HYDROGEOLOGY AND SIMULATED EFFECTS OF GROUND-WATER DEVELOPMENT OF THE FLORIDAN AQUIFER SYSTEM, SOUTHWEST GEORGIA, NORTHWEST FLORIDA, AND SOUTHERNMOST ALABAMA

REGIONAL AQUIFER-SYSTEM ANALYSIS

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1403–H

Hydrogeology and Simulated Effects of Ground-Water Development of the Floridan Aquifer System, Southwest Georgia, Northwest Florida, and Southernmost Alabama

By Morris L. Maslia, *and* Larry R. Hayes

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FOREWORD

THE REGIONAL AQUIFER-SYSTEM ANALYSIS PROGRAM

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

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

Dallas L. Peck
Director

CONTENTS

ILLUSTRATIONS

[Plates are in pocket]

TABLES

CONVERSION FACTORS

Factors for converting inch-pound units to the International System (SI) of units are given below:

Multiply	*By*	*To obtain*
	Length	
inch (in)	25.40	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.4047	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
	0.003785	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
inch per acre (in/acre)	62.76	millimeter per hectare (mm/ha)
	Flow	
gallon per minute (gal/min)	0.06309	liter per second (L/s)
	0.00006309	cubic meter per second (m^3/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
inch per year (in/yr)	25.40	millimeter per year (mm/yr)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile [(ft^3/s)/mi^2]	0.07335	cubic meter per second per square kilometer [(m^3/s)/km^2]
	Transmissivity	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Leakance	
gallons per day per cubic foot [(gal/d)/ft^3]	0.1337	meter per day per meter [(m/d)/m]
foot per day per foot [(ft/d)/ft]	1.000	meter per day per meter [(m/d)/m]
	Specific conductance	
micromho per centimeter at 25° Celsius (μmho/cm at 25°)	1.000	microsiemens per centimeter at 25° Celsius (μS/cm at 25°C)
	Temperature	
degree Fahrenheit (°F)	C=5/9°F−32	degree Celsius (°C)

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By MORRIS L. MASLIA and LARRY R. HAYES

ABSTRACT

The Floridan aquifer system underlies parts of South Carolina, Georgia, and Alabama and all of Florida. Two areas have experienced increases in ground-water withdrawals from the Floridan aquifer system: the Dougherty Plain in southwest Georgia and the Fort Walton Beach area of northwest Florida. In southwest Georgia, seasonal withdrawals for irrigation increased from about 47 billion gallons in 1977 to about 76 billion gallons in 1980, and to about 107 billion gallons in 1981—a drought year. However, these withdrawals have not resulted in appreciable water-level declines in the Floridan aquifer system in southwest Georgia. Long-term water-level declines within the upper part of the Floridan aquifer system, characterized by a widespread cone of depression, have resulted from moderate pumpage for municipal use in southern Okaloosa and Walton Counties, Florida. Total pumpage amounted to approximately 5.7 billion gallons in 1978 (15.5 million gallons per day). At the center of the cone of depression near Fort Walton Beach, water levels have declined more than 140 feet below predevelopment levels.

In southwest Georgia, the Floridan aquifer system is overlain by sandy clay residuum that has an average thickness of approximately 50 feet and was derived from the chemical weathering of the Ocala Limestone. In the western panhandle of Florida, the aquifer is overlain by the Pensacola Clay, which varies in thickness from 50 to 450 feet. Above the Pensacola Clay is a surficial sand-and-gravel aquifer ranging in thickness from less than a few tens of feet in the easternmost area to more than 400 feet in the westernmost part of the panhandle.

Mean annual precipitation is about 51 and 63 inches, respectively, in the Dougherty Plain area of southwest Georgia and in northwest Florida. Because the Floridan aquifer system is thinly covered in southwest Georgia, during September to May streamflow and ground-water levels are directly correlated with precipitation. Water-level peaks usually occur about 1 month after major precipitation peaks. In northwest Florida, the aquifer system is generally deeply buried. Thus, although ground-water levels respond to variations in rainfall, these responses are changes in artesian pressure rather than additions of water to the saturated and unsaturated zones.

Aquifer-test data indicate that transmissivities of the Upper Floridan aquifer in southwest Georgia range from 2,000 to 300,000 feet squared per day and storage coefficients range from 2×10^{-4} to 3×10^{-2}. In southern Okaloosa and Walton Counties, Florida, transmissivities based on aquifer tests range from 250 to 25,000 feet squared per day and storage coefficients range from about 2×10^{-5} to 6×10^{-4}.

Pesticides were detected in water from 10 wells open to the residuum and 4 wells open to the Upper Floridan aquifer in southwest Georgia. None of the samples from the wells in the Floridan aquifer contained pesticide concentrations exceeding the recommended limits for public drinking water supplies. Throughout southwest Georgia and adjacent Florida, water is low in chloride (less than 10 milligrams per liter) except for coastal Okaloosa and Walton Counties, where chloride concentrations exceed 500 milligrams per liter.

Three two-dimensional finite-difference numerical models—the subregional flow model, the Dougherty Plain flow model, and the Fort Walton Beach flow model—were developed to simulate ground-water flow in the Floridan aquifer system in the study area. The subregional flow model is intended to simulate the major features of the flow system. The detailed Dougherty Plain and Fort Walton Beach flow models are intended to simulate the effects of ground-water development in these areas. The subregional flow model, covering an areal extent of 20,000 square miles, was used to obtain aquifer hydraulic parameters and to establish aquifer recharge-discharge relations prior to development. The detailed Dougherty Plain flow model was used to simulate the potentiometric surface and to evaluate water-level declines during drought conditions over a 4,400-square-mile area of southwest Georgia. The Fort Walton Beach flow model was used to simulate water-level declines from 1941 to 1978 and to evaluate water-level declines to the year 2000 within a 1,700-square-mile area of southern Okaloosa and Walton Counties, Florida.

Simulation of a consecutive 3-year hydrologic drought in southwest Georgia, with total pumpage of 339 billion gallons, resulted in a mean water-level decline of 26 feet. In some areas, water levels declined from a few feet to as much as 10 feet below the top of the Upper Floridan aquifer. Pumpage of 1,224 billion gallons resulted in mean water-level declines of 33 feet. In about 30 percent of the modeled area, water levels declined from a few feet to as much as 10 feet below the top of the aquifer. A 10-year simulation under average recharge conditions with pumpage increased to 287 billion gallons per year resulted in mean water-level declines of 4 feet and a 30-percent reduction of the present-day (1980) Floridan aquifer system ground-water discharge to streams.

In southern Okaloosa and Walton Counties, Florida, pumpage of 15.5 million gallons per day was increased to 20.5 million gallons per day in March 1978 to simulate the effect of development in the year 2000. Simulated declines in the year 2000 for the Upper Floridan aquifer ranged from 40 to 60 feet in Fort Walton Beach and from 20 to 30 feet in Destin, Valparaiso, Niceville, and Mary Esther. Relocating four Santa Rosa Island wells to areas of higher transmissivity resulted in smaller water-level declines.

INTRODUCTION

The Floridan aquifer system (previously referred to as the Floridan aquifer in Florida and the principal artesian aquifer in Georgia) underlies parts of South Carolina, Georgia and Alabama and all of Florida. This aquifer system is one of the most productive sources of water in the United States and is the major source of water in its area of occurrence, except where it contains saline water.

