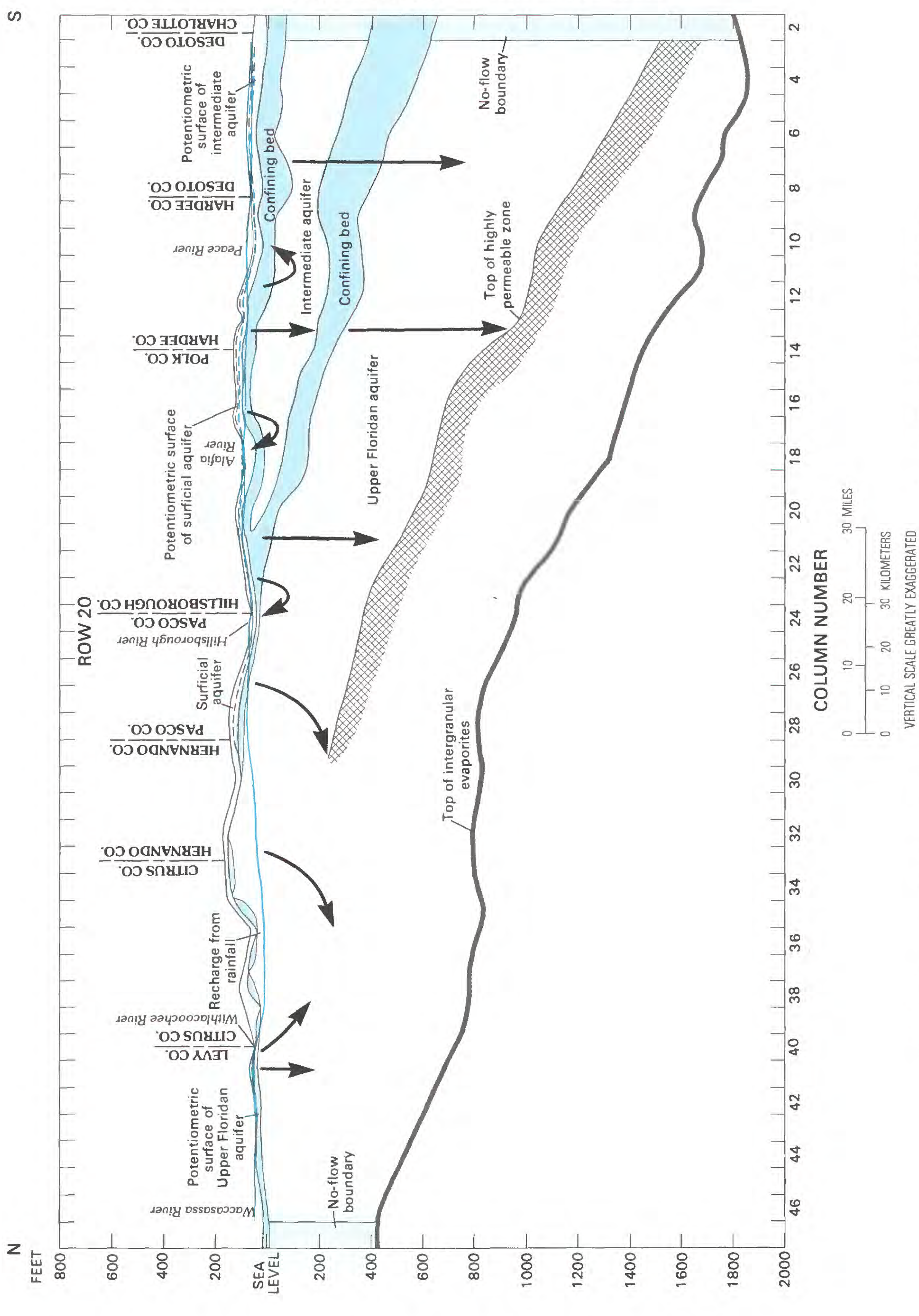


FIGURE 20.—Generalized hydrogeologic section along row 20 showing steady-state flow nearly perpendicular to flow lines.

northern coastal area and in the Tampa Bay area. Small rates of upward leakage occur in a large area in the south that includes a large offshore area. Recharge rates in the model compare well with initial estimates from water-balance calculations for surface-water basins made by P.W. Bush of the U.S. Geological Survey (discussions presented in Professional Paper 1403-C.)

SPRING DISCHARGE

The most important component of ground-water discharge in the study area is discharge from springs. Locations of 34 springs that have a combined average annual freshwater discharge of about 2,300 Mgal/d are shown in figure 21. Names and discharge rates for springs are listed in table 3. Spring discharge probably accounts for about 84 percent of all water discharging from the Upper Floridan aquifer under predevelopment conditions. Many of the springs are located along the coast, and submarine springs are known to exist off the coastal areas of Pasco, Pinellas, and Lee Counties. Rainbow and Silver Springs are located inland in Marion County and have a combined average discharge of about 1,000 Mgal/d. For comparison, model-derived estimates of spring discharge are shown in table 3. On the average, the model estimate of discharge is 90 percent of the measured discharge.

SUMMARY OF FLOW COMPONENTS

An analysis of the calibrated model simulating predevelopment conditions shows that the total recharge rate for the modeled area is about 2,500 Mgal/d; of this, 2,110 Mgal/d (84 percent) is discharged as springflow, and 390 Mgal/d (16 percent) is discharged as diffuse upward leakage. The upward leakage is mainly along the Gulf Coast; some leakage occurs as seepage into coastal swamps or as unmeasured spring discharge, including that from submarine springs.

LONG-TERM CHANGES IN REGIONAL FLOW SYSTEM

Water levels and quantities and patterns of flow in the Upper Floridan aquifer and overlying aquifers change in response to: (1) deviations from normal amounts of rainfall and natural recharge; (2) activities of man, which include construction of withdrawal and recharge wells, impoundments, and dredging; and (3) combinations of the above.

For discussion purposes, the study area was divided into three subareas according to the amount of ground-water development and consequent effects: (1) areas with negligible development; (2) areas with substantial development but only localized water-level declines; and (3) areas with substantial development and regional water-level declines. Records from hydrologic monitoring sites were selected from each of the three subareas to show seasonal and long-term changes in ground-water levels, spring discharges, lake stages, and rainfall (fig. 22).

AREAS WITH NEGLIGIBLE GROUND-WATER DEVELOPMENT

At the present time (1983), the ground-water resource from about the Pasco-Hernando County line northward is relatively undeveloped. The area is characterized by a relatively small population in scattered small towns and cities. Withdrawals for crop irrigation are light. A substantial part of total ground-water withdrawal is for a few rock quarrying operations.

The flow system in the northern area, typified by high rates of natural recharge and spring discharge, has probably changed little from predevelopment conditions. The hydrograph of water levels for Chassahowitzka well 1 (fig. 23), which taps the Upper Floridan aquifer, is typical of much of the area. Water levels in the observation well are relatively constant and show little seasonal fluctuation despite large seasonal fluctuations in rainfall. No long-term trends are evident. Water levels in an adjacent surficial aquifer well, completed in about 40 ft of saturated sand, have been identical to or within a few hundredths of a foot of water levels in the Upper Floridan aquifer.

Periodic measurements of discharge from Chassahowitzka Springs, about 1.5 mi southwest of the Chassahowitzka observation well, have been made since 1930 (Rosenau and others, 1977). The discharge hydrograph (fig. 23) shows variations in spring discharge in response to variations in rainfall. Individual discharge measurements, however, may have been affected by tidal fluctuations.

A hydrograph of annual discharges for Silver Springs, a spring of much larger magnitude than Chassahowitzka and located about 40 mi inland from the coast, is shown in figure 24. A fairly good correlation exists between annual discharge and annual rainfall. Similar to Chassahowitzka Springs, there was prolonged below-average discharge from Silver Springs during the 1970's.

A large quantity of water in the northern area flows under low hydraulic gradients through a highly transmissive aquifer from recharge areas to points of discharge (springs). Rainfall deficits generally cause heads to decline only a few feet below normal; however, the change in flow quantity could be several hundred cubic feet per second.

Probably the most significant change in the ground-water flow system due to man's activities in the northern

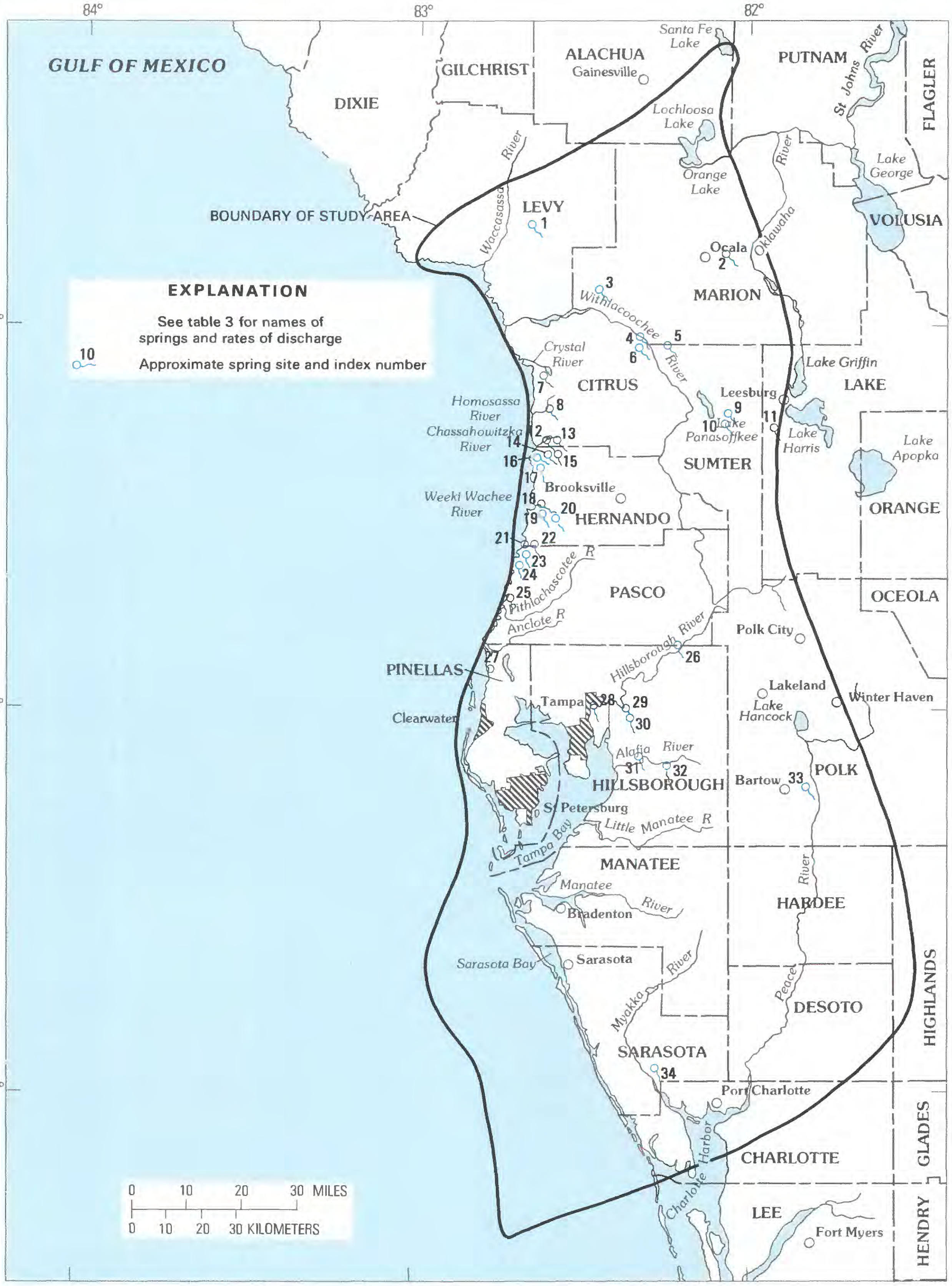


FIGURE 21.—Locations of springs that discharge from the Upper Floridan aquifer.

TABLE 3.—*Observed and simulated predevelopment spring discharge from the Upper Floridan aquifer*

Index[1] number	Spring(s)	Discharge observed[2] (Mgal/d)	Discharge simulated (Mgal/d)	Grid block row, column
1	Wekiva	36	24	20,44
2	Silver	530	481	28,40
3	Rainbow	493	447	22,40
4	Wilson Head	2	0	23,37
5	Gum	32	13	24,37
6	Blue	10	0	23,37
7	Crystal River Group	592	549	18,37-38
8	Homosassa	113	107	18,36
9	Fenny	10	23	25,33
10	Miscellaneous	19		
11	Bugg	10	3	27,32
12	Potter and Ruth	19	78	17,35
13	Chassahowitzka	89		
14	Nos. 10, 11, 12	6	21	17,34
15	No. 9	13		
16	Blind	26	35	16,34
17	No. 7	16		
18	Salt	19	60	16,32
19	Mud	32		
20	Weeki Wachee	114	104	16,31
21	Boat	3	6	14,31
22	Bobhill	2	4	15,31
23	Magnolia	6	13	14,30
24	Horseshoe	4		
25	Salt	3	5	13,29
26	Crystal	39	33	19,24
27	Health	3	5	11,26
28	Sulphur	28	25	15,23
29	Lettuce Lake	6	18	16,22
30	Eureka	1		
31	Buckhorn	8	10	16,20
32	Lithia	33	27	17,19
33	Kissengen	10	7	23,16
34	Warm Mineral	19	15	11,6

[1]See figure 21.
[2]Discharge is mean of values given in Rosenau and others (1977).

area has occurred in northwestern Citrus and southern Levy Counties. A dam was constructed in the early 1900's about 10 mi upstream from the mouth of the Withlacoochee River, and an 8-mi reach of the Cross-Florida Barge Canal was completed in the late 1960's. The canal segment extends inland from the Gulf Coast roughly parallel to the Withlacoochee River (fig. 2). Lack of data precludes analysis of the effects of the dam on the flow system. However, Faulkner (1973b) estimated the effect of the canal on the potentiometric surface of the Upper Floridan aquifer. His estimated maximum water-level changes in the aquifer ranged from about 15 ft of rise to about 15 ft of decline in areas close to the canal.

AREAS WITH SUBSTANTIAL GROUND-WATER DEVELOPMENT CAUSING MODERATE, LOCAL WATER-LEVEL DECLINES

The Tampa Bay area, which includes the cities of Tampa, St. Petersburg, and Clearwater (fig. 2), has the largest concentration of population in the study area. In much of the urbanized area, the underlying highly permeable dolomite zone contains saline water and is not usable

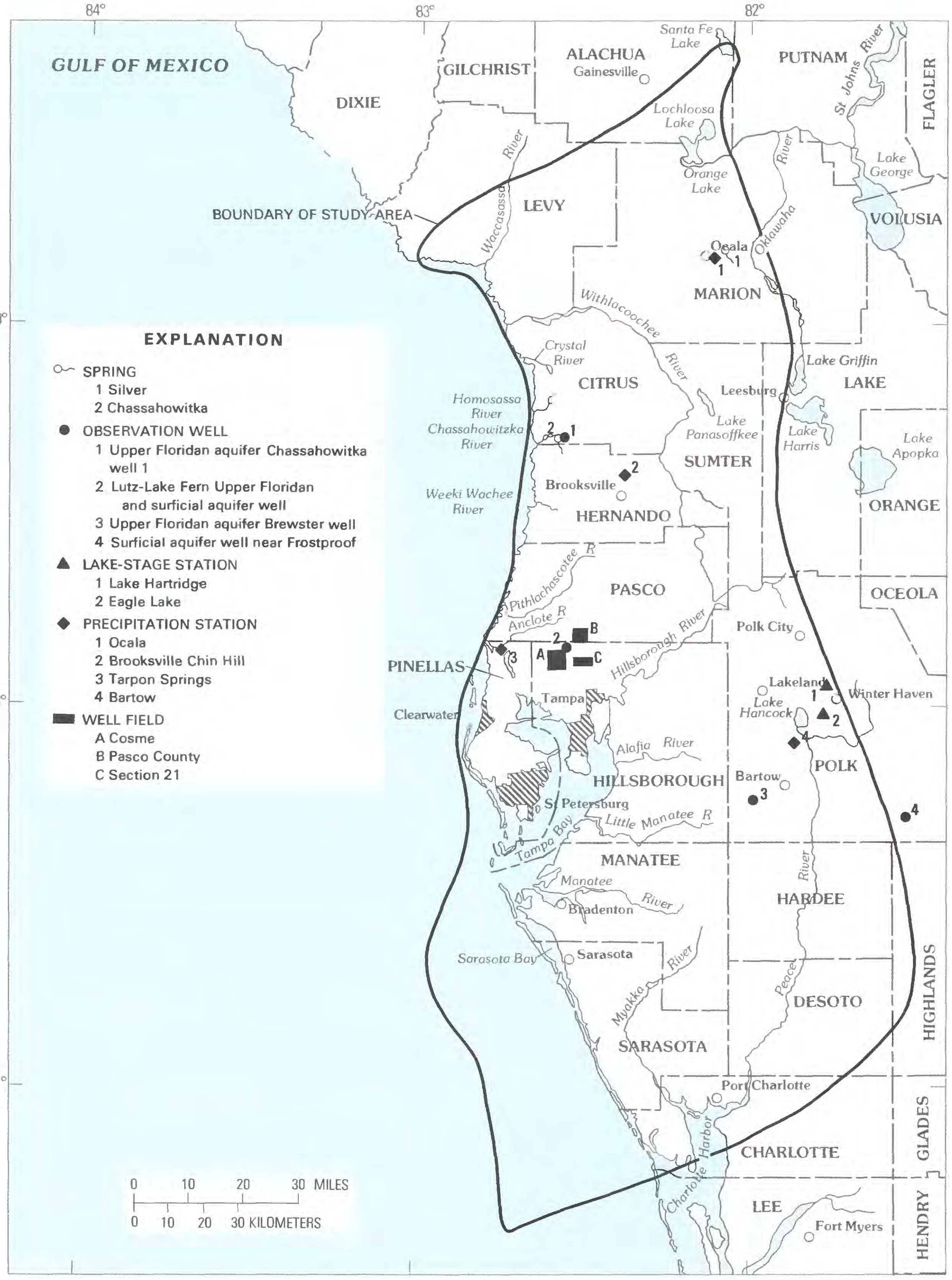


FIGURE 22.—Locations of selected springs, observation wells, lake-stage stations, and precipitation stations.