The objectives of the Floridan aquifer system analysis are to (1) provide a complete description of the hydrogeologic framework and geochemistry of the aquifer system, (2) define the regional flow system, and (3) assess the effects of large withdrawals of ground water from the aquifer. Computer simulation is used extensively to evaluate the flow system, and locally the computer models are used to evaluate the effects of increased development. The results of the Floridan study have been described in a number of preliminary reports as well as in U.S. Geological Survey Professional Papers (PP). Professional Papers 1403-A and 1403-C summarize the regional hydrology and development and PP 1403-B describes the hydrogeologic framework.

To address the hydrology in more detail and to investigate local water problems, the Floridan aquifer system study was divided into five subprojects. The division is based on location of natural (predevelopment) boundaries and similarity of water problems. Figure 1 shows the five subproject areas and the corresponding letter designations within the Professional Paper 1403 series.

Professional Paper 1403-D discusses the hydrology of the coastal strip from southernmost South Carolina to northeast Florida, PP 1403-E summarizes the hydrology of the Floridan aquifer system in east-central Florida, PP 1403-F describes the hydrology of the Floridan aquifer system in west-central Florida, and PP 1403-G discusses the hydrogeology in south Florida, where the Floridan aquifer system contains saline water and development for water supply is insignificant.

Professional Paper 1403-H (this report) describes the Floridan aquifer system in southwest Georgia, northwest Florida, and southernmost Alabama. It primarily reports on the analyses of two areas where pumping is done on a large scale: (1) the Dougherty Plain area of southwest Georgia, where seasonal withdrawals for irrigation are very large, and (2) the Fort Walton Beach area of northwest Florida, where moderately large pumpage has produced a cone of depression in southern Okaloosa, Walton, and Santa Rosa Counties.

SCOPE AND PURPOSE

The study reported in this paper is part of a regional study of the Floridan aquifer system in the Southeastern United States that includes all of Florida and the southern parts of Alabama, Georgia, and South Carolina—a total area of about 100,000 mi^2 and area covered in this report is about 20,000 mi^2 and includes southwest Georgia, northwest Florida, and southernmost Alabama (fig. 1). The northern boundary is generally coincident with the updip limit of the Floridan aquifer system (Miller, 1986). The eastern, southern, and western boundaries were determined by natural hydrologic conditions where lateral ground-water flow within the aquifer is negligible.

The objectives of this study are to (1) define the hydrogeologic framework in the study area, (2) describe the flow regimen prior to and after man-induced stresses, and (3) develop a digital ground-water-flow model capable of evaluating the ground-water-flow and recharge-discharge system and of simulating alternate stresses and their impact on the ground-water system. Objectives of the study were accomplished using data from studies by Bush (1982), Barr and others (1985), Hayes and others (1983), Hayes and Barr (1983), and Miller (1986).

Within the area of investigation, only two areas are significantly stressed by pumping: (1) southwest Georgia, where large ground-water withdrawals are made for irrigation, and (2) southern Okaloosa and Walton Counties, Fla., where moderate ground-water withdrawals are made for public supply. More refined digital models capable of describing localized transient-flow conditions were developed for these areas: the lack of large-scale pumping stresses in and data for locations outside these areas did not justify development of other than a preliminary steady-state flow model. This report discusses, in general terms, the predevelopment flow system of the entire study area (southwest Georgia, northwest Florida, and southernmost Alabama) and discusses, in detail, the hydrogeology and present (1980) flow system of southwest Georgia and southern Okaloosa and Walton Counties, Fla.

PREVIOUS INVESTIGATIONS AND ACKNOWLEDGMENTS

The hydrogeology of the Floridan aquifer system has been investigated extensively in the areas of greatest withdrawals (southwest Georgia and southern Okaloosa and Walton Counties, Fla.). Outside these areas, however, very little hydrogeologic data have been collected and no detailed hydrologic studies have been conducted.

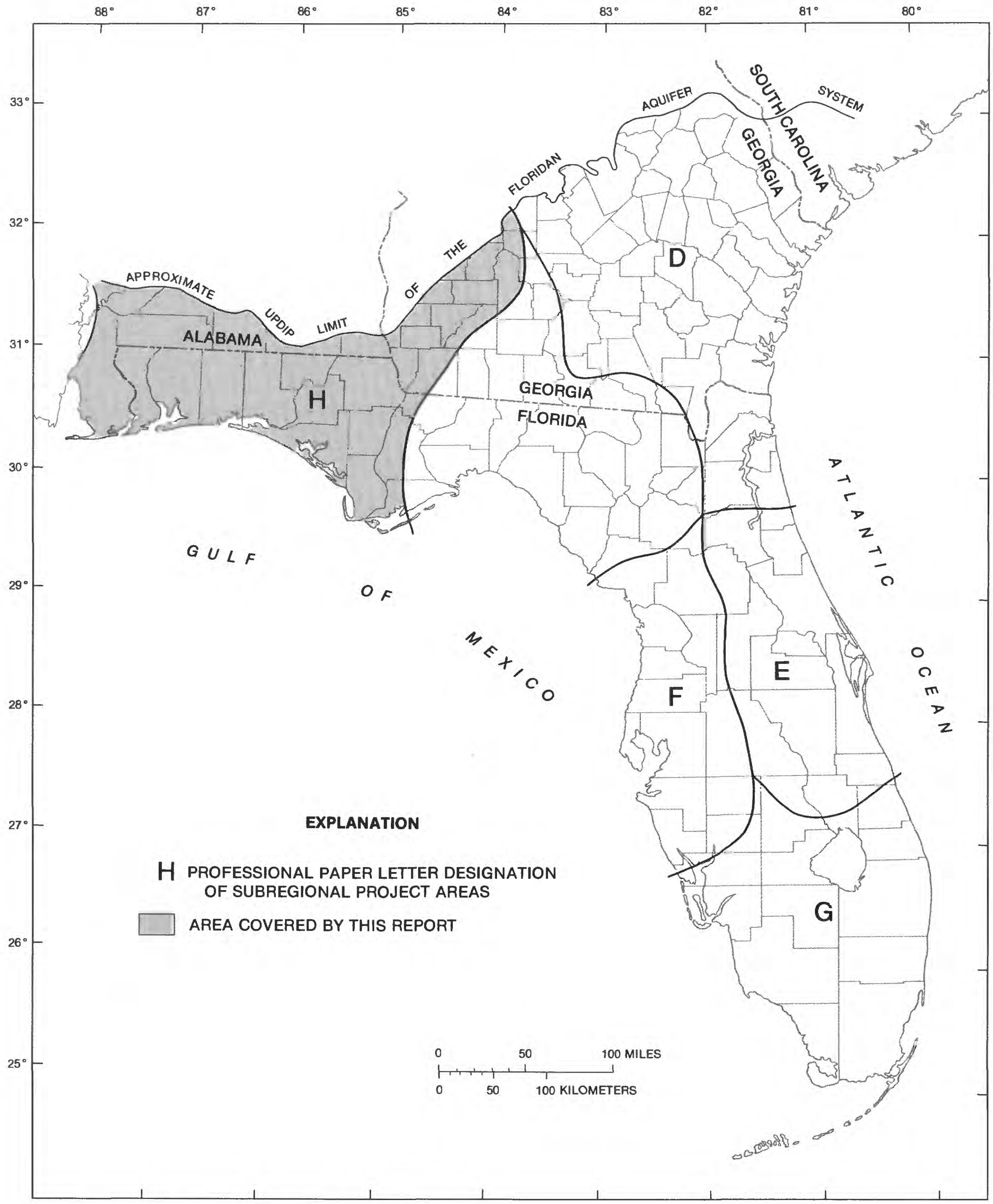


FIGURE 1.—Subregional project areas and letter designations in U.S. Geological Survey Professional Paper 1403.