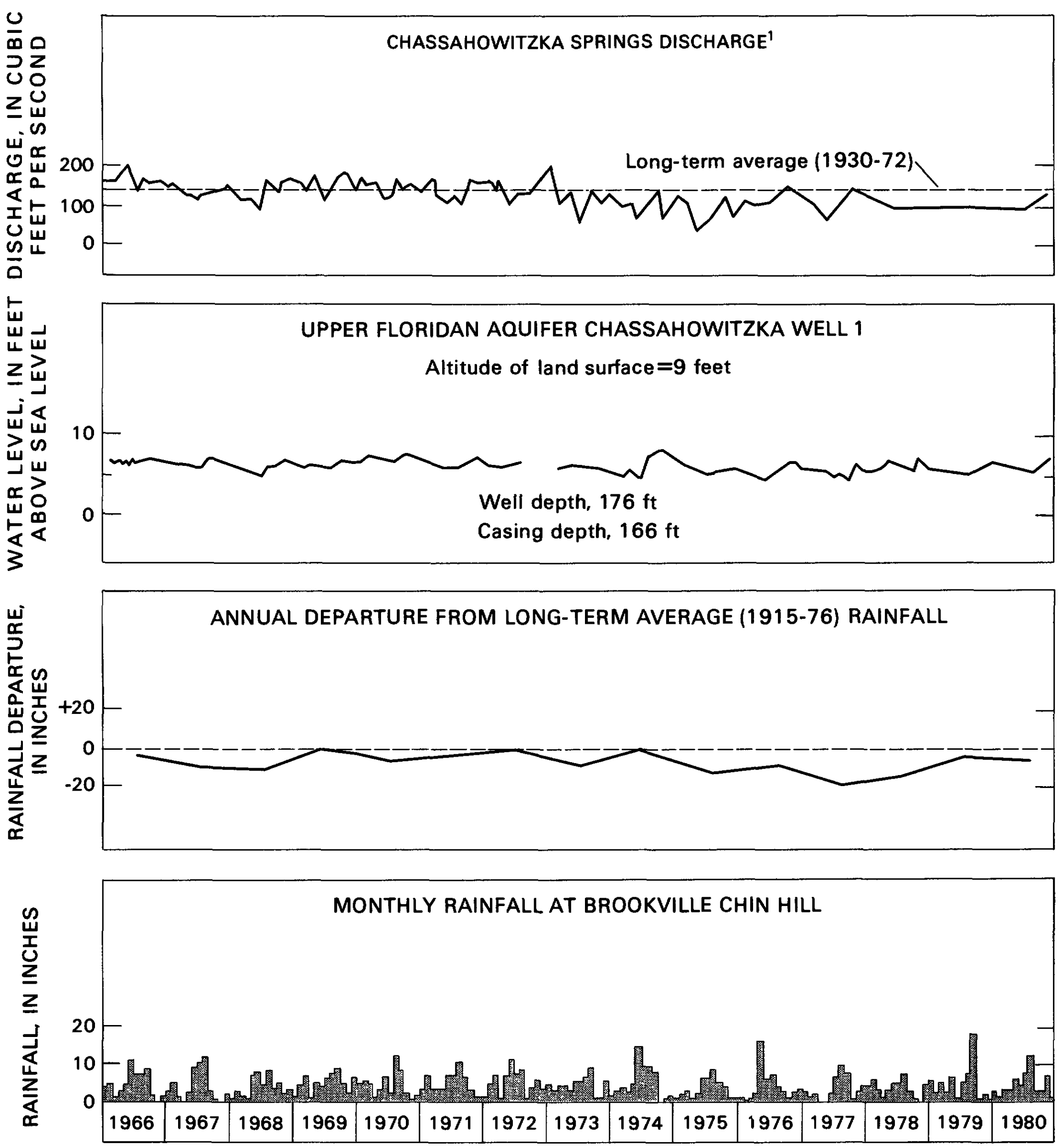


FIGURE 23.—Ground-water levels, spring discharge, and rainfall data for Chassahowitzka Springs area (site locations in fig. 22).

for municipal supplies. To supply potable water to these areas, water managers and planners have located large municipal well fields inland from the coast in northeastern Pinellas County; in northwestern and north-central Hillsborough County; and in southwestern, central, and north-central Pasco County.

The hydrogeology of the Tampa Bay area is characterized by relatively thin confining beds with high leakance values (fig. 12). The capacity for inducing additional large amounts of ground-water recharge when the head difference between the Upper Floridan aquifer and the surficial aquifer is increased is comparatively great. Thus, somewhat moderate water-level declines (on the order of 15 or 20 ft) occur in the Upper Floridan aquifer in the well-field areas. Lesser declines also occur in the surficial aquifer within the well fields; these water-table heads generally recover during each rainy season.

Figure 25 shows water-level hydrographs for wells in the surficial and Upper Floridan aquifers. The observation wells are about equidistant from three municipal well fields in northwestern Hillsborough and southwestern Pasco Counties (fig. 22). Water levels in the surficial aquifer average about 15 ft higher than those in the Upper Floridan aquifer; slight seasonal fluctuations in water levels are evident, but long-term trends are not discernible. Seasonal fluctuations are also apparent in

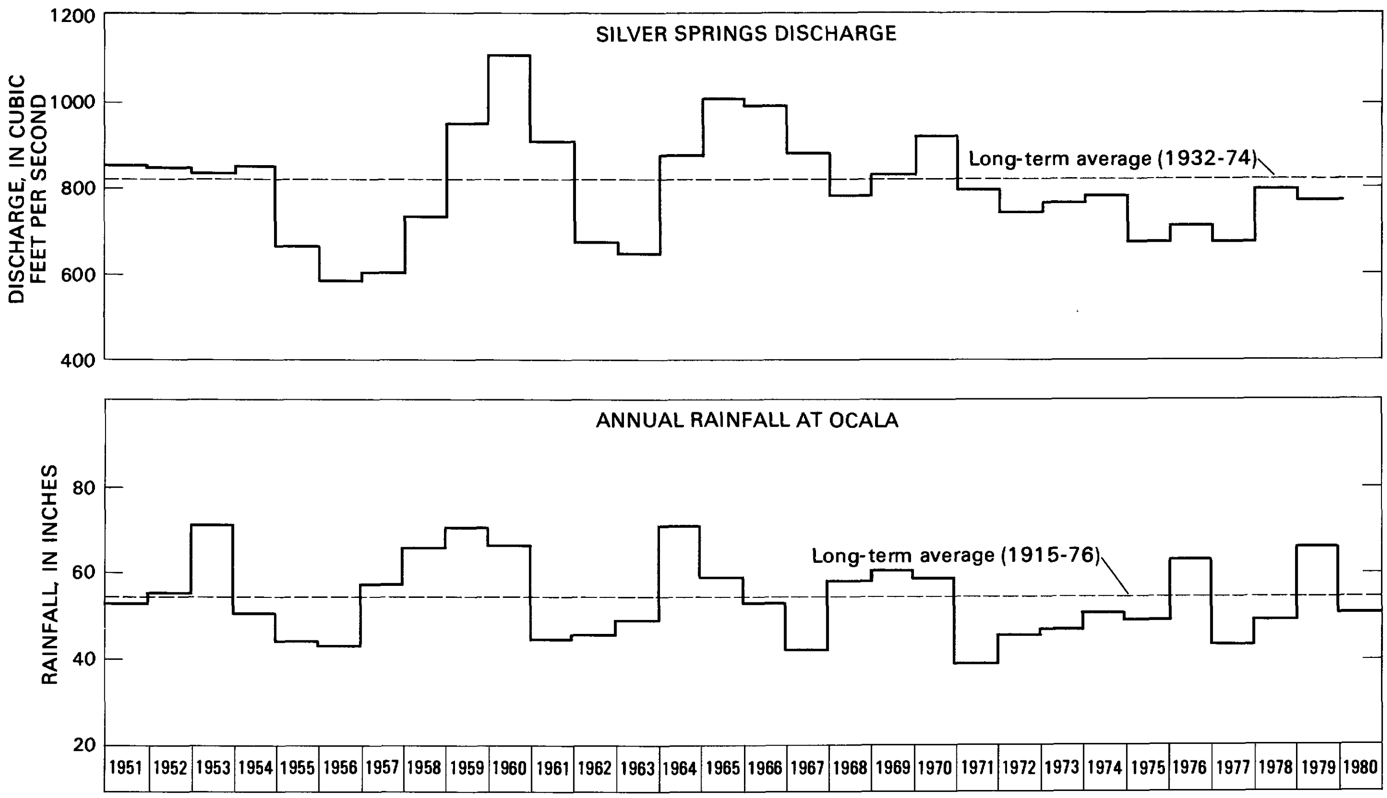


FIGURE 24.—Annual rainfall at Ocala and discharge at Silver springs, 1951-80 (site locations in fig. 22).

water levels in the Upper Floridan aquifer. Peaks and troughs in water levels coincide with those in the surficial aquifer, but amplitudes are significantly greater.

Ground-water pumpage has only been one of the many activities of man that have had a significant impact on the aquifer flow system in the Tampa Bay area. In addition to ground-water pumpage, activities related to urban development that impact the flow system include (1) construction of dams and levees and impoundment of surface water; (2) construction of drain fields, canals, and ditches; (3) general urban construction that includes roads, borrow pits, parking areas, and buildings; and (4) dredging for ship channels in Tampa Bay and for canals that provide access to the bay and Gulf.

The Tampa Bypass Canal (fig. 2), completed in 1982, was constructed to allow floodwater in the Hillsborough River above tampa to be diverted to Tampa Bay. In several places, the canal was excavated into the top of the Upper Floridan aquifer. The canal thus acts as a line sink in those areas, and water discharges from the aquifer into the canal. Structures on the canal allow water levels, and thus ground-water discharge, to be controlled. Hydrologic data (Causseaux and Rollins, 1979) suggest that aquifer head declines due to the canal are as much as 4 ft at the canal and diminish to zero away from the canal. On the basis of streamflow analyses, the canal has caused an average increase in aquifer discharge at least 27 Mgal/d.

Past dredging in the ship channels of Tampa Bay has thinned or eliminated the confining bed, and new dredging will further expose the Upper Floridan aquifer to direct contact with saltwater from the bay. Hutchinson (1982), in studying the effects of proposed dredging, concluded that increased upward leakage caused by the proposed channelization would be about 4 Mgal/d.

In summary, the confining bed in the tampa Bay area is relatively leaky, generally thin, and discontinuous locally. In places, it is breached by sinkholes and stream channels. Because of this, the effects of man's activities on the ground-water flow system have been small. Changes in water levels and in the quantity of water moving into or out of the aquifer system have been significant, but the changes tend to be of a local nature rather than of large, regional extent.

AREAS WITH SUBSTANTIAL GROUND-WATER DEVELOPMENT CAUSING LARGE, REGIONAL DECLINES

The combination of thick confining beds and large withdrawals from the Upper Floridan aquifer in areas south of central Hillsborough and north-central Polk

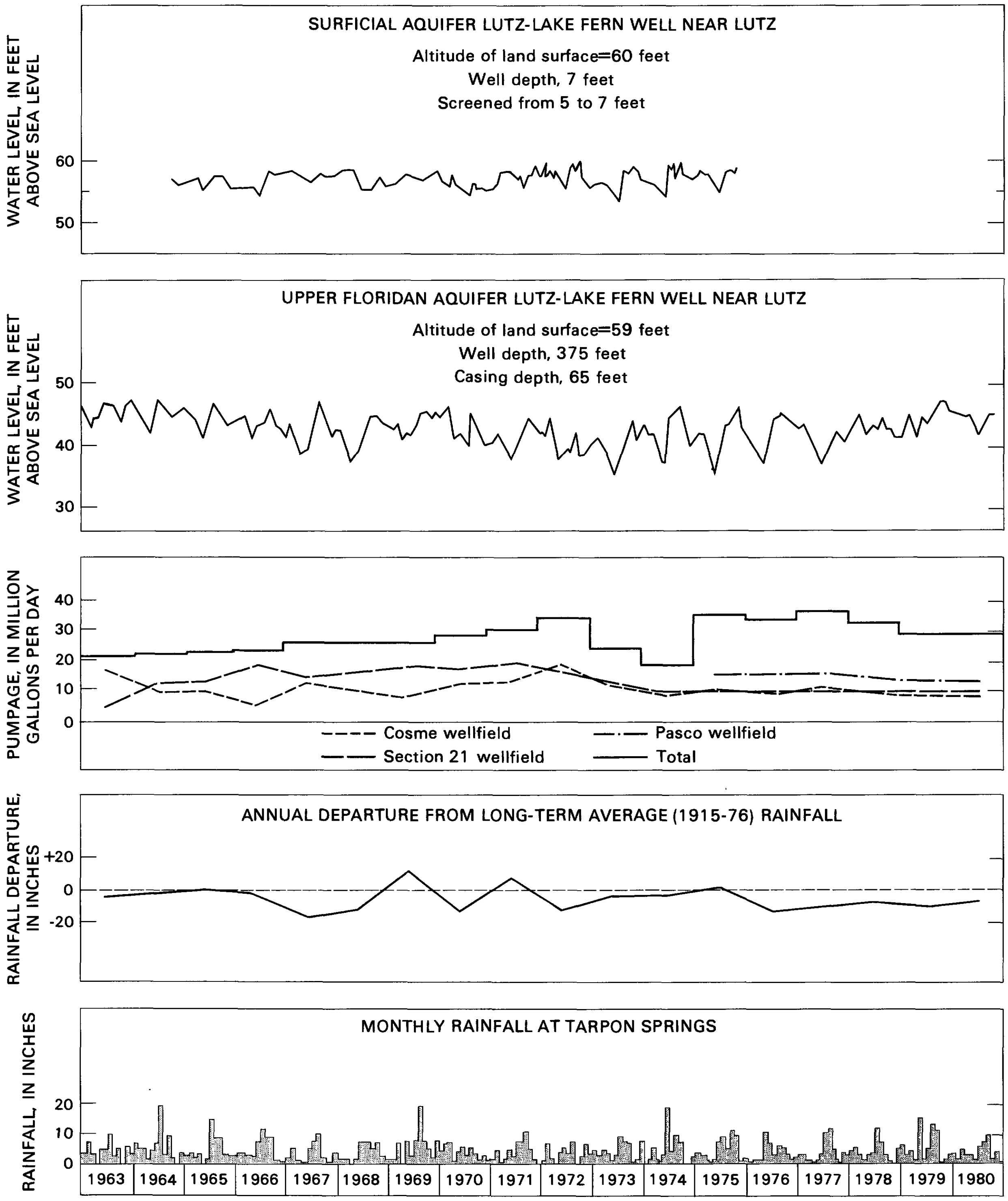


FIGURE 25.—Ground-water levels, pumpage, and rainfall data for area north of Tampa Bay (site locations in fig. 22).

Counties has resulted in large declines in the potentiometric surface of the Upper Floridan aquifer over a relatively large area. Figure 26 shows lake stages, ground-water levels, and rainfall data for selected sites in Polk County. The head in the Upper Floridan aquifer in the Brewster observation well has declined about 45 ft from near predevelopment levels in the 1950's to all-time lows in the middle 1970's. Seasonal fluctuations in water levels correlate well with seasonal variations in rainfall, although the fluctuations are enhanced by pumpage.

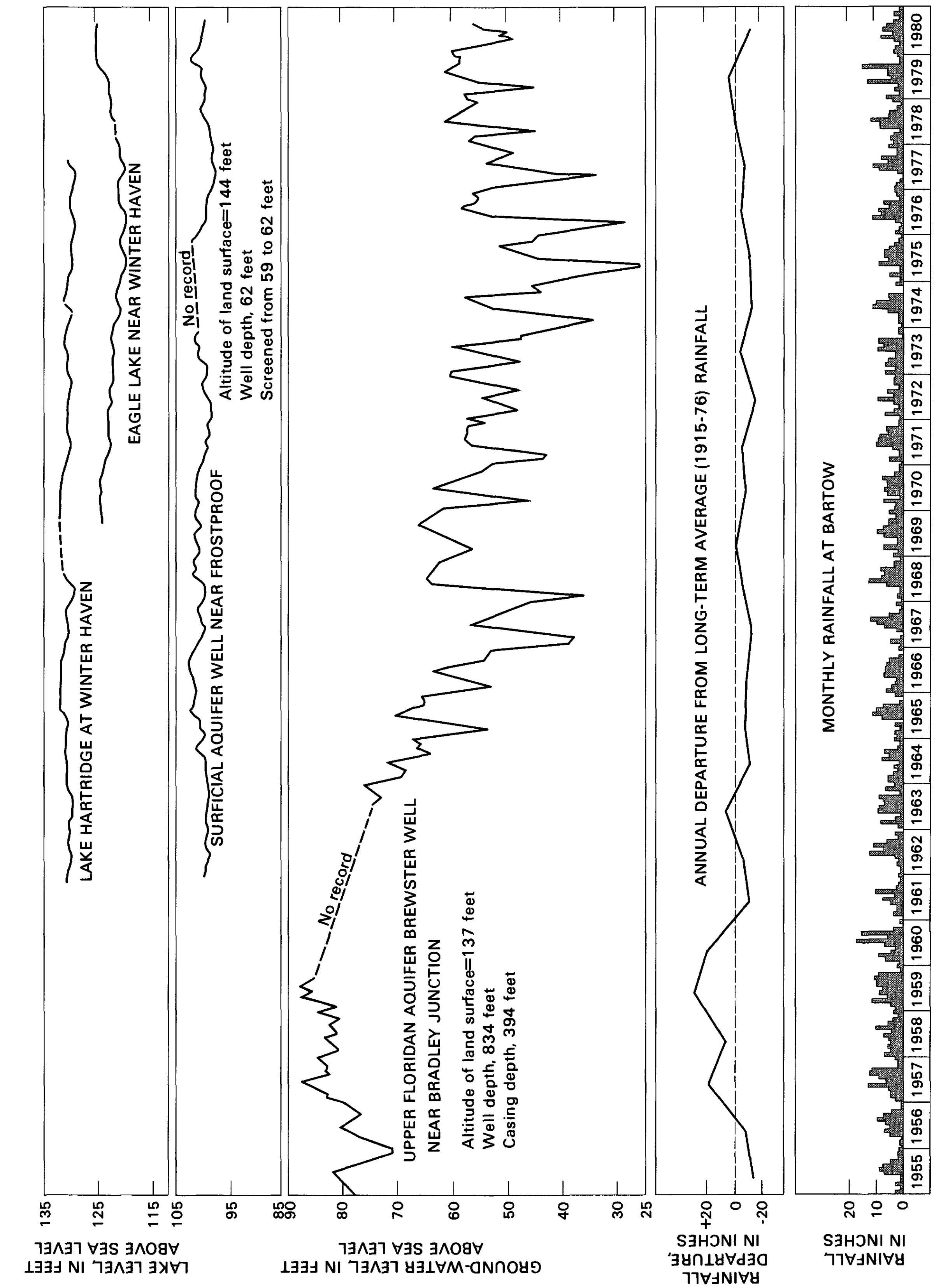


FIGURE 26.—Lake stages, ground-water levels, and rainfall data for Polk County area (site locations in fig. 22).

Long-term trends in water levels in the Upper Floridan aquifer correlate well with annual departures from long-term average rainfall. The nearly steady decline in water levels into the middle 1970's can be attributed to increased ground-water withdrawals.

Upper Floridan aquifer levels recovered slightly during the late 1970's, as shown in figure 26 for the Brewster well. Although recoveries were greatest in the phosphate mining area centered in southwestern Polk County, they also occurred over most of the southern part of the study area. Recoveries are related to reductions in withdrawals for industry and irrigation.

Long-term records of water levels in the surficial aquifer in southwestern Polk County are lacking. Wilson and Gerhart (1982, p. 6 and fig. 4) analyzed water levels collected during 1965-77 for a surficial aquifer well located about midway between the Brewster well and Bartow and centered over the large cone of depression in the Upper Floridan aquifer. They concluded that, although water levels fluctuated a few feet seasonally, no significant trends occurred in peaks of the hydrograph, and recharge from summer rains was generally adequate to replenish the aquifer.

Water levels for the surficial aquifer, as shown in figure 26, are for a well on the fringe of the area of greatest water-level decline in the Upper Floridan aquifer. Seasonal fluctuations of water levels in this well are small. Long-term trends are noticeable, but are not pronounced. A rise in water levels during the period 1977-80 correlates with a rise in water levels in the Upper Floridan aquifer measured in the Brewster well.