The general geology and ground-water resources of the Coastal Plain of Georgia were previously discussed in McCallie (1898), Stephenson and Veatch (1915), Cook (1943), and Herrick (1961). Geohydrologic reports primarily concerned with southwest Georgia include those by Wait (1963), Sever (1965a, 1965b), Pollard and others (1978), and Hicks and others (1981). The most recent and most comprehensive investigation of ground water and surface water of southwest Georgia is by Hayes and others (1983). Data from that study, which were gathered by the U.S. Geological Survey in cooperation with the Georgia Geologic Survey, were used extensively in this study.

Barraclough and Marsh (1962) describe the general hydrology and quality of water of aquifers along the coastal area from Walton County to Escambia County, northwest Florida. Trapp and others (1977) describe the geology and hydrology of Okaloosa County and a small part of western Walton County and eastern Santa Rosa County. Pascale (1974) describes ground-water and surface-water conditions and availability in Walton County, including an analysis and interpretation of six aquifer tests, and the hydrologic effects of increased pumpage for irrigation.

Among the most recent and comprehensive hydrogeologic investigations are those by Barr and others (1985) and Hayes and Barr (1983). Data from both studies, which were gathered by the U.S. Geological Survey in cooperation with the Northwest Florida Water Management District, also are used extensively in this study.

Appreciation is extended to all those whose participation in previous studies made this study possible. In particular, the many contributions made by Douglas Barr, Northwest Florida Water Management District, and Ram Arora, Georgia Geologic Survey, are sincerely appreciated.

RAINFALL

Annual rainfall in the area of investigation averages about 51 in in southwest Georgia and about 63 in in northwest Florida (fig. 2). Rainfall varies considerably from year to year and from month to month, however, as shown in figure 3. Rainfall in the winter months is usually of long duration and moderate intensity; rainfall in the summer months is usually of short duration and high intensity.

In southwest Georgia, because the Floridan aquifer system is not deeply buried, during September through May there is usually a direct correlation of streamflow and aquifer water levels with precipitation (fig. 3). Streamflow peaks occur soon after rainfall peaks as a result of direct runoff and precipitation falling directly into the stream channel. Ground-water peaks generally occur about 1 month after major precipitation peaks, as shown in figure 3. This lag occurs because the precipitation moves slowly downward through the low-permeability residuum that overlies the aquifer. Rainfall has little effect on streamflow and water levels from June through September (fig. 3), however. This is because evapotranspiration is extremely high during these months (approximately 35 in per year), and almost all rainfall is lost to the evaporation–transpiration process.

In northwest Florida, the Floridan aquifer system is generally deeply buried. Thus, although variation in rainfall produces similar responses in water-level fluctuations, these responses are changes in artesian pressure rather than the addition of water to the saturated and unsaturated zones, as occurs in southwest Georgia.

STREAMFLOW

An important characteristic of streamflow is its variability with time and location. To measure and record streamflow on a systematic basis, the U.S. Geological Survey has operated, and has made periodic measurements of streamflow at continuous-record gaging stations in much of the study area since the early 1900's. Streams in parts of the study area are used appreciably for both irrigation and power generation, and collection and analysis of streamflow records are important for evaluation of streamflow characteristics so that surface-water resources may better be used. Additionally, streamflow data, particularly flow duration and base flow, are needed to evaluate the water budget in the study area. Water-budget data were one component in testing the accuracy of the model simulations, which will be discussed later in the report.

FLOW DURATION

A flow-duration curve is a cumulative frequency curve that shows the percentage of time specified discharges were equaled or exceeded during a given period (Searcy, 1959). A flow-duration curve simply provides a means of representing streamflow characteristics. It is important to note, however, that a flow-duration curve does not show the chronological sequence of flows and, therefore, is not a reliable method of evaluating the dependability of flow. It also, generally, is not applicable to flood or drought studies. If the curve is based on a sufficiently long period of stream-discharge data, it may be used to project the distribu-

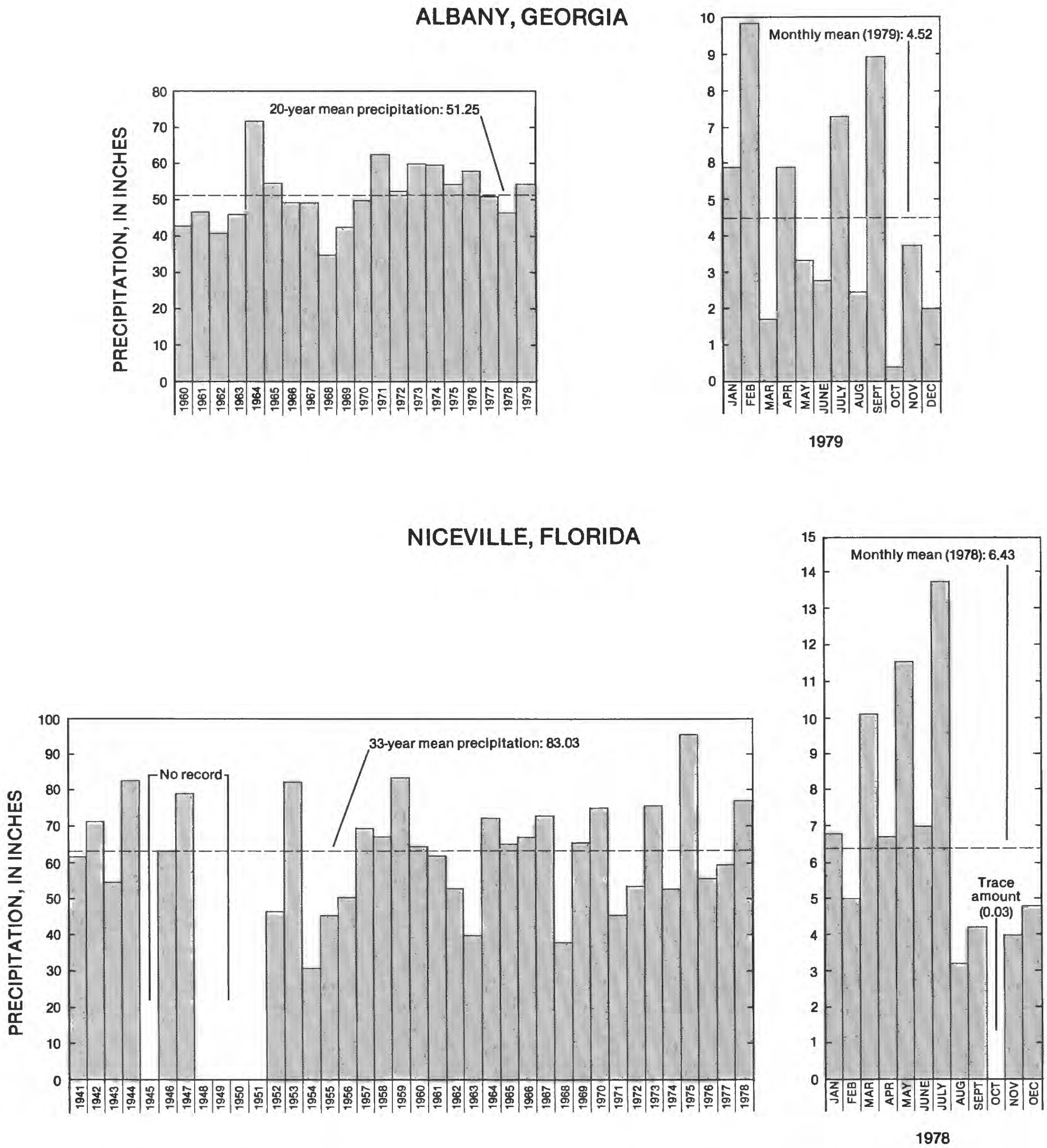


FIGURE 2.—Monthly and annual precipitation at Albany, Georgia, and Niceville, Florida.

tion of future flows for water-power, water-supply, and pollution-load studies. A flow-duration curve also may be used for studying and comparing watershed characteristics.

Except in watersheds where soils are highly permeable, the distribution of high flows is governed mainly by climate, watershed physiography, and plant cover. Low-flow distribution is controlled mainly by basin geology. Consequently, the high end of a flow-duration curve is an indicator of direct-runoff characteristics and the low end is an indicator of base runoff or ground-water contribution to streamflow.

Flow-duration curves (fig. 4) were developed for stations in southwest Georgia and northwest Florida

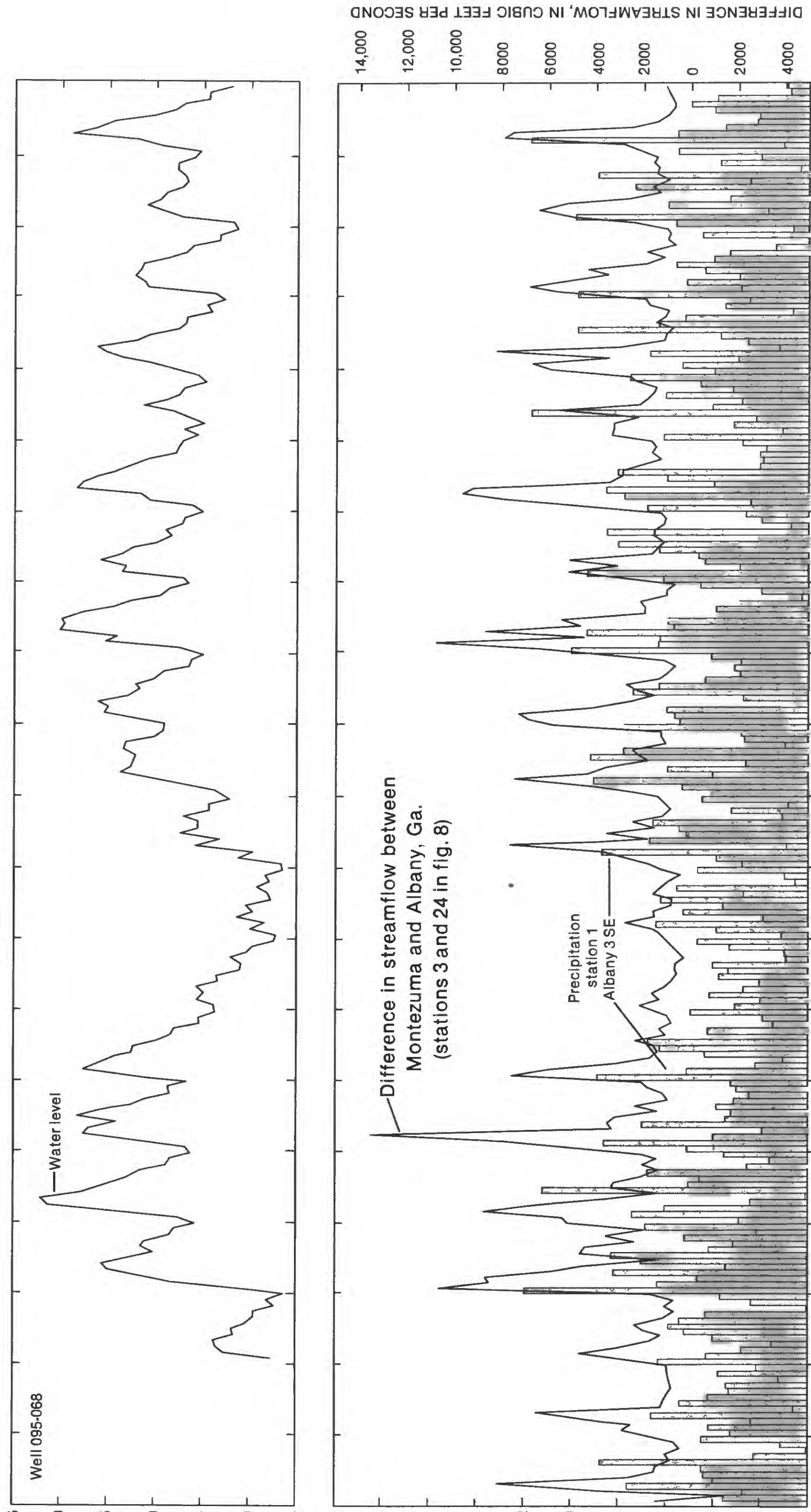


FIGURE 3.—Streamflow, precipitation, and Upper Floridan aquifer water levels near Albany, Georgia. From Hayes and others (1983).