Many lakes are east and north of the area of greatest decline of water levels in the Upper Floridan aquifer. Analysis of long-term trends in lake levels is complicated because lakes that have long-term stage records and whose levels have not been artificially controlled are rare. Sinclair and Reichenbaugh (1981) studied a chain of 14 interconnected lakes in the Winter Haven area of Polk County. Stages of the lakes had declined during the 1970's, and the investigators concluded that rainfall deficits were the major factor in the declines. A secondary factor affecting the lake levels was the lowering of the potentiometric surface of the Upper Floridan aquifer

Figure 26 shows a stage hydrograph for Lake Hartridge that is on the upstream end of the 14 interconnected lakes. Long-term trends in the lake's stage are small when compared to those of Eagle Lake (fig. 26), which is a short distance southward but closer to the area of greatest decline in water levels in the Upper Floridan aquifer. Eagle Lake is an isolated lake whose stage is not regulated by control structures or by pumping into or out of the lake. The long-term decline in stage during 1970-76 and rise during 1976-80 correlate well with trends in water levels of the Upper Floridan aquifer measured in the Brewster well.

A profile of the potentiometric surface of the Upper Floridan aquifer across Polk County (fig. 27) shows changes in the potentiometric surface and in the levels of Lakes Otis and McLeod from 1934 to 1976. The decline in lake levels corresponds closely to the decline in the potentiometric surface.

Changes in the flow system that are caused only by changes in pumping and those that are caused only by rainfall departure from average are difficult to identify and document because pumping for irrigation, and often for other uses, is linked to rainfall amounts and distribution.

STEADY-STATE FLOW CONDITIONS FOR 1976

Analysis of representative hydrologic data in the previous section has shown that the predevelopment regional flow system has been altered significantly over much of the study area. Flow-system changes have been caused mainly by the combined effects of pumpage and rainfall departures from average.

The modern-day regional flow system was analyzed using the same digital computer model as utilized in the predevelopment simulation. The digital model was calibrated for steady-state conditions and provides (1) a check on the accuracy of the predevelopment calibration and a refinement of modeled confining-bed and aquifer parameters and (2) a quantitative description and evaluation of changes in recharge, upward leakage, and spring discharge since predevelopment times.

In selecting the period during which the pumping model is calibrated, two criteria were considered: (1) pumpage must be known with reasonable accuracy, and (2) steady-state or quasi-steady-state conditions must apply. Therefore, changes in storage in the aquifers can be considered negligible.

The 1976 water year (October 1, 1975, to September 30, 1976) met these conditions and was chosen as the model calibration period. Details of the calibration, which include input data and boundary conditions, analysis of residuals, and sensitivity analyses, are given in the section "Digital model of the 1976 flow system." Model-derived and observed data that describe flow-system components for the 1976 water year are presented in the following sections. Changes in the flow system—predevelopment to 1976—are also discussed.

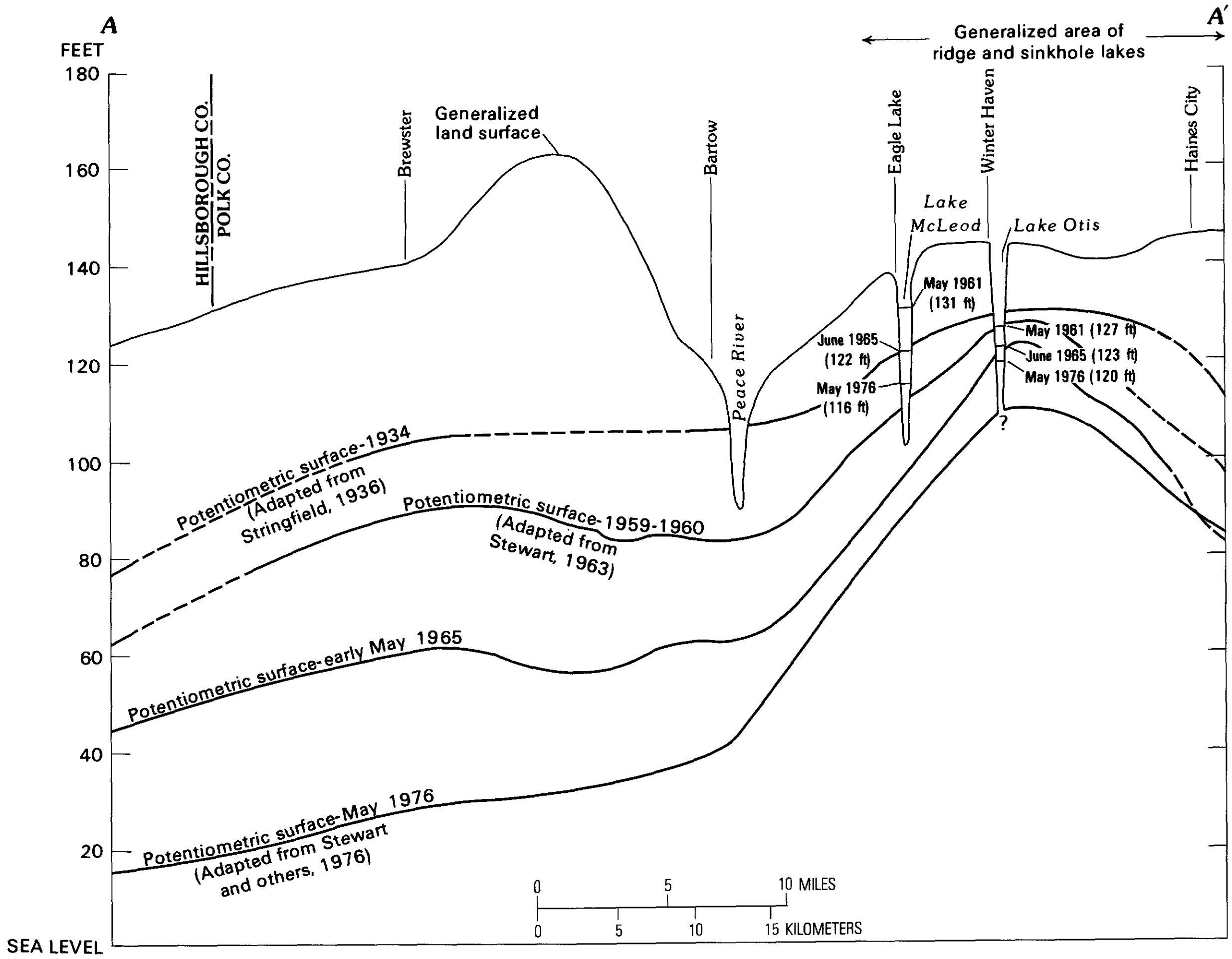


FIGURE 27.—Profiles of the potentiometric surface of the Upper Floridan aquifer across Polk County (modified from Kaufman, 1967, fig. 9). Line of section shown on figure 34.

RECHARGE AND UPWARD LEAKAGE

The average potentiometric surface of the Upper Floridan aquifer for the 1976 water year is shown in figure 28. The general pattern of flow within the aquifer is essentially the same as for predevelopment conditions. The major difference between the 1976 potentiometric surface and the predevelopment potentiometric surface is that water levels had been substantially lowered in the south. Because the water table in the surficial aquifer has remained relatively constant, rates of Floridan recharge have increased and rates of upward leakage have decreased in the heavily pumped areas. Average 1976 recharge and discharge rates (excluding spring discharge) from the calibrated model are show on plate 1.

SPRING DISCHARGE

The amount of discharge from springs for the 1976 water year is shown in table 4. Discharges from the large springs were measured a sufficient number of times to provide a reasonable estimate of the annual discharge; however, measurements were not made for many of the small springs. Based on observed springflow, discharges from the nine springs for which 1976 discharges are shown in table 4 were estimated to account for about 85 percent of total spring discharge. Model-simulated spring discharges (table 4) range from 83 to 110 percent of observed spring discharges.

PUMPAGE

Average ground-water withdrawal rates for west-central Florida during the 1976 water year are shown in figure 29. Details of the derivation of pumping rates are given in the section "Digital model of 1976 flow system." Total pumpage was about 950 Mgal/d. This takes into account anbout 33 Mgal/d of recharge through wells into the Upper Floridan aquifer. Most of the recharge wells are at International Minerals and Chemical Corporation's Kingsford Mine in Polk County (fig. 29), where water

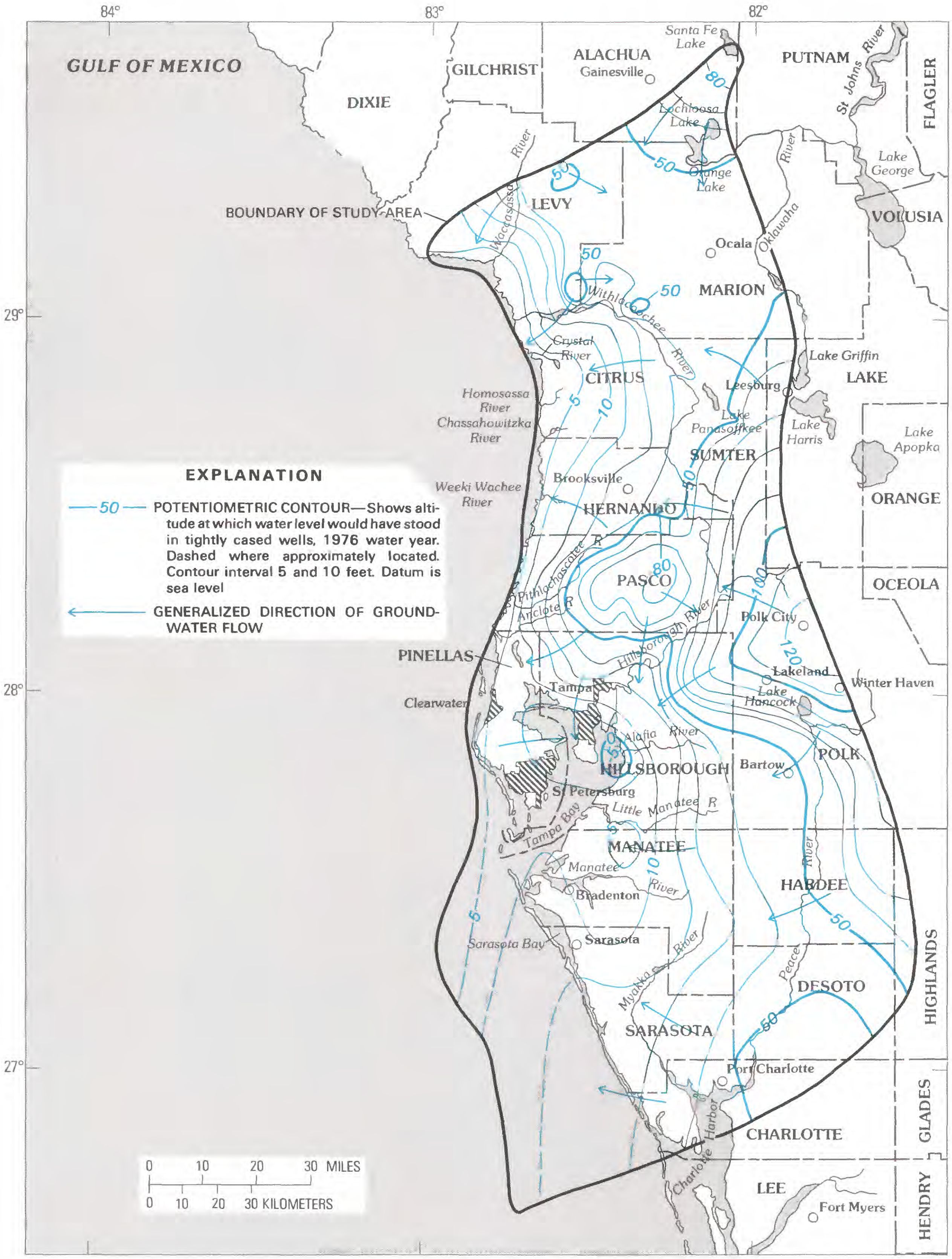


FIGURE 28.—Potentiometric surface of the Upper Floridan aquifer, 1976.

TABLE 4.—*Observed and simulated spring discharge from the Upper Floridan aquifer for predevelopment and 1976 conditions*

Index[1] number	Spring(s)	Predevelopment: Discharge observed[2] (Mgal/d)	Predevelopment: Discharge simulated (Mgal/d)	1976 Water Year: Discharge observed[3] (Mgal/d)	1976 Water Year: Discharge simulated (Mgal/d)
1	Wekiva	36	24	—	24
2	Silver	530	481	445	480
3	Rainbow	493	447	406	446
4	Wilson Head	2	0	—	0
5	Gum	32	13	—	13
6	Blue	10	0	—	0
7	Crystal River Group	592	549	597	546
8	Homosassa	113	107	105	105
9	Fenny	10	23	—	21
10	Miscellaneous	19		—	
11	Bugg	10	3	—	1
12	Potter and Ruth	19	78	—	76
13	Chassahowitzka	89		70	
14	Nos. 10, 11, 12	6	21	—	20
15	No. 9	13		—	
16	Blind	26	35	—	34
17	No. 7	16		—	
18	Salt	19	60	—	58
19	Mud	32		—	
20	Weeki Wachee	114	104	109	96
21	Boat	3	6	—	6
22	Bobhill	2	4	—	3
23	Magnolia	6	13	—	12
24	Horseshoe	4		—	
25	Salt	3	5	—	5
26	Crystal	39	33	31	30
27	Health	3	5	—	0
28	Sulphur	28	25	23	19
29	Lettuce Lake	6	18	—	11
30	Eureka	1		—	
31	Buckhorn	8	10	—	4
32	Lithia	33	27	32	32
33	Kissengen	10	7	0	0
34	Warm Mineral	19	15	—	9
	Total discharge	2,346	2,113		2,051

[1]See figure 21.
[2]Discharge is mean of values given in Rosenau and others (1977).
[3]Spring discharge from files of U.S. Geological Survey.

flows downward, by gravity drainage, from permeable zones overlying the Upper Floridan aquifer.

Of the 950 Mgal/d pumped in 1976, about 905 Mgal/d were withdrawn from the Upper Floridan aquifer and 45 Mgal/d from the intermediate aquifer. All water withdrawn was fresh with the exception of 45 Mgal/d of saline water pumped from the Upper Floridan aquifer at a phosphate processing plant at the mouth of the Alafia River.

In the digital model, pumpage was distributed, based on known or estimated geographic occurence of withdrawals, among the 16-mi grid blocks for the Upper Floridan aquifer (fig. 30) and for the intermediate aquifer (fig. 31). Heaviest pumpage from the Upper Floridan aquifer occurs

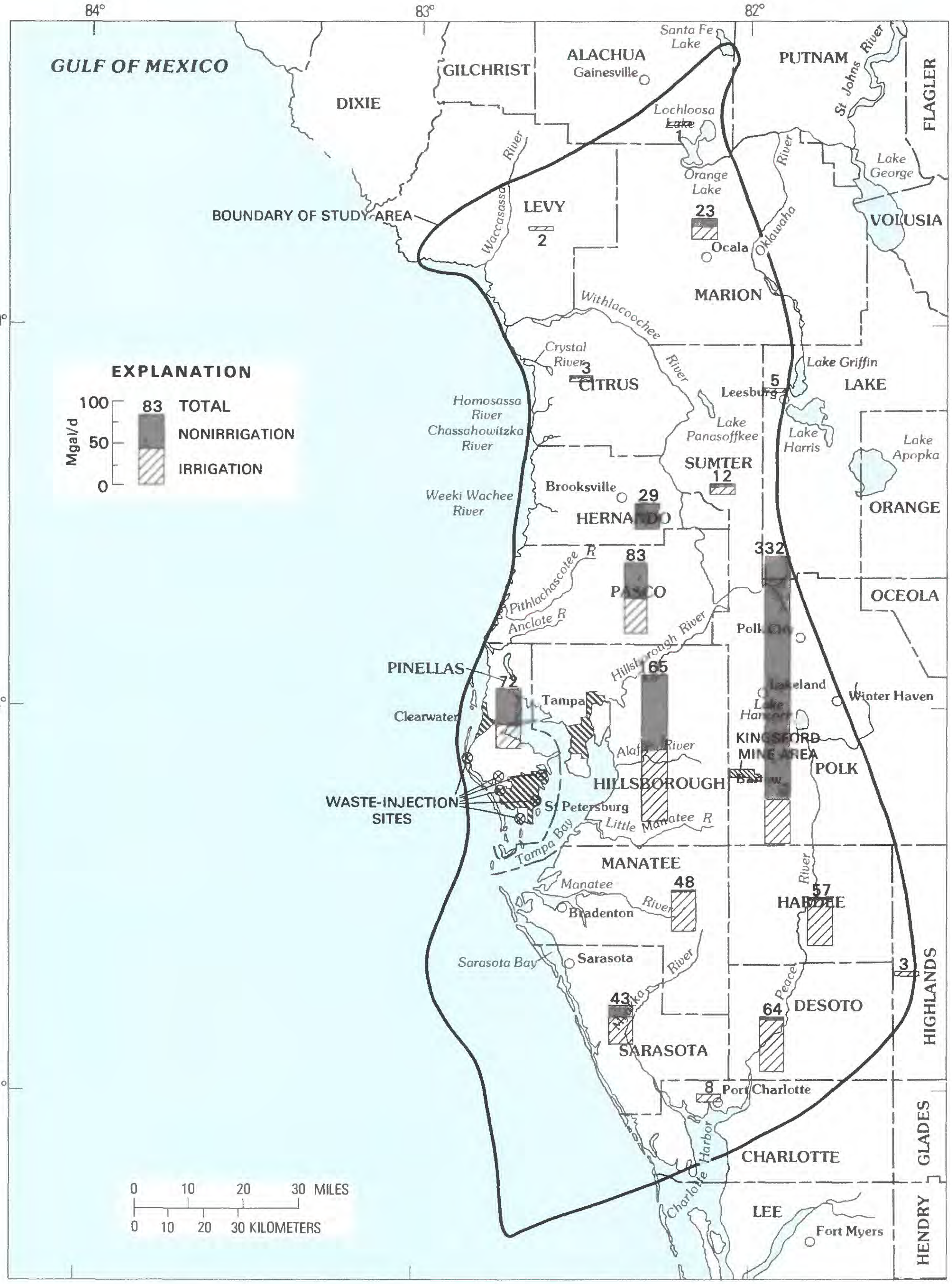


FIGURE 29.—Pumpage, by county, from the Upper Floridan aquifer and intermediate aquifer, 1976.