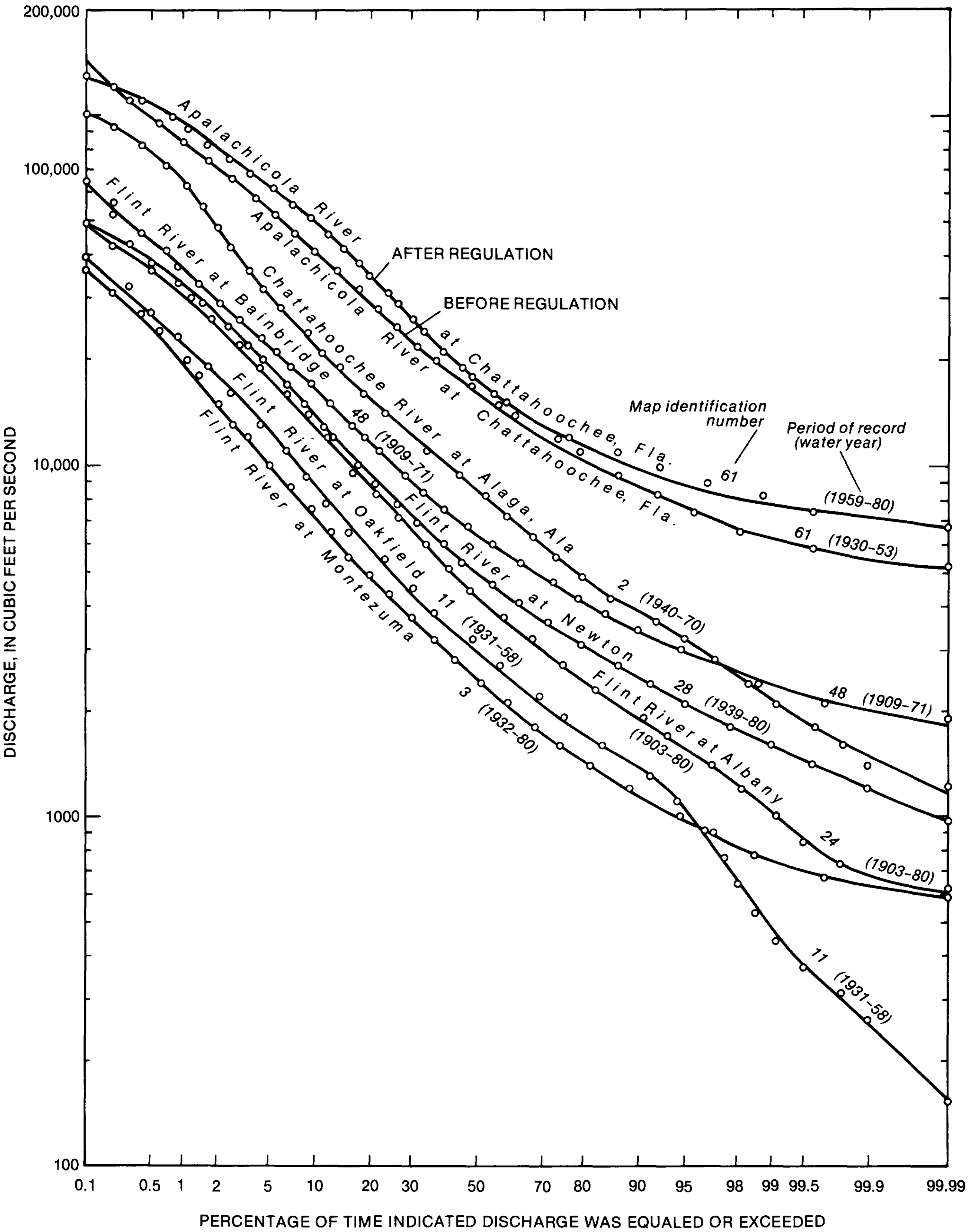


FIGURE 4.—Duration of daily flow at selected stations for seven major streams, southwest Georgia and northwest Florida. From Hayes and others (1983).

using standard computer programs developed by the U.S. Geological Survey. The moderately steep slopes of the upper halves of the southwest Georgia flow-duration curves shown in figure 4 indicate that direct runoff significantly contributes to the higher flows; the relatively flat slopes of all curves, particularly at the lower end except the Flint River at Oakfield, indicate that low flows are maintained by ground-water discharge or that a large amount of ground- or surface-water storage occurs in the watershed.

The base flow of streams in southwest Georgia, which is essentially ground-water discharge, is about 80 percent of total streamflow (Hayes and others, 1983, figs. 15, 17). In the western panhandle of Florida, the base flow component is even higher (Barr and others, 1985). Note that streams in southwest Georgia derive their base flow from the Upper Floridan aquifer and its residuum cover, whereas streams in the Florida Panhandle derive their best flow from a surficial sand-and-gravel aquifer.

Because this study is primarily concerned with the Floridan aquifer system and with discharge to and from the system, the remainder of this section will discuss only the base flow of streams in southwest Georgia.

The flow-duration curve for a particular station usually is based on all flow observations throughout the year for the available period of record, and, as indicated earlier, a curve computed in this manner fails to take into account time and seasonal effects. However, the seasonal nature of streamflow can be defined from a partial duration curve based on daily mean discharges from the historical records of individual months. For example, all the daily mean discharges for the January's for which records are available are used to define a January curve. Because of the seasonal importance of low flows, and to allow the low-flow season to be considered as a unit, the climatic year (April 1 to March 31) was used as a basis for the period of record for monthly flow-duration data.

Table 1 summarizes individual monthly flow-duration data for 10 southwest Georgia stations and indicates seasonal variability in expected streamflows. If a graphical presentation is desired, the data can be plotted on log-probability paper; this would give curves similar to those shown in figure 5, which illustrates the seasonal variation of flow-duration curves for Turkey Creek at Byromville (station 02349900).

The seasonal nature of streamflow is of particular importance to those who use streamflow for supplemental irrigation. Those in southwest Georgia who use streamflow for irrigation are primarily concerned with the streamflow available from May through September. Data in table 1 can be used to estimate probable streamflows of selected streams for those months. This applies, however, only if the historical period of record from which the data were derived can be considered representative of the period with which the streamflow is to be evaluated. As will be discussed later, declines of ground-water levels associated with irrigation pumpage may result in some streams becoming losing streams, that is, some streams may lose water to the ground-water system, whereas, prior to irrigation, ground water discharged to the streams. Where losing reaches occur, streamflow will be less than discussed above. Additionally, flow-duration data from table 1 were used to estimate ground-water discharge, primarily from the Upper Floridan aquifer, to streams in southwest Georgia.

BASE FLOW

The base flow of streams in the Dougherty Plain area of southwest Georgia is primarily ground-water discharge from the Upper Floridan aquifer. The base flow of a stream can be determined by separating the overland runoff from the total discharge of a streamflow hydrograph. Hydrographs for nine streams were separated into overland-flow and base-flow components, using a method described by Riggs (1963). This method requires construction of a master base-flow recession curve using composite long-term records. The master curve is overlain on a hydrograph of mean daily flows for a specific period. In preparing master base-flow recession curves for streams in the Dougherty Plain, the following assumptions were made: (1) each of the streams was at base flow 10 days after cessation of rainfall; (2) base flow was ground-water discharge, which came primarily from the Upper Floridan aquifer; and (3) evaporation–transpiration losses in summer caused a steepening of the base-flow recession curve, resulting in distinctly different summer and winter curves.

Figure 6 illustrates preparation of a base-flow recession curve for Turkey Creek at Byromville (station 02349900). Using the entire period of record, the discharge after 10 days of no rainfall is plotted against the discharge after 20 days of no rainfall, the 20-day discharge is plotted against the 30-day discharge, and so on.

Application of this method throughout the period of record for both summer and winter data results in two sets of points describing the upper plots shown in figure 6. These plots are then used to construct the summer and winter master base-flow recession curves shown in the lower part of figure 6.

Although the master base-flow recession curves thus constructed represent simplified approximations