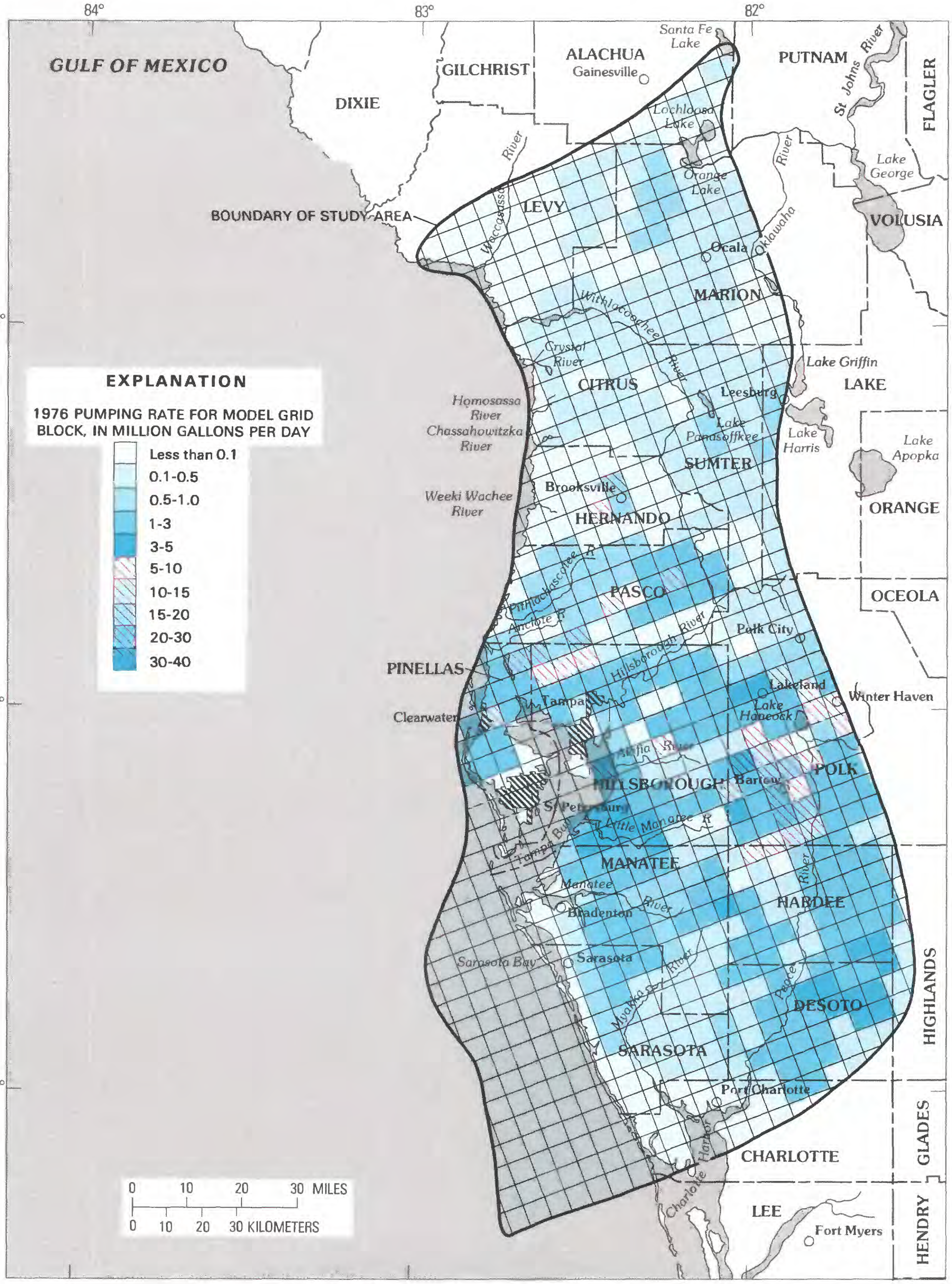


FIGURE 30.—Simulated pumpage from the Upper Floridan aquifer, 1976.

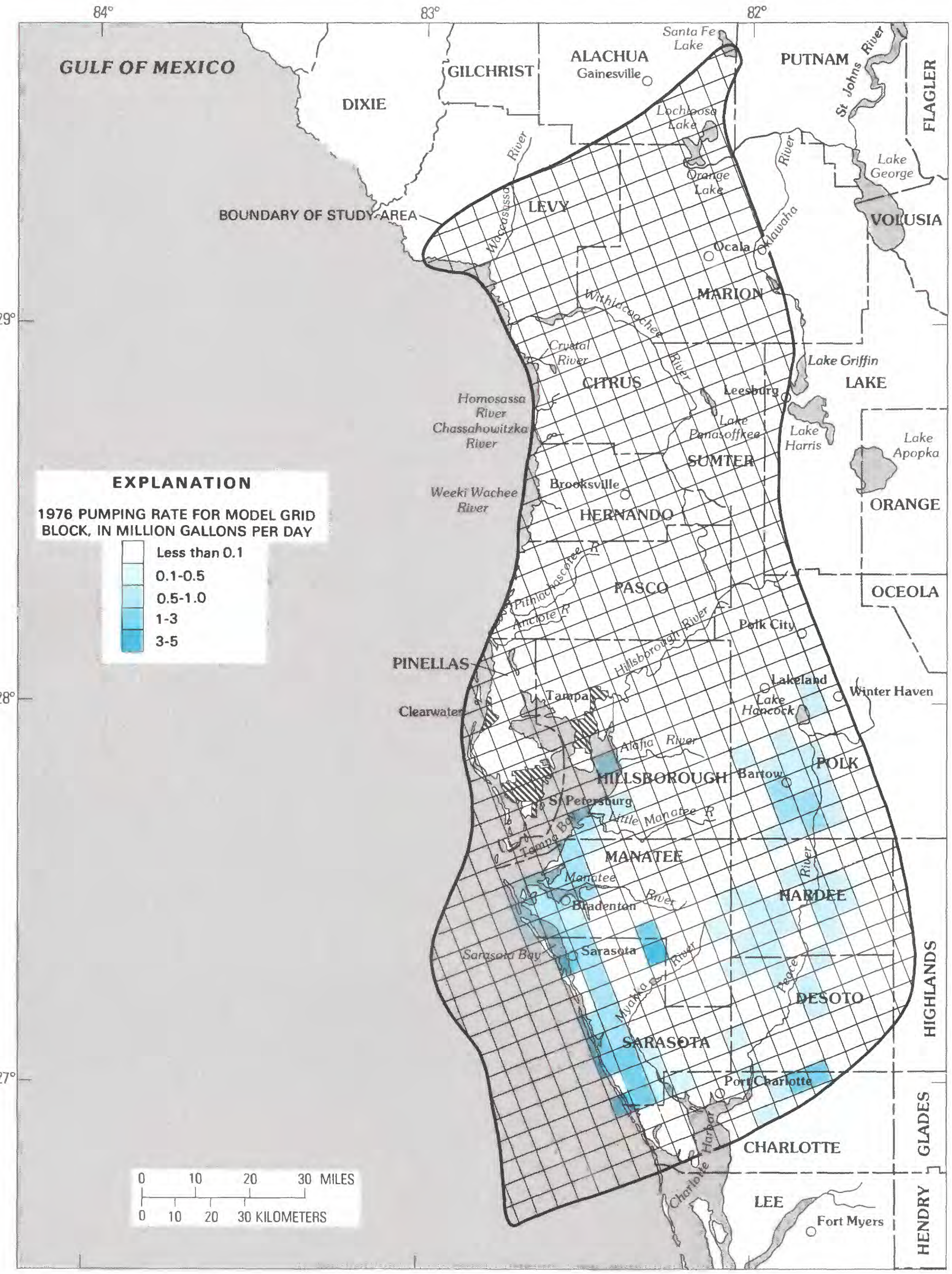


FIGURE 31.—Simulated pumpage from the intermediate aquifer, 1976.

in the northwest corner of Hillsborough County, southwestern Polk County, and at the phosphate processing plant on the Alafia River.

CHANGES IN FLOW SYSTEM, PREDEVELOPMENT TO 1976

The 1976 potentiometric surface was compared to the predevelopment potentiometric to depict regional water-level changes that have occurred in the Upper Floridan aquifer (fig. 32). From Hernando County northward, the potentiometric surface changed very little. In the northeast corner, however, the potentiometric surface had declined significantly (although less than 10 ft). The decline resulted in flatter gradients in the vicinity of Silver and Rainbow Springs in Marion County. As a result, discharges from the springs were about 17 percent lower in 1976 compared to the long-term average. Yobbi and Chappell (1979), working in a nearby area, correlated ground-water levels in shallow and deep wells with rainfall; in some wells water-level declines of about 6–8 ft for the 1976 water year were the result of rainfall deficits.

In Pasco County and in the area north of Tampa Bay, declines in the potentiometric surface of the Upper Floridan aquifer exceeded 10 ft only near large pumping centers, such as municipal well fields. On a regional basis, however, declines were less than 10 ft. The most important feature in figure 32 is the regional cone of depression centered in southwestern Polk County, where declines exceeded 50 ft. The declines tapered off gradually toward the southwest and south.

The effect of the decline of the potentiometric surface on springflow in Polk County had reached a maximum in 1950. Rosenau and others (1977, p. 307) report that Kissengen Spring (no. 33, fig. 21, table 4) with a long-term average discharge of about 10 Mgal/d, ceased flowing in February 1950. The regional decline of the 1976 potentiometric surface in the vicinity of Lithia Springs in southwestern Hillsborough County (no. 32, fig. 21, table 4) was about 30 ft. Springflow, however, was maintained at about the same rate as prior to the decline in the potentiometric surface. This was apparently accomplished by a widening of the spring orifice (J.W. Stewart, U.S. Geological Survey, oral commun., 1981). Changes in observed spring discharge, predevelopment to 1976, ranged from essentially no change at the Crystal River group of springs to cessation of flow at Kissengen Spring (table 4). Total discharge for nine springs measured in 1976 averaged about 10 percent less than predevelopment discharge.

Changes in simulated rates of recharge and upward leakage for the Upper Floridan aquifer for 1976 (compared to predevelopment rates) are shown on plate 1. From mid-Pasco County southward to the Tampa Bay area, a combination of increased vertical gradients and high leakance caused some of the largest increases in recharge rates in west-central Florida. Mush of the area around Tampa Bay has changed from an area of discharge to one of recharge.

Another area of large increase in recharge rates is in southwestern Polk County in the area of greatest pumpage and largest decline of the potentiometric surface. Moderately large increases in recharge rates occurred in the remainder of Polk County, the southeast corner of Hillsborough County, most of Hardee County, and in eastern De Soto County. Elsewhere, the increase in recharge rates is generally zero to 2 in./yr.

SUMMARY OF FLOW COMPONENTS, PREDEVELOPMENT AND 1976

An analysis of the calibrated model simulating 1976 steady-state conditions indicates that the total recharge rate (in round numbers) is 3,200 Mgal/d (3,100 Mgal/d of vertical recharge and 100 Mgal/d of lateral inflow). Of this amount, 2,050 Mgal/d (64 percent) is discharged as springflow; 950 Mgal/d (30 percent) is discharged as pumpage; and 200 Mgal/d (6 percent) is discharged as diffuse upward leakage. The pumpage of 950 Mgal/d is offset by an increase in recharge of 600 Mgal/d, a net lateral boundary inflow of 100 Mgal/d, a decrease in upward leakage of 190 Mgal/d, and a decrease in spring discharge of 60 Mgal/d. Most of the lateral inflow is from the southeast. The following table summarizes the components of the predevelopment and 1976 flow systems as simulated by the digital model:

	Source		Discharge		
	Recharge (Mgal/d)	Net lateral inflow (Mgal/d)	Upward leakage (Mgal/d)	Spring discharge (Mgal/d)	Pumpage (Mgal/d)
Predevelopment	2,501	0	388	2,113	0
1976 water year	3,099	96	196	2,051	948
Change	598	96	192	62	948

GROUND-WATER DEVELOPMENT AND POTENTIAL

Ground-water pumpage and hydrologic effects of pumpage have been included as part of many investigative reports in west-central Florida. Some reports have focused on ground-water use within a part of the study area. Robertson and Mills (1974) and Robertson and others (1978) described ground-water use in the heavily pumped upper Peace and upper Alafia River basins. Other reports have focused on the hydrologic effects of ground-water pumping. For example, Kaufman (1967) analyzed the effects of pumping in the Peace and Alafia River basins from 1934 to 1965.

A detailed inventory of water use for the study area and for Florida was done for 1965 (Pride, 1970) and for 1970 (Pride, 1973). A "benchmark farm" program was

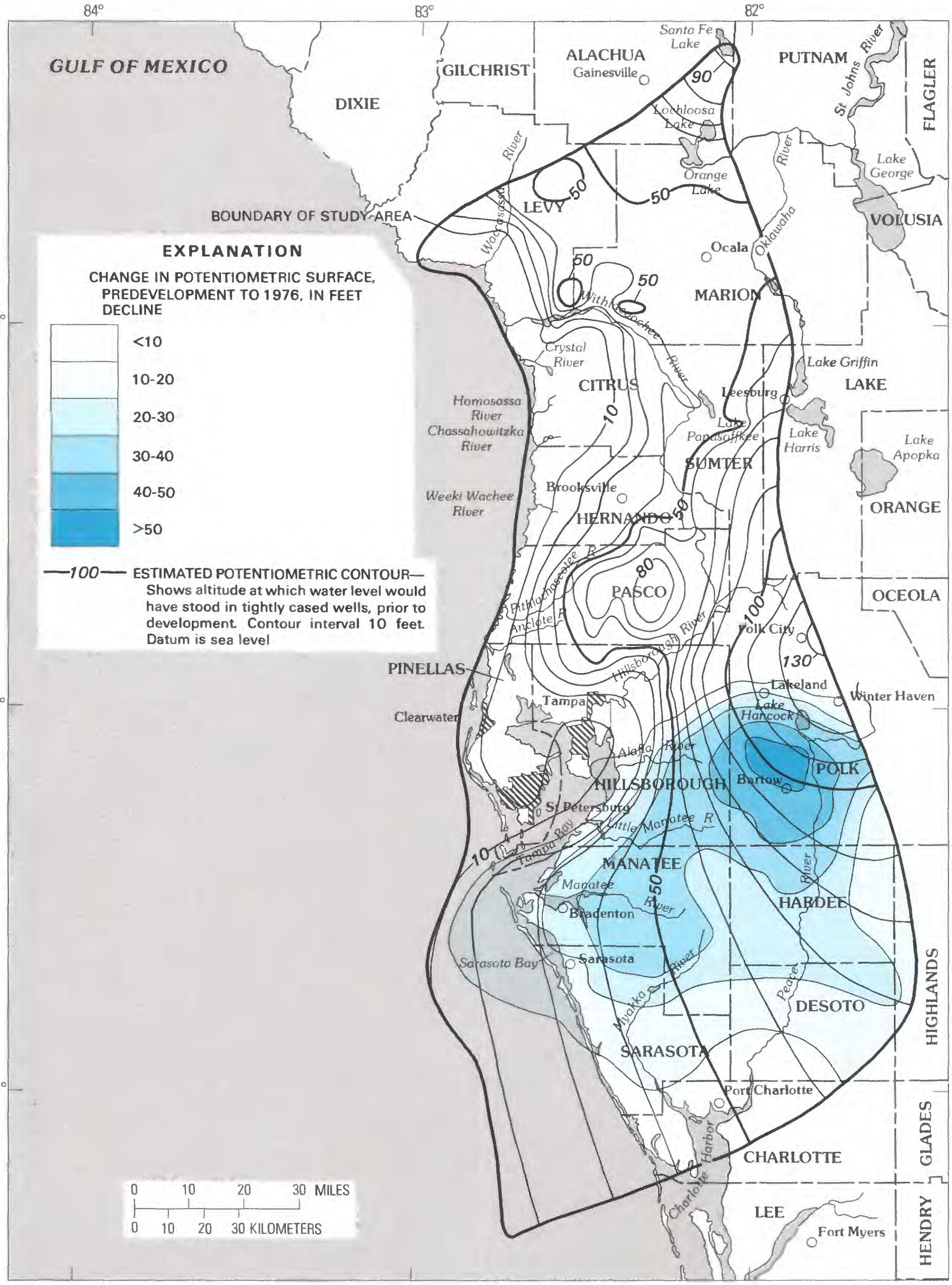


FIGURE 32.—Change of potentiometric surface of the Upper Floridan aquifer, predevelopment to 1976.

begun in the early 1970's to provide improved estimates of irrigation water-use data (Duerr and Trommer, 1982). These data led to more accurate water-use inventories for 1975 (Leach, 1978), 1977 (Leach and Healy, 1980), and 1980 (Leach, 1982). Water-use inventories have been conducted annually for the study area since 1977 (Duerr and Trommer, 1981a, 1981b; Duerr and Sohm, 1983). Data from these and other reports were used in the following discussion of ground-water development. A study by the U.S. Army Corps of Engineers (1980) was used to discuss water-supply alternatives and potential areas for ground-water withdrawals.

HISTORY OF DEVELOPMENT AND HYDROLOGIC EFFECTS IN SELECTED AREAS

MUNICIPAL WELL FIELDS NORTH OF TAMPA BAY

Some of the earliest problems associated with development of the Upper Floridan aquifer concerned saltwater contamination of municipal well-field supplies in the Tampa Bay area. The city of St. Petersburg had to abandon its downtown well field in the late 1920's because of saltwater encroachment. The cause of the saltwater encroachment was lowered water levels due to pumping form the wells and dredging of estuaries, finger canals, and drainage channels (Parker, 1975, p. 14).

The city of St. Petersburg and Pinellas County have developed well fields in Pinellas, Hillsborough, and Pasco Counties to insure safe, dependable water supplies for a growing population. An extensive network of well fields (fig. 33, Morris Bridge excluded), interconnected by pipelines as large as 84 in., supplies the urban population of Pinellas County and coastal Pasco County. The eight well fields (Morris Bridge excluded) were pumped at an average combined rate of 99 Mgal/d during 1981; the rate ranged from 84 Mgal/d for August to 120 Mgal/d for April and May (Duerr and Sohm, 1983). Average 1981 pumping rates at each well field are shown in figure 33.

Keeping pace with the increasing water demands has not been without problems. The intercounty transport of water and environmental changes that have been associated with well-field pumping have led to political repercussions and court tests. Parker (1975, p. 2) noted that the average discharge of a creek that drains most of the area in which the Eldridge-Wilde, Cosme, and Section 21 well fields are located had been reduced about 50 percent by 1963. The reduction was accompanied by lowered ground-water levels, lowered lake levels, and stress on vegetation. Complicating factors, such as drought conditions, drainage ditches, and road and home construction, coupled with inadequate hydrologic data, preclude an accurate assessment of hydrologic effects caused by well-field pumping.

Stewart and Hughes (1974, p. 4) concluded that pumping from the Section 21 well field in the middle 1960's was an important cause of excessive decline in lake levels. They also investigated the efficacy of maintaining lake levels by pumping water from the Upper Floridan aquifer into the lakes. Although the method appears to be effective, further study and monitoring were recommended to (1) document whether long-term ecological changes are likely to occur and (2) determine whether lake-level maintenance would increase the permeability of materials under the lake and, thus, require significantly increased pumpage to maintain lake levels.

The city of Tampa's water-supply wells also began to yield water with excessively high chloride content in the early 1900's. Several wells were abandoned, and in 1924, the city decided to use the Hillsborough River as a source of water; plant operations began in 1925 (J. W. Stewart, U.S. Geological Survey, written commun., 1981). A dam was subsequently built about 10 mi above the mouth of the Hillsbouough River to store additional water. In the early 1960's, Sulphur Springs was purchases and a pumping station was constructed to provide as much as 20 Mgal/d to augment river supplies. Test pumping from the Tampa Bypass Canal showed that the Canal could augment city supplies by about 18 Mgal/d (Geraghty and Miller, Inc., 1982). The Morris Bridge well field (fig. 33) was completed in the late 1970's; it is designed to contribute up to 40 Mgal/d to Tampa's supply. The average pumping rate for this well field in 1981 was 18 Mgal/d.

HEAVILY STRESSED UPPER PEACE AND UPPER ALAFIA RIVER BASINS

The most intensive ground-water development is in the upper parts of the Peace River and Alafia River basins, mainly in southwestern Polk County (fig. 34). The population in this area is small, and withdrawals for public supply have been relatively moderate. Large amounts of water are withdrawn for irrigating citrus crops and for industrial use in the mining and processing of phosphate ore and the processing of citrus products.