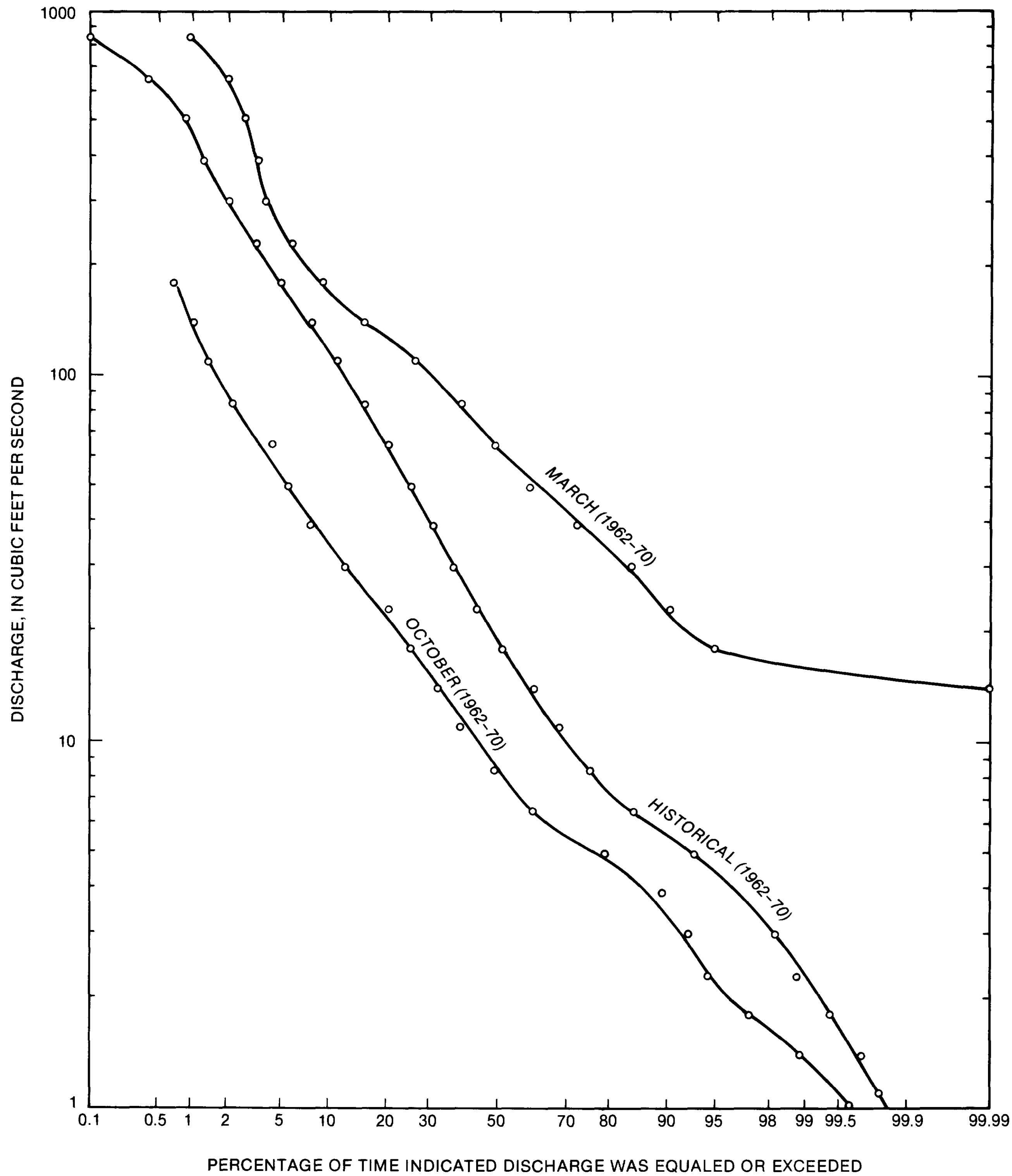


FIGURE 5.—Flow-duration curves for Turkey Creek at Byromville (station 02349900), based on historical mean daily discharges and individual months for water years 1962-70, southwest Georgia.

TABLE 1.—*Monthly flow durations at selected streamflow gaging stations, southwest Georgia*

[Period of record, climatic years 1959–70]

Month	Percent of time flow, in ft^3/s, was equaled or exceeded					Percent of time flow, in ft^3/s, was equaled or exceeded					Percent of time flow, in ft^3/s, was equaled or exceeded				
	10	25	50	75	90	10	25	50	75	90	10	25	50	75	90
	Station 44000 (2)[1]					**Station 49900 (5)**					**Station 50500 (11)**				
Jan	29,000	23,000	14,000	8,800	4,600	160	84	41	18	8.3	15,000	7,500	5,600	3,700	2,500
Feb	33,000	23,000	14,000	9,300	5,100	220	140	76	36	14	14,000	9,700	5,400	4,000	2,500
Mar	40,000	26,000	17,000	11,000	5,700	180	120	71	39	20	19,000	11,000	6,900	5,500	3,300
Apr	44,000	24,000	14,000	9,400	3,900	210	89	42	21	11	15,000	8,500	5,800	3,900	2,500
May	23,000	14,000	9,400	5,900	3,600	68	28	15	9.3	5	8,500	5,100	3,600	2,600	1,400
June	15,000	11,000	8,000	5,600	3,500	68	28	14	8.3	5.4	5,800	3,800	3,000	2,100	1,000
July	13,000	10,000	7,700	4,700	2,700	100	29	14	7.6	4.5	6,900	4,300	3,300	2,400	1,400
Aug	13,000	10,000	7,300	4,800	3,300	71	31	11	7.1	4.9	5,700	3,800	2,900	2,100	1,100
Sept	11,000	8,800	6,600	4,600	3,600	27	16	8.2	5.7	3.4	3,500	2,700	2,100	1,600	520
Oct	12,000	9,100	5,700	3,900	2,400	30	14	7.5	5.6	2.7	3,400	2,600	2,000	1,600	620
Nov	15,000	11,000	6,900	4,900	3,600	24	16	8.9	6.5	4.5	5,600	3,300	2,400	1,600	980
Dec	25,000	15,000	9,700	6,000	3,800	58	25	13	8.5	5.3	12,000	5,300	3,500	2,600	1,500
	Station 52500 (24)					**Station 53000 (28)**					**Station 53500 (34)**				
Jan	19,000	11,000	6,700	4,400	3,100	19,000	11,000	7,400	4,700	3,700	2,000	1,200	750	570	450
Feb	21,000	15,000	9,100	5,300	3,900	21,000	16,000	9,700	5,900	4,500	2,400	1,600	1,100	660	500
Mar	23,000	15,000	10,000	6,700	5,000	24,000	16,000	11,000	7,600	5,700	2,300	1,600	1,100	790	630
Apr	22,000	14,000	7,100	4,800	3,700	23,000	15,000	8,500	5,700	4,400	2,100	1,300	860	550	390
May	11,000	6,300	4,300	3,200	2,500	12,000	7,400	5,100	4,000	3,300	1,200	690	480	350	280
June	9,300	5,400	3,600	2,700	2,100	9,800	6,200	4,300	3,600	3,000	1,200	720	440	330	210
July	7,100	4,900	3,500	2,600	2,000	7,600	5,600	4,300	3,300	2,600	1,000	680	480	320	250
Aug	6,900	4,900	3,000	2,200	1,500	7,600	5,700	3,800	2,800	2,200	860	570	420	320	240
Sept	4,400	3,200	2,300	1,700	1,100	5,200	4,000	3,000	2,300	1,800	590	440	330	240	180
Oct	6,300	3,400	2,300	1,600	940	6,600	3,900	2,900	2,200	1,600	840	490	330	250	200
Nov	5,300	3,900	2,700	1,700	1,200	5,800	4,400	3,100	2,200	1,700	690	530	370	300	250
Dec	8,700	6,000	3,900	2,800	2,100	8,700	6,200	4,200	3,200	2,700	1,100	720	520	400	350

See footnote at end of table.