The quantity of ground water used in the upper Peace and Alafia basins for the period 1935–74 is shown in figure 35. Trends in population and in industrial and agricultural activity are shown in figure 36. Figure 35 shows (1) a steady increase in municipal-supply pumpage, which reflects a steadily increasing population (fig. 36);

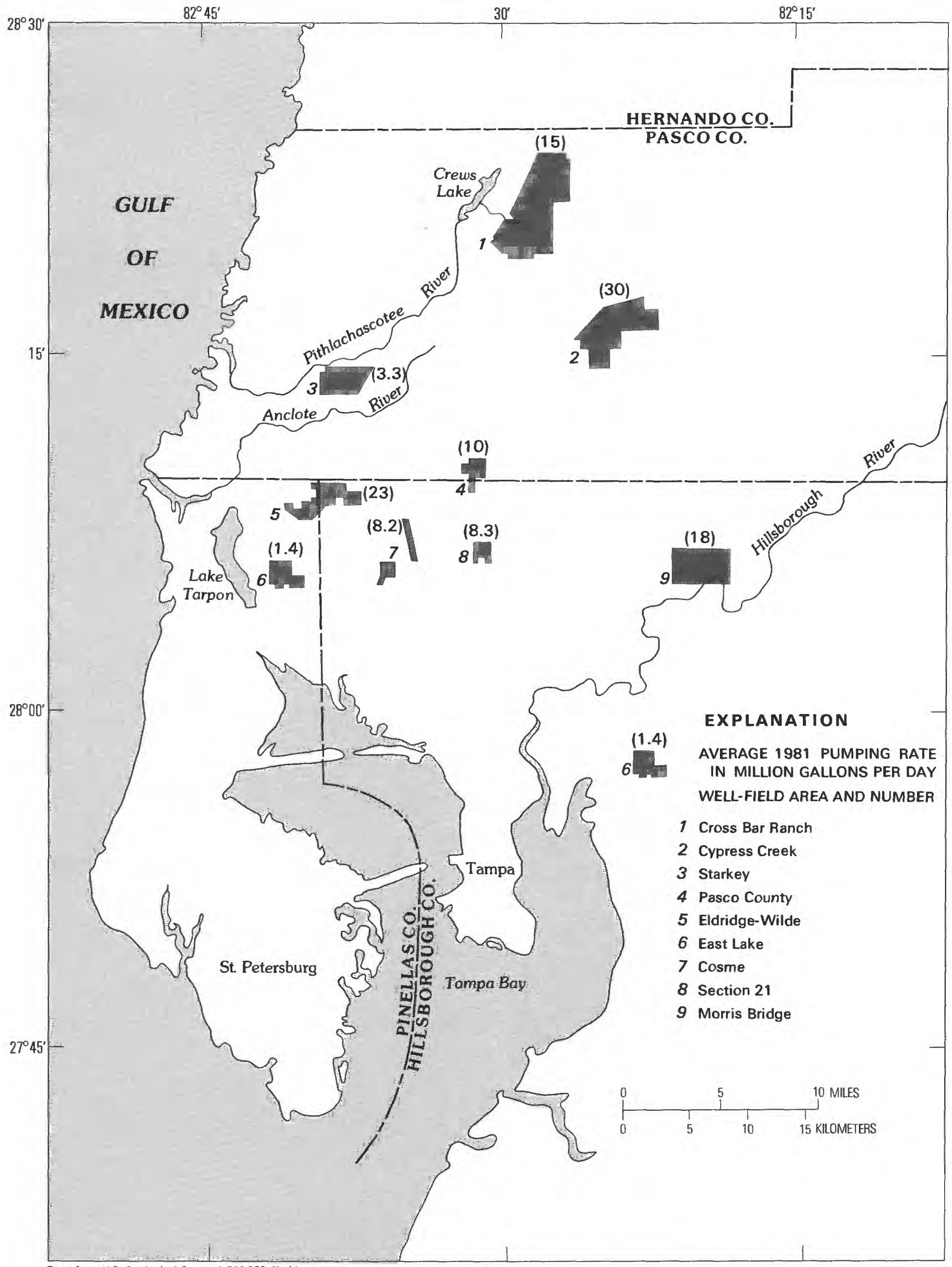


FIGURE 33.—Municipal well fields north of Tampa Bay.

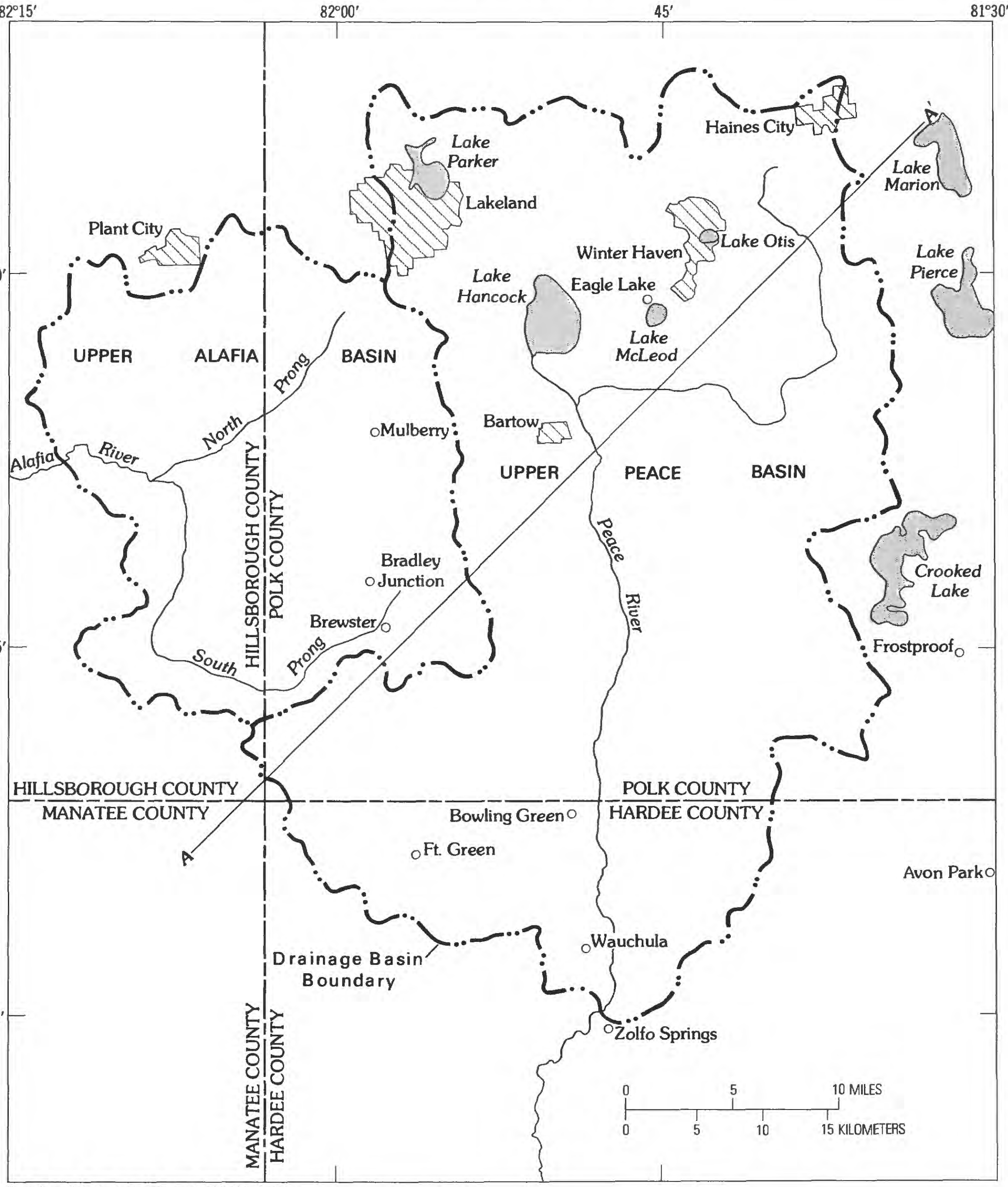


FIGURE 34.—Heavily pumped area of upper Peace and upper Alafia River basins (modified from Robertson and others, 1978, fig. 1).

(2) an increase in pumpage for citrus irrigation during the 1960's and a leveling off in the 1970's; and (3) sharply increasing rates for industrial withdrawals from 1946 to the middle 1960's.

The leveling off of pumping rates for citrus irrigation in the late 1960's and early 1970's is partly due to the decline in citrus acreage (fig. 36). Of greater significance in the leveling off and decline of irrigation and industrial pumpage, however, was the development of water-conservation practices during this period by irrigators, who turned to more efficient irrigation systems and techniques, and by the phosphate industry, which developed recycling systems for process water.

Water-use data for Polk County for the period 1975–81

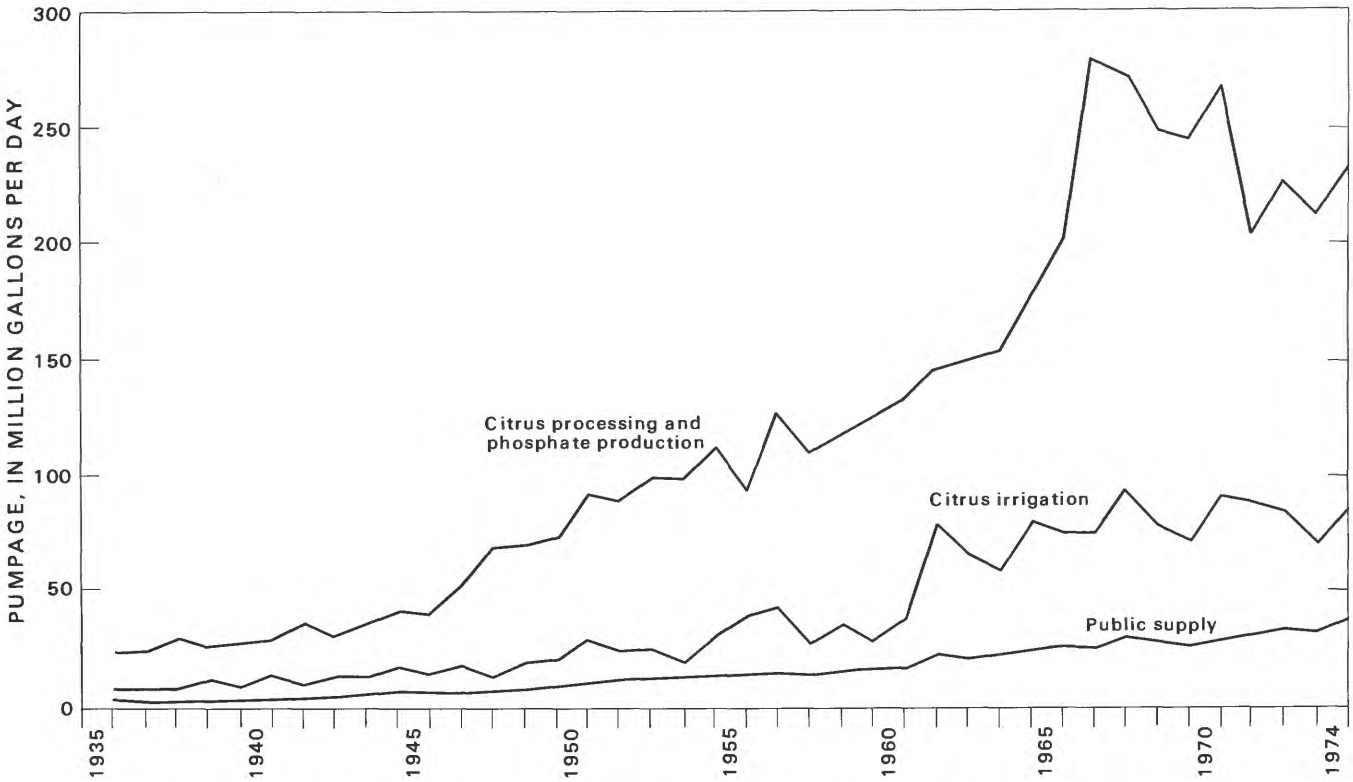


FIGURE 35.—Estimated annual ground-water pumpage for selected uses in upper Peace and Alafia River basins, 1935–74 (from Robertson and others, 1978 fig. 3).

indicate a continuing decline in the use of ground water for irrigation and industry. However, pumpage for irrigation increased during 1981, a year during which prolonged, severe drought conditions prevailed.

CONNECTOR-WELL RECHARGE AND WASTE INJECTION

Two important locations where water is recharged into the Upper Floridan aquifer through wells include (1) the Kingsford Mine area in southwest Polk County (fig. 29), where water drains by gravity into the Upper Floridan aquifer from the surficial aquifer, and (2) the Pinellas County waste-injection sites (fig. 29), where treated sewage is injected under pressure into a saline zone of the Upper Floridan aquifer.

CONNECTOR WELLS AT KINGSFORD MINE AREA

Gravity-flow connector wells in phosphate-mining areas have a two-fold purpose: (1) dewatering of the overburden and ore matrix, and (2) recharging the heavily pumped Upper Floridan aquifer with water that would otherwise discharge into streams.

About 90 connector wells were constructed at the Kingsford Mine area in the early 1970's. Most of the wells were constructed so that water enters a screened interval in the surficial aquifer, flows downward through a casing, and leaves through an open-hole section in the Upper Floridan aquifer. Other wells were constructed to permit water to flow from the surficial aquifer into the intermediate aquifer, or from the surficial and intermediate aquifers into the Upper Floridan aquifer.

About 60 connector wells were in operation at any one time during 1979. The flow rates of the wells ranged from 40 to 300 gal/min and averaged 150 gal/min. The Composite recharge rate for 1979 was about 13 Mgal/d (L. Cawley, International Minerals and Chemical Corp., oral commun., 1980) Connector wells are also used at other mining sites, but to a much lesser extent than at the Kingsford Mine.

WASTE INJECTION IN PINELLAS COUNTY

Pinellas County and the city of St. Petersburg have constructed six waste-injection test sites (fig. 29) to test the feasibility of injecting and storing treatment-plant effluent in the Upper Floridan aquifer. The injection zone is the permeable dolomite section in the lower part of the Upper Floridan aquifer. This zone is in the saltwater part of the aquifer, where chloride concentrations approximate that of seawater.

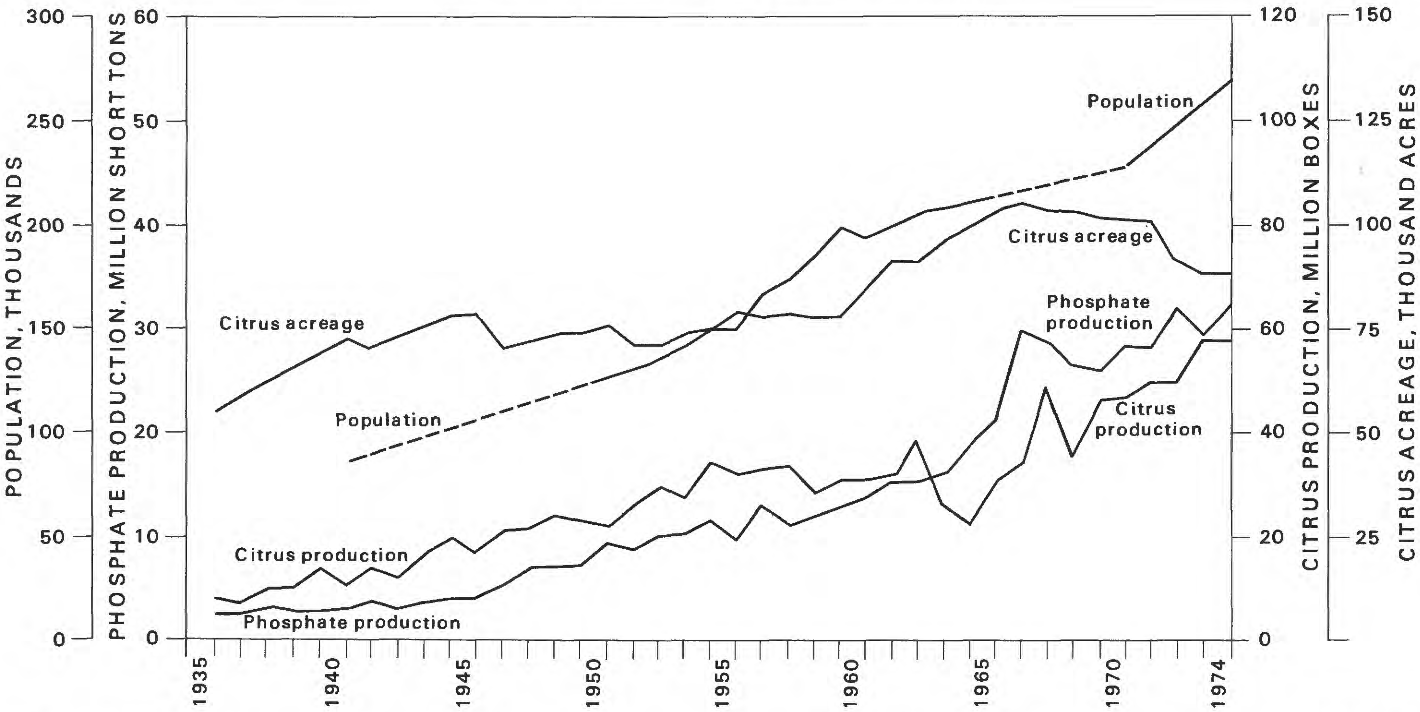


FIGURE 36.—Citrus acreage and production and phosphate production in the upper Peace and Alafia River basins, 1935–74, and Polk County population, 1940–74 (from Robertson and others, 1978, fig. 4).

Hickey (1981) estimated a projected maximum injection rate of about 40 Mgal/d when all sites become operational. Using results of model computations, Hickey suggested that regional pressure and velocity changes caused by 20 years of injection will be small, generally not exceeding 3 ft of head change and 0.1 ft/d of velocity change.

POTENTIAL FOR DEVELOPMENT

Several models for projecting population growth in west-central Florida have been developed. All the models indicate that Florida's population will continue to increase at a rapid rate well into the next century. One estimate of the projected population in west-central Florida is shown in table 5. As shown, each county will experience some growth; the most rapid growth and the greatest population density will continue to be centered in the Tampa Bay area. Total population in the Southwest Florida Water Management District for 1980 was approximately 2.5 million. It is projected to increase by about 52 percent by the year 2000 to a total of 3.8 million. The population in 2020 is projected to be about 4.6 million, an increase of 84 percent over the 1980 population.

WATER-DEMAND PROBLEM AREAS AND WATER-SUPPLY AREAS

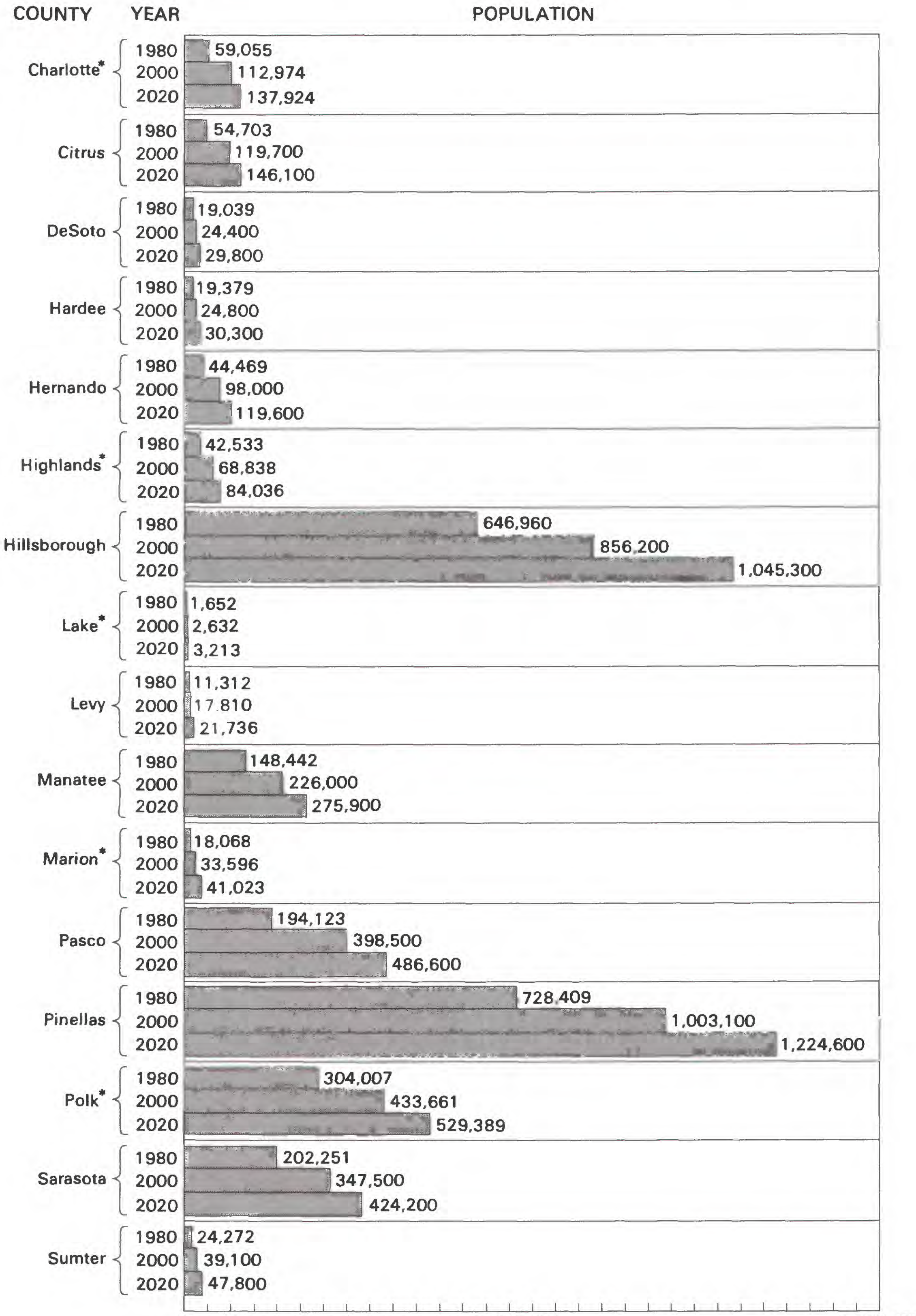
Ground-water resources in certain areas, such as most of the northern half of the study area, are relatively undeveloped at the present time (1983). In these areas, good potential for development exists. Ground-water resources just north of Tampa Bay have been heavily developed. Further development in this area will continue, but the problem of environmental effects will have to be addressed.

In much of the southern half of the study area, large withdrawals of water for industry and irrigation have resulted in greatly lowered water levels in the Upper Floridan aquifer. The large projected increase in population for the southern coastal areas will result in increases in withdrawals for municipal supplies that will compete for the already heavily stressed ground-water resource.

During the latter 1970's, the U.S. Army Corps of Engineers (1980) studied the problems of water-resource development and management for an area of west-central Florida that coincides with the Southwest Florida Water Management District. The major water-supply problems were determined to be those of municipalities near the coastal zone (fig. 37). Local water resources in those areas would be insufficient to meet projected demands. The projected increase in demand from 1975 to 2035 is shown for each major area in table 6. The total projected increase is 380 Mgal/d.

The remainder of the study area, according to the Corps' study, would have sufficient water available locally to meet demands. The study (U.S. Army Corps of Engineers, 1980, p. 115) concluded that sufficient water is available to meet all projected demands, but that intergovernmental coordination and agreement is essential for the optimum utilization and distribution of supplies.

TABLE 5.—*Projected county population within the Southwest Florida Water Management District, 1980–2020 (from the Southwest Florida Water Management District, written commun., October 1982)*



*Only that portion of the county within the SWFWMD

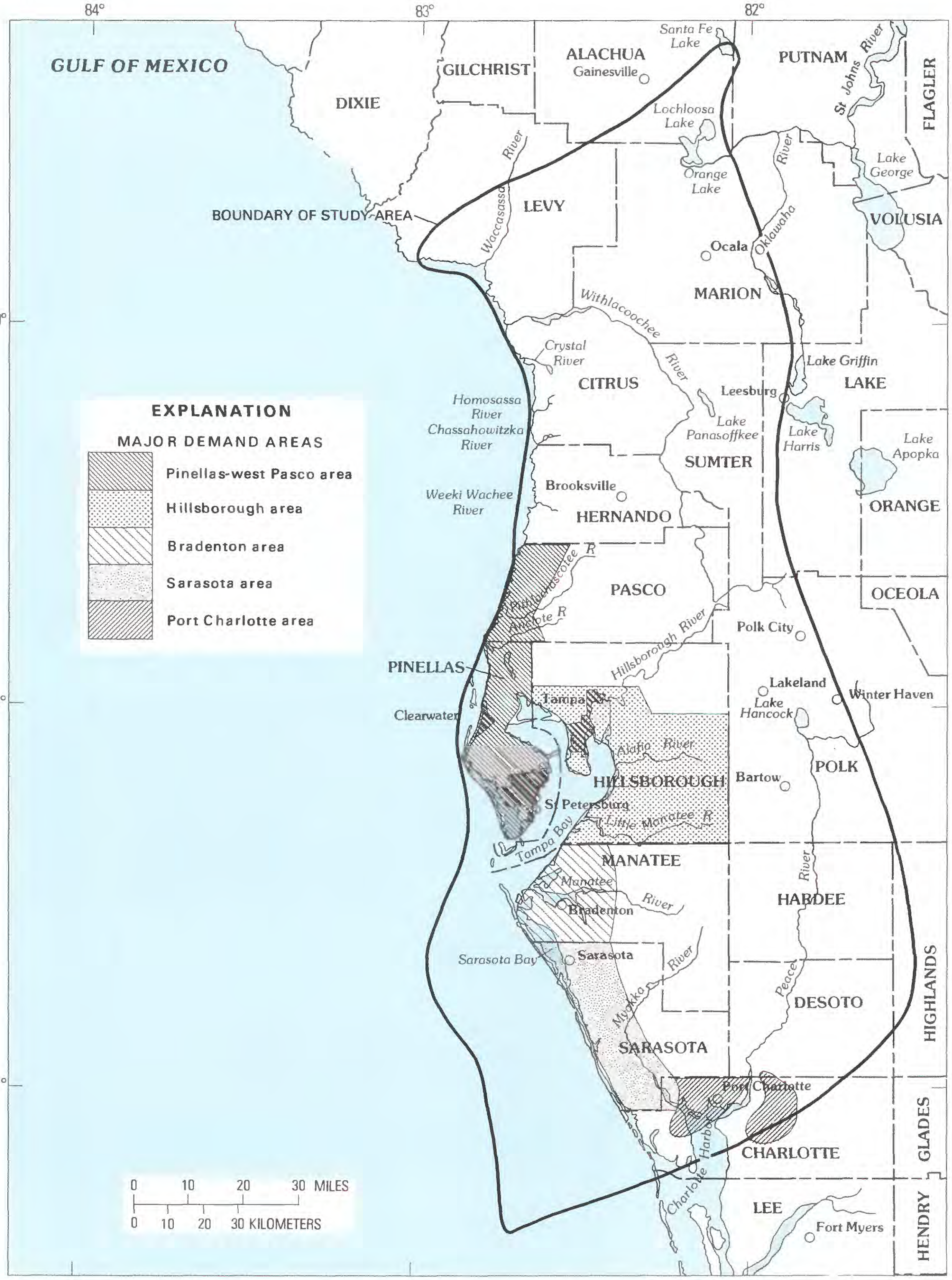


FIGURE 37.—Areas where major municipal water-supply problems are likely to occur (from U.S. Army Corps of Engineers, 1980, pl. 1).

TABLE 6—*Projected increase in water use by 2035 in major water-demand areas (data from U.S. Army Corps of Engineers, 1980, p. 17)*

Water-demand area (fig. 38)	Projected increase, 1975 to 2035 (Mgal/d)
Pinellas-West Pasco	150
Hillsborough	100
Bradenton	35
Sarasota	65
Port Charlotte	30
Total increase	380

The Corps' study listed the major water-supply options as being well fields, surface-water storage, river-flow diversion, and artificial underground storage. The study concluded that "well field alternatives were generally more economical and less environmentally disruptive than surface-storage plans" (U.S. Army Corps of Engineers, 1980, p. 115). Locations of future well fields must be carefully considered by water managers and planners if the adverse impacts of proposed well-field withdrawals on the hydrologic flow system are to be minimized. Digital simulation of aquifer response to increased pumpage can be used as a management tool in this effort.

SIMULATION OF INCREASED DEVELOPMENT

As an example of using the digital model for assessing effects of proposed well fields, two potential sites were selected for analysis (plate 1). Hypothetical well fields, each pumping 30 Mgal/d, were located near the coast at the Citrus-Hernando County line and in northeastern Manatee County. The sites are landward of the saltwater-freshwater zone of transition in the Upper Floridan aquifer. These areas are under consideration for development of large well fields.

Analysis of the simulated withdrawals is subject to the following assumptions and conditions:

1. The new pumpage is superimposed on the 1976 steady-state flow system, and a new condition of steady-state equilibrium is reached.
2. Head declines at the saltwater-freshwater interface are insignificant.
3. An insignificant amount of water is induced laterally through the aquifer into the study area.
4. For the Hernando County site, the recharge rate remains fixed at the 1976 rate; the new pumpage is derived almost entirely from a reduction in spring discharge.
5. For the Manatee County site, the water table in the surficial aquifer remains fixed; the new pumpage is derived almost entirely from an increase in downward leakage (or decrease in upward leakage) within the superimposed cone of depression.

The difference in the cones of depression for the two pumping locations is striking (plate 1). At the Hernando County site, the cone is relatively shallow and of small areal extent. This condition would be expected in this area of high recharge and high transmissivity and where water that discharges to large springs can be intercepted by the pumping wells. Springs most affected by the superimposed pumpage are as follows:

Spring(s) (see table 3)	Simulated 1976 discharge (Mgal/d)	Simulated discharge with new well field (Mgal/d)	Percent decrease
Crystal River Group	546	537	2
Homosassa	105	101	4
Chassahowitzka, Potter, and Ruth	76	69	9
Nos. 9, 10, 11, and 12	20	18	10

The northern areas can sustain a great deal of new development. The major impact on the flow system will be reduced spring discharge. New developments, even if located many miles inland, can reduce the flow of the coastal springs. Springs that are near the coast are generally in the zone of freshwater-saltwater transition, and some are affected by tides. A reduction of freshwater flow to these springs would result in increased chloride concentrations in the springflow-aquifer system. New development farther inland, for example in the ground-water basins drained by Rainbow Springs and by Silver Springs, would have the least impact on the flow system and on water quality.

At the site in northeastern Manatee County, the cone of depression from the superimposed pumpage is steeper and of much greater areal extent than at the northern site. The combination of moderately high transmissivity and thick, effective overlying confining beds causes the cone to spread laterally over a relatively greater distance until a sufficient amount of downward leakage (or reduced upward leakage) is induced to equal the amount of water being pumped. In contrast to the Hernando County site, only about 7 precent of the pumpage is derived from a reduction in spring discharge (about 2 Mgal/d from Lithia Springs in Hillsborough County).

The sustenance of additional large ground-water development in the south is less certain than in the north. Intense competition for municipal, industrial, and irrigation supplies could cause further declines in the potentiometric surface; however, the potential effects of such declines have not been quantitatively evaluated.

The well-field simulation described above is one of many possible pumping patterns that can be simulated by the digital model. When needed, the model could be used in conjunction with the multistate regional model (described in Professional Paper 1403-C) to simulate flows across the boundary of the study area. These simulations could provide generalized data concerning impacts on the flow system that could be useful in initial phases of planning for future development. But eventually, some basic hydrologic questions must be answered:

1. At what point will development become so great that further development will render quality and quantity of spring discharge unacceptable?
2. How much development can occur before the assumption of a fixed saltwater-freshwater interface (or zone of transition) is no longer justifiable?
3. How much development can occur before the assumption of a fixed water table in the surficial aquifer is no longer valid and widespread permanent declines in the water table prevail? Such declines are well documented in areas that contain large well fields and where confining-bed leakage is relatively high.
4. At what point will development become so great that aquifer discharge exceeds aquifer recharge and an assumption of steady-state conditions is no longer applicable? Such conditions of long-term decline prevailed during the 1960's and early 1970's in certain areas.

DIGITAL MODEL OF 1976 FLOW SYSTEM

The digital model used for simulating the 1976 flow system is identical to that used to simulate the predevelopment flow system; only the input data and boundary conditions were changed to reflect 1976 conditions. A complete description and discussion of the model, including references, significant computer code changes, theory, and important assumptions and limitations were reported by Ryder (1982).

1976 STEADY-STATE CALIBRATION

A long-term decline in lake levels and ground-water levels occurred into the mid-1970's, especially in the heavily pumped upper Peace and Alafia River basins. Significant recovery of water levels occurred during the latter 1970's and into the 1980's. Records of ground-water levels, lake stages, and rainfall were examined for the transition period (1974-76) between long-term water-level decline and recovery. The 1976 water year (October 1, 1975, to September 30, 1976) was considered to be a suitable period for steady-state model calibration because: (1) net change in storage in the regional flow system was negligible; and (2) pumpages are known or can be reasonably estimated.

PROCEDURE

During model calibration, the initial hydrologic input data were estimated, and computed hydraulic heads were compared with observed heads. The input data were then adjusted until differences between computed and observed heads were within acceptable limits. Computed and observed rates of spring discharge were also compared.

HYDROLOGIC INPUT DATA

Most of the initially estimated input data for the 1976 model calibration were obtained from the predevelopment model calibration (Ryder 1982). these data included transmissivity of the intermediate aquifer and Upper Floridan aquifer and leakance of the confining beds. Other data sets from the predevelopment model required only slight modification before being entered as input data for the stressed model. These included:

1. Water table of the surficial aquifer: Heads were lowered about 6 ft in the northeast corner of the modeled area to reflect observed head declines associated with long-term rainfall deficits.
2. Direct recharge to the unconfined Upper Floridan aquifer in northern areas: Slight adjustments were made in grid blocks that contained pumping wells. Recharge was increased by a small fraction of the pumping rate to simulate induced recharge that was formerly rejected, but in no case did the increase exceed 1 in./yr. Predevelopment recharge rates that exceeded 14 in./yr were arbitrarily assumed to be maximum rates, and increases were not made in those grid blocks.
3. Head difference-spring discharge functions: The constant that describes the linear relation between head difference and discharge rate was changed substantially for Lithia Springs in Hillsborough County. This change was necessitated because artificial widening of the spring orifice modified flow conditions.
4. Spring pool elevations were lowered slightly for Rainbow Springs and Silver Springs to reflect mean 1976 water levels as determined from stage record.

Data sets that required extensive modification included the potentiometric surfaces of the intermediate aquifer and Upper Floridan aquifer. A new data set was required to simulate 1976 pumpage.

POTENTIOMETRIC SURFACE

Maps of the potentiometric surface of the Upper Floridan aquifer for May 1976 (Stewart and others, 1976) and September 1976 (Ryder and others,1977) were used in conjunction with continuous records from numerous wells to construct the mean potentiometric surface for the

1976 water year (fig. 28). The mean of the May and September water levels was nearly identical to the 1976 annual mean based on continuous records for most of the area. In some southern areas, the mean of the two water levels differed from the annual means by about 1 to 3 ft, and water levels in these areas were adjusted in constructing the 1976 map. Recorder wells and miscellaneous periodic measurements for the southern area and September 1975 and May 1976 potentiometric-surface maps for the upper Peace and Alafia River basins (Hutchinson, 1978) were used to estimate the 1976 potentiometric surface of the intermediate aquifer.

PUMPAGE

In compiling pumpage data for the 1976 water year, water-use data collected by Wilson and Gerhart (1982) for 1975–76 were examined. These data had been collected for use in a digital model of a seven-county area that approximates the southern half of the study area. Public and industrial pumpage were used virtually unchanged as input to the 1976 model. Because of improved estimates of irrigation water-use data, irrigation application rates and number of irrigation acres were recalculated for Polk, De Soto, Manatee, and Sarasota Counties.

For the northern areas, telephone surveys were used in conjunction with data in the files of the U.S. Geological Survey (A. D. Duerr, U.S. Geological Survey, written commun., 1980) to estimate 1976 pumpage. Pumpage distribution for the entire study area is shown by county in figure 29 and by model grid blocks on figures 30 and 31. Total 1976 pumpage was about 950 Mgal/d, which takes into account about 22 Mgal/d of recharge injected through wells into the Upper Floridan aquifer. About 905 Mgal/d were withdrawn from the Upper Floridan aquifer and 45 Mgal/d from the intermediate aquifer.

BOUNDARY CONDITIONS

The no-flow lateral boundary used in the predevelopment model was replaced by a constant-head boundary for the 1976 steady-state calibration, except at the freshwater-saltwater boundary, which remained a no-flow boundary. The finite-difference grid and boundaries are shown in figure 38. After calibration, the constant-head boundary was replaced by a constant-flux boundary. The fluxes were generated by the regional model that was used to simulate pumpage in all of Florida. The close similarity in computed heads when using the constant-head boundary and the constant-flux boundary demonstrates the effectiveness of the regional model for supplying flows across the boundaries. The regional model was also used to supply boundary flows during an attempted transient model calibration.

RESULTS

A comparison between the observed and the simulated 1976 potentiometric surfaces of the Upper Floridan aquifer is shown in figure 39. This comparison shows that (1) the potentiometric surface simulated by the model is reasonable accurate, and (2) the greatest accuracy is in the north.

The observed and simulated potentiometric surfaces can also be compared statistically by analyzing the differences between observed and simulated heads for all model grid blocks. The average difference in head was 4.1 ft for the Upper Floridan aquifer and 6.5 ft for the intermediate aquifer. [Note: The average difference in head is the average of the absolute values of the head differences in all grid blocks.]

Another means of measuring the accuracy of the model calibration is to compare observed 1976 spring discharge to model-simulated discharge (table 4). Table 4 shows that only nine springs were measured during 1976 (excluding Kissengen Spring, which ceased to flow in the 1950's). However, it is estimated that the discharge from these nine springs comprises about 85 percent of total spring discharge in the study area. For the nine springs, simulated discharges ranged from 83 percent of observed discharge at Crystal Springs to 110 percent of observed discharge at Rainbow Springs. The average simulated discharge was 100 percent of the 1976 measured discharge.

Transmissivity and leakance values were changed slightly in the south to obtain the best calibration under pumping conditions. Rerunning the predevelopment model with the changed parameters produced essentially the same results as the initial predevelopment calibration.

MAY TO SEPTEMBER 1976 TRANSIENT SIMULATIONS AND SENSITIVITY ANALYSIS

Unlike the steady-state models, heads computed during transient simulations are a function of starting heads and time. Thus, initial input data must include an estimate of the storage coefficient for the Upper Floridan aquifer and intermediate aquifer. As described previously, distribution of Upper Floridan aquifer storage coefficient in confined areas was estimated by applying an average specific storage of 1.0×10^{-6} times aquifer thickness shown in figure 10. This procedure was followed for the permeable deposits of the intermediate aquifer, whose thickness is shown in figure 12. In unconfined areas, the storage coefficient (specific yield) of the Upper Floridan aquifer was estimated at 0.2.