TABLE 1.—*Monthly flow durations at selected streamflow gaging stations, southwest Georgia*—Continued

Month	Percent of time flow, in ft³/s, was equaled or exceeded					Percent of time flow, in ft³/s, was equaled or exceeded					Percent of time flow, in ft³/s, was equaled or exceeded				
	10	25	50	75	90	10	25	50	75	90	10	25	50	75	90
	Station 54500 (39)[1]					**Station 56000 (48)**					**Station 57000 (57)**				
Jan	1,300	810	400	250	110	21,000	13,000	8,900	6,100	4,800	1,600	800	410	220	140
Feb	1,200	850	510	310	200	24,000	19,000	12,000	7,200	5,700	2,100	1,400	810	320	220
Mar	1,900	1,200	680	460	230	26,000	21,000	14,000	10,000	7,400	2,000	1,400	900	590	370
Apr	1,700	810	510	320	120	27,000	18,000	12,000	7,500	5,900	1,900	1,000	610	370	220
May	800	440	210	110	45	14,000	10,000	7,100	5,400	4,500	680	430	260	180	130
June	380	170	92	42	16	13,000	8,700	6,100	4,700	3,800	790	330	190	130	90
July	480	260	120	78	41	9,800	7,700	5,900	4,600	3,500	610	370	180	100	65
Aug	520	290	170	75	24	9,800	7,200	5,400	4,000	3,200	450	290	200	110	73
Sept	230	140	75	34	12	6,700	5,400	4,300	3,300	2,600	330	160	110	68	46
Oct	230	120	63	33	6.3	8,900	5,700	4,200	3,300	2,700	470	230	120	68	36
Nov	250	120	70	36	12	7,500	6,200	4,300	3,400	2,700	390	170	110	68	39
Dec	1,300	400	120	76	41	11,000	7,900	5,800	4,500	3,800	430	250	170	97	75
	Station 58000 (61)														
Jan	53,000	36,000	25,000	16,000	12,000										
Feb	62,000	47,000	31,000	20,000	14,000										
Mar	65,000	52,000	38,000	24,000	17,000										
Apr	73,000	50,000	31,000	19,000	13,000										
May	38,000	26,000	17,000	13,000	11,000										
June	30,000	21,000	15,000	13,000	11,000										
July	25,000	19,000	14,000	12,000	10,000										
Aug	22,000	17,000	13,000	11,000	9,800										
Sept	19,000	14,000	12,000	9,800	8,600										
Oct	22,000	13,000	11,000	8,800	7,500										
Nov	21,000	16,000	11,000	9,200	7,400										
Dec	34,000	22,000	14,000	12,000	10,000										

[1]Numbers in parentheses are station numbers used in Hayes and others (1983) and shown on map in figure 8.

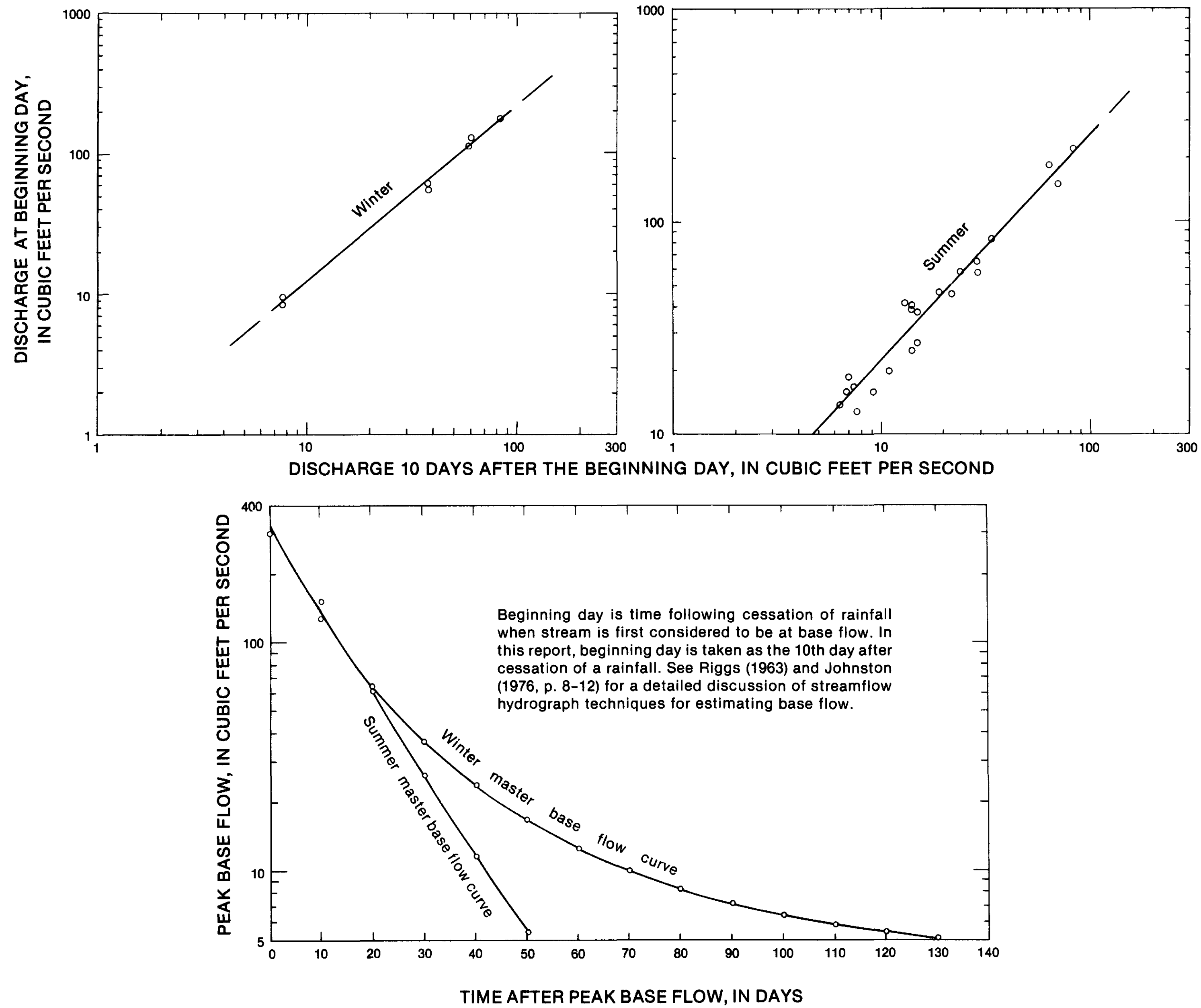


FIGURE 6.—Method of preparing master base-flow recession curves for Turkey Creek at Byromville (station 02349900) using selected hydrograph segments during water years 1958-80.

of a complex situation, the small scatter of data points used to prepare the curves (fig. 6 is representative of most of the curves) suggests that the curves provide a reasonably valid means of estimating base flow from streamflow hydrographs.

In separating base flow from total flow, the master base-flow recession curve is overlain on the streamflow hydrograph coincident with the best fit; the area above the master curve is considered overland runoff and the area below the curve is considered base runoff. The most likely error in this method is believed to be slightly high base-flow values for high-runoff periods when rainfall is frequent. This error could result from two conditions: some streams may not reach base flow between rainfalls, and during high-flow periods, the discharge from the residuum overlying the Upper Floridan aquifer contributes significantly to base runoff.