The quasi-three-dimensional model used in this study is not programmed to deal with water that may be released from or taken into storage in the confining beds. However,

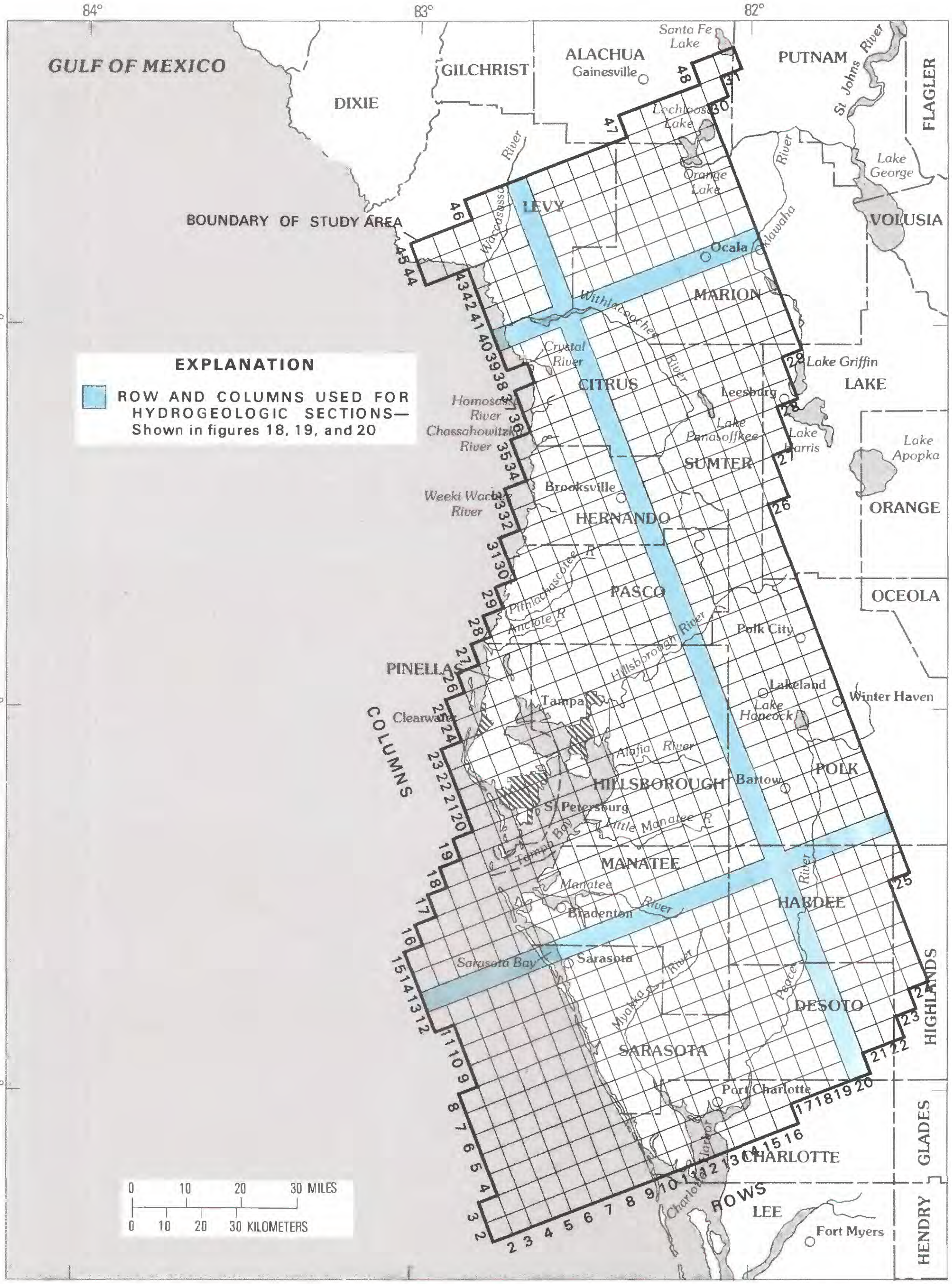


FIGURE 38.—Model area of the Upper Floridan aquifer with finite-difference grid and boundaries.

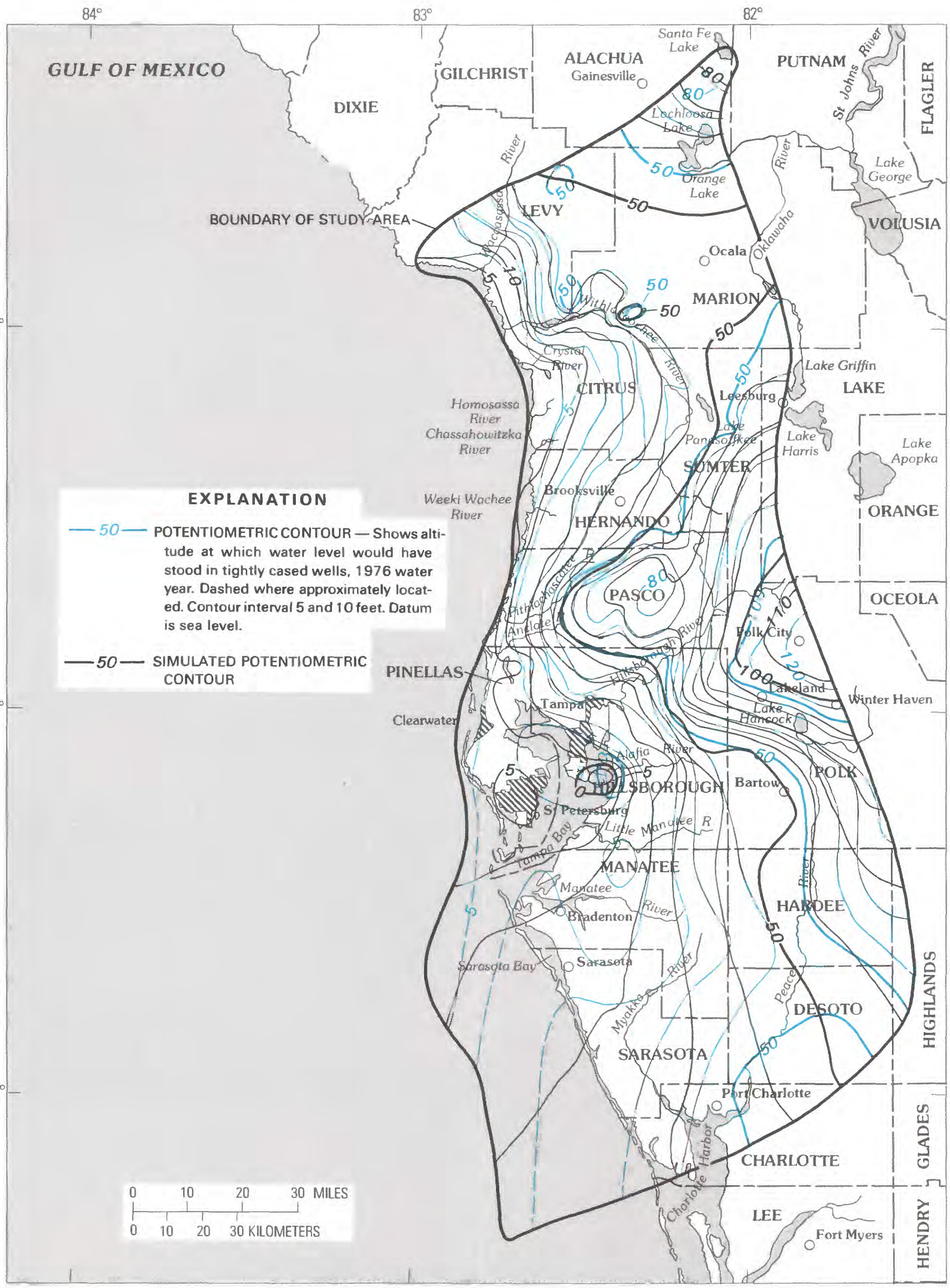


FIGURE 39.—Comparison of observed 1976 potentiometric surface of the Upper Floridan aquifer to that simulated by the model.

figures 11 and 14 show that confining beds are absent or relatively thin over most of the study area. Water associated with change in storage in confining beds could be significant in the southern third of the study area, where the beds generally exceed 200 ft in thickness and attain a maximum thickness of about 400 ft in De Soto County.

To test the estimated aquifer storage properties and other model parameters, a transient simulation was made that started with May 1976 conditions and ended with September 1976 conditions. An essential element of the simulation was a procedure of using the model to correct for a large water-level recession that occurred in the aquifer in early May. The recession was steepest in areas with heavy irrigation withdrawals, as normally occurs in late spring each year. The procedure for the transient model simulation was furnished by J. M. Gerhart (U.S. Geological Survey, written commun., 1981) and is described in detail as follows:

1. Initial input data for the transient simulation were derived from the 1976 steady-state calibration with the following exceptions: (a) the May potentiometric surface (Stewart and others, 1976) was used to provide starting heads for the Upper Floridan aquifer, (b) a May potentiometric surface was estimated for the intermediate aquifer, (c) average 1976 pumpage was replaced by the estimated pumping rate for April to May 1976, and (d) lateral boundary fluxes for the 1976 steady-state model were deleted and replaced by fluxes, as explained below.
2. The model was run in four pumping periods (six time steps per pumping period) from May 12 to September 12; each pumping period was 31 days. Each pumping period was preceded by a run with the large regional model so that boundary fluxes could be applied to the small model at the beginning of each pumping period. The heads generated for September 12 were saved.
3. The April to May 1976 pumping rate was replaced by the rate estimated for September 1976, and the procedure described in step 2 was repeated.
4. The heads generated for September 12 in step 2 were subtracted from those generated in step 3. These differences were added to the observed May 1976 heads, and the resulting heads were compared to the observed September 1976 potentiometric surface (Ryder and others, 1977).

The heads computed by the transient simulation were very similar to those observed for September 1976 for most of the study area, including the heavily stressed Polk and Hillsborough County areas. This similarity indicated that the initial estimate of storage coefficient was good for most of the study area. However, simulated heads were much higher, about 15 to 20 ft, than observed heads in De Soto County and in parts of Hardee, Manatee, and Sarasota Counties. Nearly all pumpage in these counties is irrigation pumpage, the most difficult of all water-use data to estimate. Also, confining beds attain maximum thickness in these areas. To complete a transient calibration, it would be necessary to reduce pumping rates or increase aquifer storage coefficient, or both, in problem areas and perhaps change other model parameters as well. It would also be necessary to assume that amounts of water released from or taken into storage in confining beds is insignificant, by no means a safe assumption for these areas.

The uncertainty concerning which parameters should be changed suggests that a transient model calibration not be completed until (1) irrigation pumping rates can be measured more accurately, and (2) the model code is modified to simulate changes in storage in confining beds.

Peter Bush (U.S. Geological Survey, written commun., 1982) used the large regional model (as described in Professional Paper 1403–C) to test the sensitivity of the model to changes in storage coefficient and pumpage. Using predevelopment starting heads, and the average annual pumpage and storage coefficient estimated as previously described, a series of 183-day runs were made. For each run, storage coefficient or pumpage was changed through a feasible range while holding all other parameters unchanged. The results of the sensitivity analysis are shown in figure 40. The center of the grid block used to construct the time-drawdown curves in figure 40 is about 8 mi south of Bartow in Polk County. The sensitivity analysis shows that for less than 20 days, an order of magnitude change in storage coefficient can cause a change in drawdown very similar in magnitude to a 30-percent change in pumping rates. Also, changes in drawdown attributable to changes in storage coefficient diminish with time, so that after about 120 days, the drawdown curves for a given pumping rate nearly converge to a quasi-steady-state condition. For smaller values of storage coefficient, 1.2×10^{-4}, quasi-steady-state conditions are essentially reached in 20 days.

SUMMARY AND CONCLUSIONS

The hydrogeologic framework and the hydraulics of the flow system in the northern half of the study area are quite different from those of the southern half. Important features of the aquifer framework and predevelopment flow system are summarized as follows:

1. In the north, the Upper Floridan aquifer is at or near land surface or it is overlain by the surficial aquifer, separated by a relatively thin confining layer. Transmis-

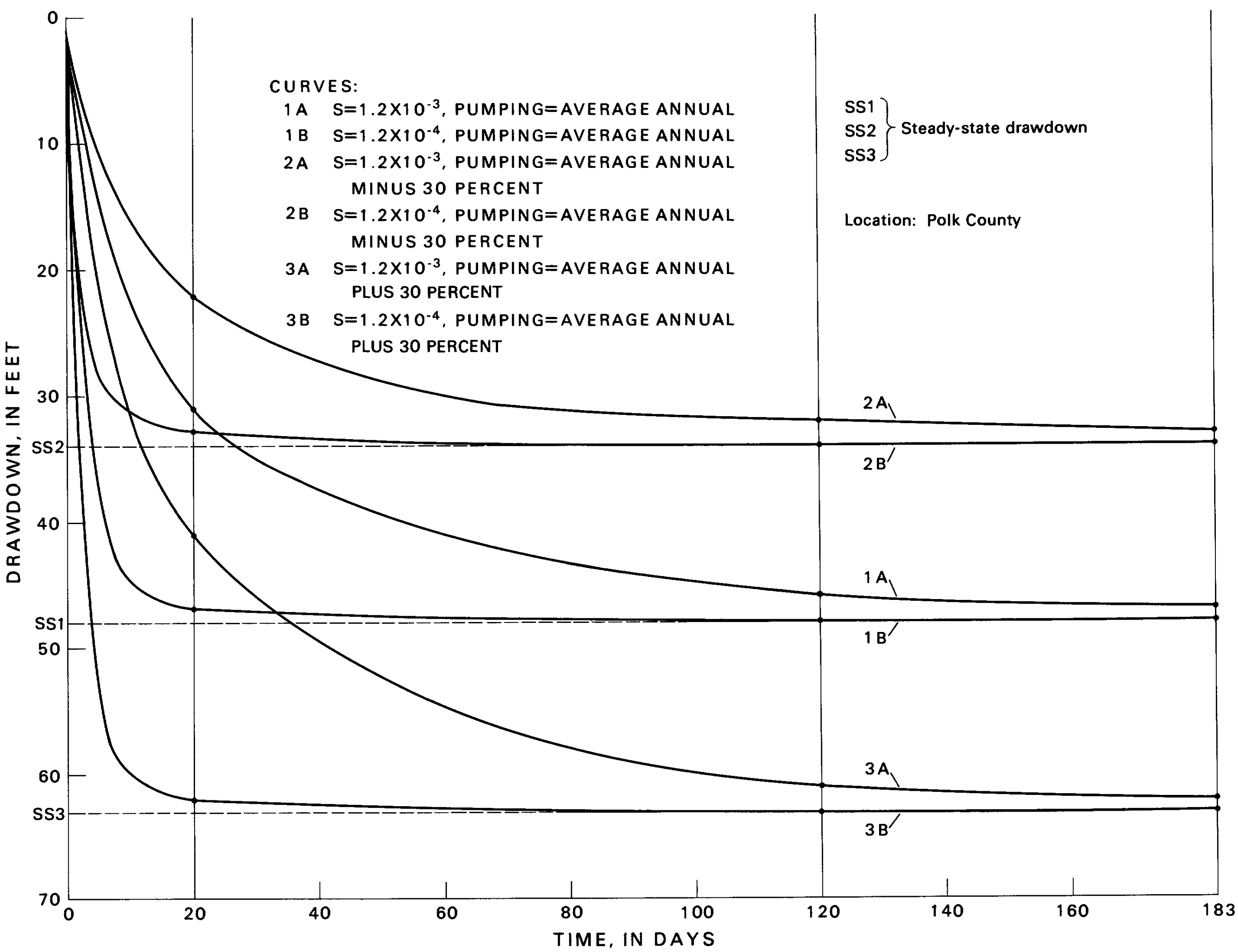


FIGURE 40.—Sensitivity of regional model to changes in storage coefficient (S) and pumpage (from P.W. Bush, U.S. Geological Survey, written commun., 1982).

sivity of the aquifer is high, with values that range upward to more than 1,000,000 ft²/d in the vicinity of high-yield springs. Recharge rates are relatively high, averaging 20 in./yr in some areas. Much of the recharge enters highly developed solution channels in the upper part of the aquifer and flows relatively short distances before emerging as spring discharge.

2. In the south, the Upper Floridan aquifer is overlain by the intermediate aquifer and confining beds. The lowermost confining bed contains less permeable material in the Tampa Limestone or in the lower part of the Hawthorn Formation. Overlying the confining layer is the intermediate aquifer, which generally consists of rocks within the Hawthorn Formation and ranges in thickness from a few feet to about 400 ft. Permeability of this aquifer is much less than that of the Upper Floridan aquifer. The permeable zone is overlain in turn by another confining layer. The uppermost hydrogeologic unit is the surficial aquifer. Recharge to the Upper Floridan aquifer in the south occurs as leakage from the surficial aquifer through the intermediate aquifer and confining beds. Discharge, prior to development, occurred principally as diffuse upward leakage through confining layers primarily along the coast. These thick confining layers result in a flow system in the south that is less vigorous than in the north.

A digital model was used to simulate the natural (prepumping) flow system and the 1976 flow system of the Upper Floridan aquifer in west-central Florida. The predevelopment flow system in the north consists of a highly transmissive, unconfined aquifer with local sources of recharge and discharge (springs). In the south, the system is confined, is less transmissive, and has less recharge occurring as downward leakage across confining beds and lower discharge through diffuse upward leakage. Total predevelopment recharge for the system was about 2,500 Mgal/d; of this, about 2,110 Mgal/d (84 percent) was discharged as springflow, and about 390 Mgal/d (16 percent) was discharged as upward leakage, mostly along the coast.

Changes in the flow system have occurred in response to: (1) man's activities, which include pumpage, impoundments, and dredging; and (2) deviations from normal amounts of rainfall. Significant declines in aquifer heads that resulted in increased pumping lifts, declining lake levels, and sinkhole development have occurred north of Tampa Bay, where large municipal well fields have been located, and in southwestern Polk County, the center of the phosphate-mining and citrus-processing industries.

A general cessation of water-level declines occurred in the mid 1970's. That period was chosen for calibration of a steady-state digital model. Comparison of the potentiometric surface in 1976, the year chosen for model calibration, with that of predevelopment conditions shows a large decline in head in the southern half of the study area. The greatest decline in head, about 50 ft, occurred in southwestern Polk County.

Comparison of simulated recharge rates for 1976 with those for predevelopment conditions shows large increases in developed areas from mid-Pasco County southward to Tampa Bay and in southwestern Polk County. Total 1976 recharge to the system was 3,200 Mgal/d (including 100 Mgal/d lateral inflow); of this,2,050 Mgal/d was discharged as springflow, 950 Mgal/d was discharged as pumpage, and 200 Mgal/d was discharged as diffuse upward leakage. The pumpage of 950 Mgal/d is balanced by an increase in vertical recharge of 600 Mgal/d (over the predevelopment rate), a net lateral inflow of 100 Mgal/d, a decrease in upward leadage of 190 Mgal/d, and a decrease in spring discharge of 60 Mgal/d.

Future demands on the water resource are expected to be large, as Florida's population continues to increase at a rapid rate. Major water-demand problem areas have been identified as the coastal zones from Pasco County southward to Charlotte County. Water use for municipal supplies in these areas is projected to increase by about 380 Mgal/d from 1975 to 2035. Well fields are expected to supply the major portion of this increase.

A digital model simulation of two hypothetical 30-Mgal/d well fields, one in the north and one in the south, demonstrates the applicability of modeling techniques to water management and planning. The northern area can sustain a large amount of development, with much of the pumpage derived from reduced spring discharge. However, the southern area has less of an ability to sustain large withdrawals.

SELECTED REFERENCES

Buono, Anthony, Spechler, R. M., Barr, G. L., and Wolansky, R. M., 1979, Generalized thickness of the confining bed overlying the Floridan aquifer, Southwest Florida Water Management District: U.S. Geological Survey Water-Resources Investigations Open-File Report 79-1171, 1 sheet.

Bush, P.W., 1982, Predevelopment flow in the Tertiary limestone aquifer system, southeastern United States; a regional analysis from digital modeling: U.S. Geological Survey Water-Resources Investigations 82-905, 41 p.

Camp Dresser & McKee, Inc., 1982, 1982-1995 update report needs and sources regional water supply: Consultant's report for the West Coast Regional Water Supply Authority.

Causey, L. V. and Levy, G. W., 1976, Thickness of the potable-water zone in the Floridan aquifer: Florida Bureau of Geology Map Series 74.

Causseaux, K.W., and Fretwell, J. D., 1982, Position of the saltwater-freshwater interface in the upper part of the Floridan aquifer, southwest Florida, 1979: U.S. Geological Survey Water-Resources Investigations Open-File Report 82-90, 1 sheet.

Causseaux, K. W., and Rollins, H. C., 1979, Summary of hydrologic data for Tampa Bypass Canal system, July 1974 to September 1976: U.S. Geological Survey Open-File Report 79-1297, 74 p.

Dames and Moore, 1979, Consumptive use permit application supporting report, Little Payne Phosphate Mine, Polk and Hardee Counties, Florida, for USS Agri-Chemicals: Consultant's report in files of the Southwest Florida Water Management District.

Dohrenwend, R. E., 1977 Evapotranspiration patterns in Florida: Florida Academy of Sciences, Journal of Florida Scientist, v. 40, no. 2, p. 184-192.

Domenico, P.A., 1972, Concepts and models in groundwater hydrology: New York, McGraw-Hill, 405 p.

Duerr, A. D., and Sohm, J. E., 1983, Estimated water use in southwest Florida, 1981, and summary of annual water use, 1970, 1975, and 1977-81: U.S. Geological Survey Open-File Report 83-45, 75 p.

Duerr, A. D., and Trommer, J. T., 1981a, Estimated water use in the Southwest Florida Water Management District, 1979: U.S. Geological Survey Open-File Report 81-56, 58 p.

——1981b, Estimated water use in the Southwest Florida Water Management District and adjacent areas, 1980: U.S. Geological Survey Open-File Report 81-1060, 60 p.

——1982, The benchmark farm program—a method for estimating irrigation water use in southwest Florida: U.S. Geological Survey Water-Resources Investigations 82-17, 49 p.

Faulkner, G. L., 1973a, Geohydrology of the Cross-Florida Barge Canal area with special reference to the Ocala vicinity: U.S. Geological Survey Water-Resources Investigations 1-73, 117 p.

——1973b, Ground-water conditions in the lower Withlacoochee River-Cross-Florida Barge Canal complex area: U.S. Geological Water-Resources Investigations 4-72, 31 p.

Franks, B. J., ed., 1982, Principle aquifers in Florida: U.S. Geological Survey Water-Resources Investigations Report 82-255.

Geraghty and Miller, Inc., 1978, Hydrologic effects of developing 15 MGD of water from the Floridan aquifer in the Pine Level area, De Soto and Manatee Counties, Florida: Consultant's report prepared for Phillips Petroleum Company in files of the Southwest Florida Water Management District.

——1982, Evaluation of the water-supply potential of the Tampa Bypass Canal: Consultant's report prepared for West Coast Regional Water Supply Authority in files of the Southwest Florida Water Management District.

Geraghty and Miller, Inc., and Reynolds, Smith and Hills, 1977, Hydrologic and engineering evaluation of the Four Rivers Basin area, west-central Florida: Consultant's report for the Department of the Army, Jacksonville District Corps of Engineers.

Grubb, H. F., and Rutledge, A. T., 1979, Long-term water supply potential, Green Swamp area, Florida: U.S. Geological Survey Water-Resources Investigations 78-99, 76 p.

Hickey, J. J., 1977, Hydrogeologic data for the McKay Creek subsurface waste-injection test site, Pinellas County, Florida: U.S. Geological Survey Open-File Report 77-802. 94 p.

———1979, Hydrogeologic data for the South Cross Bayou subsurface-injection test site, Pinellas County, Florida: U.S. Geological Survey Open-File Report 78-575, 87 p.

———1981, Hydrogeology, estimated impact, and regional well monitoring of effects of subsurface wastewater injection, Tampa Bay area, Florida: U.S. Geological Survey Water-Resources Investigations 80-18, 40 p.

———1982, Hydrogeology and results of injection tests at waste-injection test sites in Pinellas County, Florida: U.S. Geological Survey Water-Supply Paper 2183, 42 p.

Hickey, J. J., and Spechler, R. M., 1979, Hydrologic data for the Southwest subsurface-injection test site, St. Petersburg, Florida: U.S. Geological Survey Open-File Report 78-852, 104 p.

Holdridge, L.R., 1967, Life zone ecology: Tropical Science Center, San Jose, Costa Rica.

Hubbert, M.K., 1940, The theory of ground-water motion: Journal of Geology, v. 48, no. 8, pt. 1, p.785-944.

Hutchinson, C.B., 1978, Appraisal of shallow ground-water resources and management alternatives in the upper Peace and eastern Alafia River basins, Florida: U.S. Geological Survey Water-Resources Investigations 77-124, 57 p.

———1982, Assessment of the interconnection between Tampa Bay and the Floridan aquifer, Florida: U.S. Geological Survey Water-Resources Investigations 82-54, 60 p.

Hutchinson, C.B., Johnson, D.M., and Gerhart, J.M., 1981, Hydrogeology of well-field areas near Tampa, Florida, phase 1—Development and documentation of a two-dimensional finite-difference model for simulation of steady-state ground-water flow: U.S. Geological Survey Open-File Report 81-630, 129 p.

Johnston, R.H., 1978, Planning report for the Southeastern limestone regional aquifer system analysis: U.S. Geological Survey Open-File Report 78-516, 26 p.

Johnston, R.H., Healy, H.G., and Hayes, L.R., 1981, Potentiometric surface of the Tertiary limestone aquifer system, southeastern United States, May 1980: U.S. Geological Survey Open-File Report 81-486, 1 sheet.

Johnston, R.H., Krause, R.E., Meyer, F.W., Ryder, P.D., Tibbals, C.H., and Hunn, J.D., 1980, Estimated potentiometric surface for the Tertiary limestone aquifer system, southeastern United States, prior to development; U.S. Geological Survey Open-File Report 80-406, 1 sheet.

Joyner, B.F., and Sutcliffe, H., Jr., 1976, Water resources of the Myakka River basin area, southwest Florida: U.S. Geological Survey Water-Resources Investigations 76-58, 87 p.

Kaufman, M.I., 1967, Hydrologic effects of ground-water pumpage in the Peace and Alafia River basins, Florida, 1934-1965: Florida Geological Survey Report of Investigations 49, 32 p.

Krause, R.E., 1982, Digital model evaluation of the predevelopment flow system of the Tertiary limestone aquifer, southeast Georgia, northeast Florida, and southern South Carolina: U.S. Geological Survey Water-Resources Investigations 82-173, 27 p.

LaMoreaux, P.E., and Associates, 1979, Supporting report for consumptive use permit, Farmland Industries, Inc., Hardee County property: Consultant's report in files of the Southwest Florida Water Management District.

Leach, S.D., 1978, Source, use, and disposition of water in Florida, 1975: U.S. Geological Survey Water-Resources Investigations 78-17, 90 p.

———1982, Estimated water use in Florida, 1980: Florida Bureau of Geology Map Series 103.

Leach, S.D., and Healy, H.G., 1980, Estimated water use in Florida, 1977: U.S. Geological Survey Water-Resources Investigations 79-112, 76 p.

Lohman, S.W., 1972, Ground-water hydraulics: U.S. Geological Survey Professional Paper 708, 70 p.

Miller, J.A., 1982a, Thickness of the Tertiary limestone aquifer system, southeastern United States: U.S. Geological Survey Water-Resources Investigations 81-1124, 1 sheet.

———1982b, Geology and configuration of the base of the Tertiary limestone aquifer system, southeastern United States: U.S. Geological Survey Water-Resources Investigations 81-1176, 1 sheet.

———1982c, Geology and configuration of the top of the Tertiary limestone aquifer system, southeastern United States: U.S. Geological Survey Water-Resources Investigations 81-1178, 1 sheet.

———1982d, Thickness of the upper permeable zone of the Tertiary limestone aquifer system, southeastern United States: U.S. Geological Survey Water-Resources Investigations 81-1179, 1 sheet.

———1982e, Configuration of the base of the upper permeable zone of the Tertiary limestone aquifer system, southeastern United States: U.S. Geological Survey Water-Resource Investigations 81-1177, 1 sheet.

———1984, Hydrogeologic framework of the Floridan aquifer system in Florida and in parts of Georgia, South Carolina, and Alabama: U.S. Geological Survey Professional Paper 1403-B, 278 p.

Mills, L.R., and Ryder, P.D., 1977, Saltwater intrusion in the Florida aquifer, coastal Citrus and Hernando Counties, Florida, 1975: U.S. Geological Survey Water-Resources Investigations 77-100, 1 sheet.

Palmer, C.E., and Bone, L.P., 1977, Some aspects of rainfall deficits in west-central Florida, 1961-1976: Southwest Florida Water Management District Hydrometeorological Report no. 1, 19 p.

Parker, G.G., Ferguson, G.E., Love, S.K., and others, 1955, Water resources of southeastern Florida, with special reference to geology and ground water of the Miami area: U.S. Geological Survey Water-Supply Paper 1255, 965 p.

Parker, G.P., 1975, Water and water problems in the Southwest Florida Water Management District and some possible solutions: American Water Resources Association, Water Resources Bulletin, v. 11, no. 1, p. 1-20.

Poland, J.F., Lofgren, B.E., and Riley, F.S., 1972, Glossary of selected terms useful in studies of the mechanics of aquifer systems and land subsidence due to fluid withdrawal: U.S. Geological Survey Water-Supply Paper 2025, 9 p.

Pride, R.W., 1970, Estimated water use in Florida, 1965: Florida Bureau of Geology Map Series 36.

———1973, Estimated water use in Florida, 1970: Florida Bureau of Geology Information Circular 83, 31 p.

Pride R.W., Myer, F.W., and Cherry, R.N., 1966, Hydrology of the Green Swamp area in central Florida: Florida Bureau of Geology Report of Investigations 42, 137 p.

Priede-Sedgwick, Inc., 1982, Withlacoochee regional water supply study: Consultant's report prepared for Withlacoochee Regional Water Supply Authority, Withlacoochee Regional Planning Council, and U.S. Army Corps of Engineers, Jacksonville District.

Reichenbaugh, R.C., 1972, Seawater intrusion in the upper part of the Floridan aquifer in coastal Pasco County, Florida, 1969: Florida Bureau of Geology Map Series 47.

Robertson, A.F., 1973, Hydrologic conditions in the Lakeland Ridge area of Polk County, Florida: Florida Bureau of Geology Report of Investigations 64, 54 p.

Robertson, A.F., and Mills, L.R., 1974, Ground-water withdrawals in the upper Peace and upper Alafia River basins, Florida: Florida Bureau of Geology Map Series 67.

Robertson, A.F., Mills, L.R., and Parsons, D.C., 1978, Ground water withdrawn for municipal, industrial, and irrigation use in the upper Peace and Alafia River basins, west-central Florida, 1970-74: U.S. Geological Survey Open-File Report 78-29, 59 p.

Rosenau, J.C., Faulkner, G.L., Hendry, C.W., Jr., and Hull, R.W., 1977, Springs of Florida: Florida Bureau of Geology Bulletin 31 (revised), 461 p.

Ryder, P.D., 1978, Model evaluation of the Cypress Creek well field in west-central Florida: U.S. Geological Survey Water-Resources Investigations 78-79, 64 p.

———1982, Digital model of predevelopment flow in the Tertiary limestone (Floridan) aquifer system in west-central Florida: U.S. Geological Survey Water-Resources Investigations 81-54, 61 p.

Ryder, P.D., Johnson, D.M., and Gerhart, J.M., 1980, Model evaluation of the hydrogeology of the Morris Bridge well field and vicinity in west-central Florida: U.S. Geological Survey Water-Resources Investigations 80-29, 77 p.

Ryder, P.D., Laughlin, C.P., and Mills, L.R., 1977, Potentiometric surface of the Floridan aquifer, Southwest Florida Water Management District, September 1976: U.S. Geological Survey Open-File Report 77-353, 1 sheet.

Sinclair, W.C., 1978, Preliminary evaluation of the water-supply potential of the spring-river system in the Weeki Wachee area and the lower Withlacoochee River, west-central Florida: U.S. Geological Survey Water-Resources Investigations 78-74, 40 p.

———1982, Sinkhole development resulting from ground-water withdrawal in the Tampa area, Florida: U.S. Geological Survey Water-Resources Investigations 81-50, 19 p.

Sinclair, W.C., and Reichenbaugh, R.C., 1981, Hydrology of the Winter Haven Chain of Lakes, Polk County, Florida: U.S. Geological Survey Water-Resources Investigations 81-212, 1 sheet.

Sprinkle, C.L., 1982a, Sulfate concentration in water from the upper permeable zone of the Tertiary limestone aquifer system, southeastern United States: U.S. Geological Survey Water-Resources Investigations 81-1101, 1 sheet.

———1982b, Total hardness of water from the upper permeable zone of the Tertiary limestone aquifer system, southeastern United States: U.S. Geological Survey Water-Resources Investigations 81-1102, 1 sheet.

———1982c, Chloride concentration in water from the upper permeable zone of the Tertiary limestone aquifer system, southeastern United States: U.S. Geological Survey Water-Resources Investigations 81-1103, 1 sheet.

———1982d, Dissolved-solids concentration in water from the upper permeable zone of the Tertiary limestone aquifer system, southeastern United States: U.S. Geological Survey Water-Resources Investigations 82-94, 1 sheet.

Stewart, H.G., Jr., 1963, Records of wells and other water-resources data in Polk County, Florida: Florida Geological Survey Information Circular 38, 144 p.

———1966, Ground-water resources of Polk County: Florida Bureau of Geology Report of Investigations 44, 170 p.

Stewart, J.W., 1968, Hydrologic effects of pumping from the Floridan aquifer in northwest Hillsborough, northeast Pinellas, and southwest Pasco Counties, Florida: U.S. Geological Survey Open-File Report FL-68005, 241 p.

———1977, Hydrologic effects of pumping a deep limestone sink near Tampa, Florida, U.S.A. *in* Proceedings of the Twelfth International Congress KARST HYDROGEOLOGY, Huntsville, Alabama, p. 195-211.

Stewart, J.W., Goetz, C.L., and Mills, L.R., 1978, Hydrogeologic factors affecting the availability and quality of ground water in the Temple Terrace area, Hillsborough County, Florida: U.S. Geological Survey Water-Resources Investigations 78-4, 38 p.

Stewart, J.W., and Hughes, G.H., 1974, Hydrologic consequences of using ground water to maintain lake levels affected by water wells near Tampa, Florida: Florida Bureau of Geology Report of Investigations 74, 41p.

Stewart, J.W., Laughlin, C.P., and Mills, L.R., 1976, Potentiometric surface of the Floridan aquifer, Southwest Florida Water Management District, May 1976: U.S. Geological Survey Open-File Report FL-76005, 1 sheet.

Stone, H.L., 1968, Iterative solution of implicit approximations of multidimensional partial differential equations: Society of Industrial Applied Mathematics, Journal of Numerical Analysis, v. 5, no. 3, p. 530-558.

Stringfield, V.T., 1936, Artesian water in the Florida peninsula: U.S. Geological Survey Water-Supply Paper 773-C, p. 115-195.

———1966, Artesian water in Tertiary limestone in the southeastern states: U.S. Geological Survey Professional Paper 517, 226 p.

Sutcliffe, H., Jr., 1979, Hydrologic data from a deep test well, city of Sarasota, Florida: U.S. Geological Survey Open-File Report, 79-1275, 22 p.

Tibbals, C.H., 1981, Computer simulation of the steady-state flow system of the Tertiary (Floridan) limestone aquifer system in east-central Florida: U.S. Geological Survey Water-Resources Investigations 81-681, 31 p.

Tibbals, C.H., Anderson, W., and Laughlin, C.P., 1980, Ground-water hydrology in the Dade City area, Pasco County, Florida, with emphasis on the hydrologic effects of pumping from the Floridan aquifer: U.S. Geological Survey Water-Resources Investigations 80-33, 64 p.

Trescott, P.C., 1975, Documentation of finite-difference model for simulation of three-dimensional ground-water flow: U.S. Geological Survey Open-File Report 75-438, 32 p. with appendices.

Trescott, P.C., and Larson, S.P., 1976, Supplement to Open-File Report 75-438—Documentation of finite-difference model for simulation of three-dimensional ground-water flow: U.S. Geological Survey Open-File Report 76-591, 21 p.

U.S. Army Corps of Engineers, 1980, Water resources management study, Four River Basins Project, Florida: Department of the Army, Jacksonville District, U.S. Army Corps of Engineers, 116 p.

U.S. Environmental Protection Agency, 1979, National secondary drinking water regulations: Federal Register, v. 44, no. 140, Thursday, July 19, 1979, Part 143.3, p. 42198.

William F. Guyton and Associates, 1976, Hydraulic and water quality: Consultant's report prepared for Swift Agricultural Chemicals Corporation in files of the Southwest Florida Water Management District.

Wilson, W.E., 1977, Ground-water resources of De Soto and Hardee Counties, Florida: Florida Bureau of Geology Report of Investigations 82, 102 p.

———1982, Estimated effects of projected ground-water withdrawals on movement of the saltwater front in the Floridan aquifer, 1976-2000, west-central Florida; U.S. Geological Survey Water-Supply Paper 2189, 24 p.

Wilson, W.E., and Gerhart, J.M., 1982, Simulated effects of ground-water development on the potentiometric surface of the Floridan aquifer, west-central Florida: U.S. Geological Survey Professional Paper 1217, 83 p.

Wilson, W.E., Parsons, D.C., and Spechler, R.M., 1979, Hydrologic data for a subsurface waste-injection site at Mulberry, Florida, 1972-77: U.S. Geological Survey Open-File Report 79-683, 33 p.

Wolansky, R.M., Barr, G.L., and Spechler, R.M., 1979, Generalized configuration of the bottom of the Floridan aquifer, Southwest Florida Water Management District: U.S. Geological Survey Water-Resources Investigations 79-1490, 1 sheet.

——— 1980, Configuration of the top of the highly permeable dolomite zone of the Florida aquifer, Southwest Florida Water Management District: U.S. Geological Survey Water-Resources Investigations 80-433, 1 sheet.

Wolansky, R.M., Mills, L.R., Woodham, W.M., and Laughlin, C.P., 1979, Potentiometric surface of the Floridan aquifer, Southwest Florida Water Management District and adjacent areas, May 1979: U.S. Geological Survey Open-File Report 79-1255, 1 sheet.

Wolansky, R.M., Spechler, R.M., and Buono, Anthony, 1979, Generalized thickness of the surficial deposits above the confining bed overlying the Floridan aquifer, Southwest Florida Water Management District: U.S. Geological Survey Water-Resources Investigations 79-1071, 1 sheet.

Yobbi, D.K., and Chappell, G.C., 1979, Summary of the hydrology of the upper Etonia Creek basin: St. Jones River Water Management District Technical Report no. 4, 67 p.

Yobbi, D.K., Woodham, W.M., and Laughlin, C.P., 1980, Potentiometric surface of the Floridan aquifer, Southwest Florida Water Management District, September 1979: U.S. Geological Survey Open-File Report 80-46, 1 sheet.

☆U.S. GOVERNMENT PRINTING OFFICE: 1985-676-047:26004