An example of the use of the master recession curve to separate the streamflow hydrograph into overland and base-flow components is shown on plate 1. Note that yearly mean base flow makes up about 55 percent of total yearly mean streamflow of water year 1978, whereas mean base flow for January (a month of high precipitation) and for September (a month of little precipitation) make up, respectively, about 35 and 94 percent of monthly mean streamflow for these periods. The ratio of base flow to total flow is neither exceptionally low nor exceptionally high for Turkey Creek compared with other streams in southwest Georgia (the ratio varies from about 0.4 to 0.9). For the Dougherty Plain area of southwest Georgia, however, yearly mean base flow generally makes up about 77 percent of total yearly mean streamflow (Hayes and others, 1983).

The base flows of nine streams in the Dougherty Plain area of southwest Georgia were estimated by hydrograph separation techniques, discussed above, and compared with discharge at the 50-percent flow duration or median flow value. Figure 7 illustrates the results of this comparison. The upper curve is a plot of median flow for a year of record plotted against base flow for that year estimated by hydrograph separation techniques. The lower curve shows median flow for a month of record plotted against monthly base flow for that month estimated by hydrograph separation techniques. The points on both curves plot on or close to the line of equality, indicating that there is a reasonable agreement between base flow estimated by hydrograph separation techniques and base flow estimated from median flow. The yearly plot, however, more closely approximates the line of equality than does the monthly plot. Consequently, estimation of yearly mean base flow from yearly median flow is probably more valid than estimation of monthly mean base flow from monthly median flow.

The relation between base flow and median flow illustrated in figure 7 provides a means of estimating base flow in the Dougherty Plain area of southwest Georgia without using time-consuming hydrograph separation methods. Median flow at gaging stations (fig. 8) can be easily calculated by standard U.S. Geological Survey programs, using daily-flow values. Using the calculated relation between base flow and median flow, annual mean base flow and seasonal ranges of base flow were estimated for the eight watersheds in the Dougherty Plain area (fig. 8).

Assuming that median flow is equivalent to annual mean base flow, then annual mean base flow is 2,600 Mgal/d (4,000 ft^3/s), late-summer (September-November) mean base flow is about 1,500 Mgal/d (2,300 ft^3/s), and early-spring (February-April) mean base flow is about 4,800 Mgal/d (7,400 ft^3/s) for areas of the watersheds lying within the Floridan aquifer system in southwest Georgia (fig. 8). The method used herein to estimate base flow is considered subject to greater error for high flows than for low flows, and the actual early-spring base flow may be much lower than estimates made from either hydrograph separation techniques or median flow. In addition, the annual mean and early-spring values include discharge from both the Floridan aquifer system and the overlying residuum. These base flows will be used later in this report in estimating a water budget and in providing a check on digital modeling results for the southwest Georgia part of the study area.

HYDROGEOLOGY

GEOLOGIC SETTING

The Coastal Plain province of the Southeastern United States is underlain by a thick sequence of unconsolidated to semiconsolidated sedimentary rocks that range in age from Jurassic to Holocene. Coastal Plain rocks generally dip toward the Atlantic Ocean or the Gulf of Mexico, except where they are warped or faulted on a local to subregional scale. The earliest Coastal Plain sediments were laid down on an eroded surface developed on igneous intrusive rocks, low-grade metamorphic rocks, Paleozoic sedimentary rocks, and graben-filling sedimentary deposits of Triassic to Early Jurassic age (Barnett, 1975; Neathery and Thomas, 1975; Chowns and Williams, 1983). Refer to Professional Paper 1403-B (Miller, 1986) for a detailed description of the hydrogeology.

Rocks of middle Eocene to early Miocene age make up the major aquifers and confining units described in this report. The strata consist mainly of marine lime-

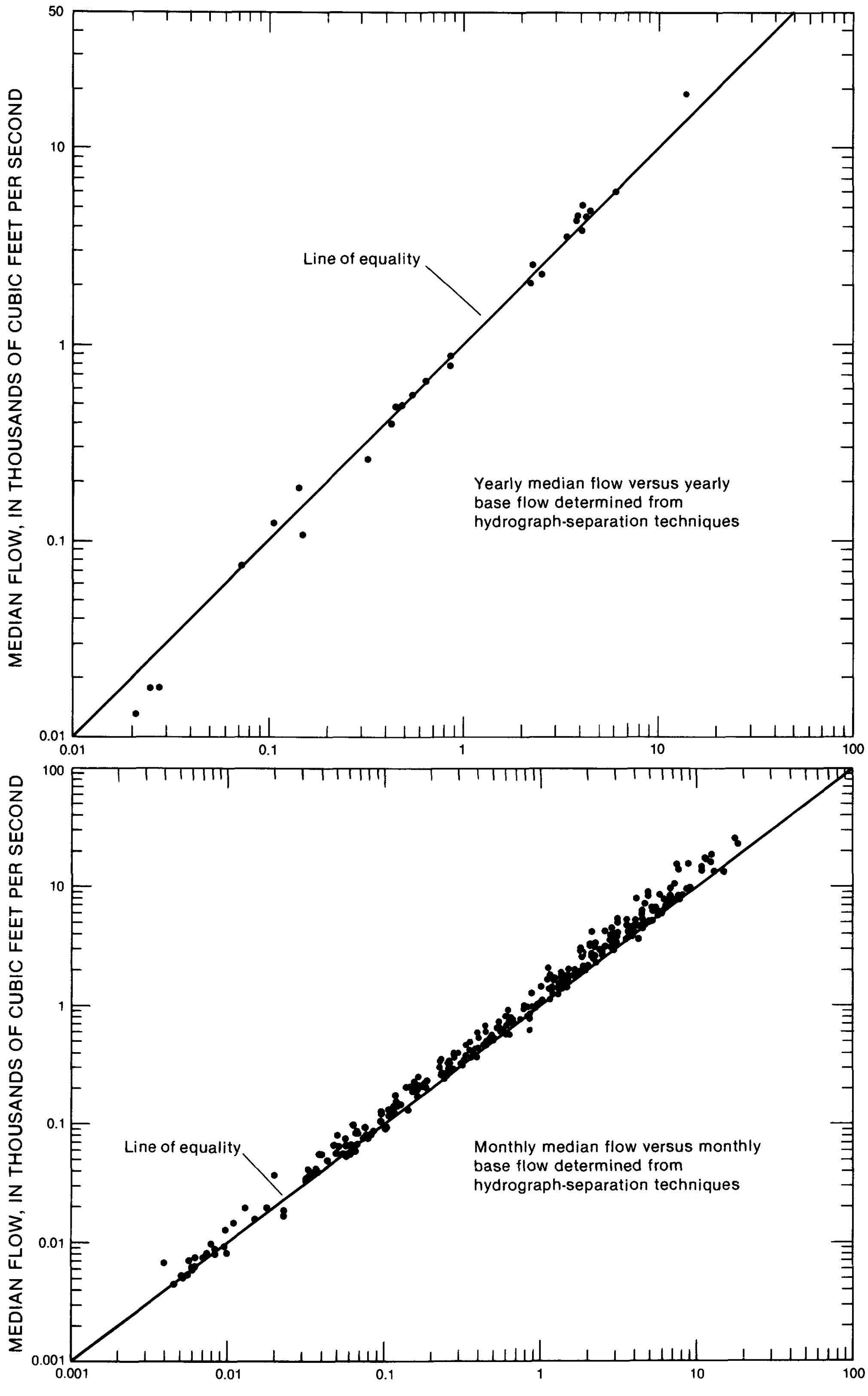


FIGURE 7.—Relation between base flow estimated from hydrograph separation and from median flow, southwest Georgia. From Hayes and others (1983).

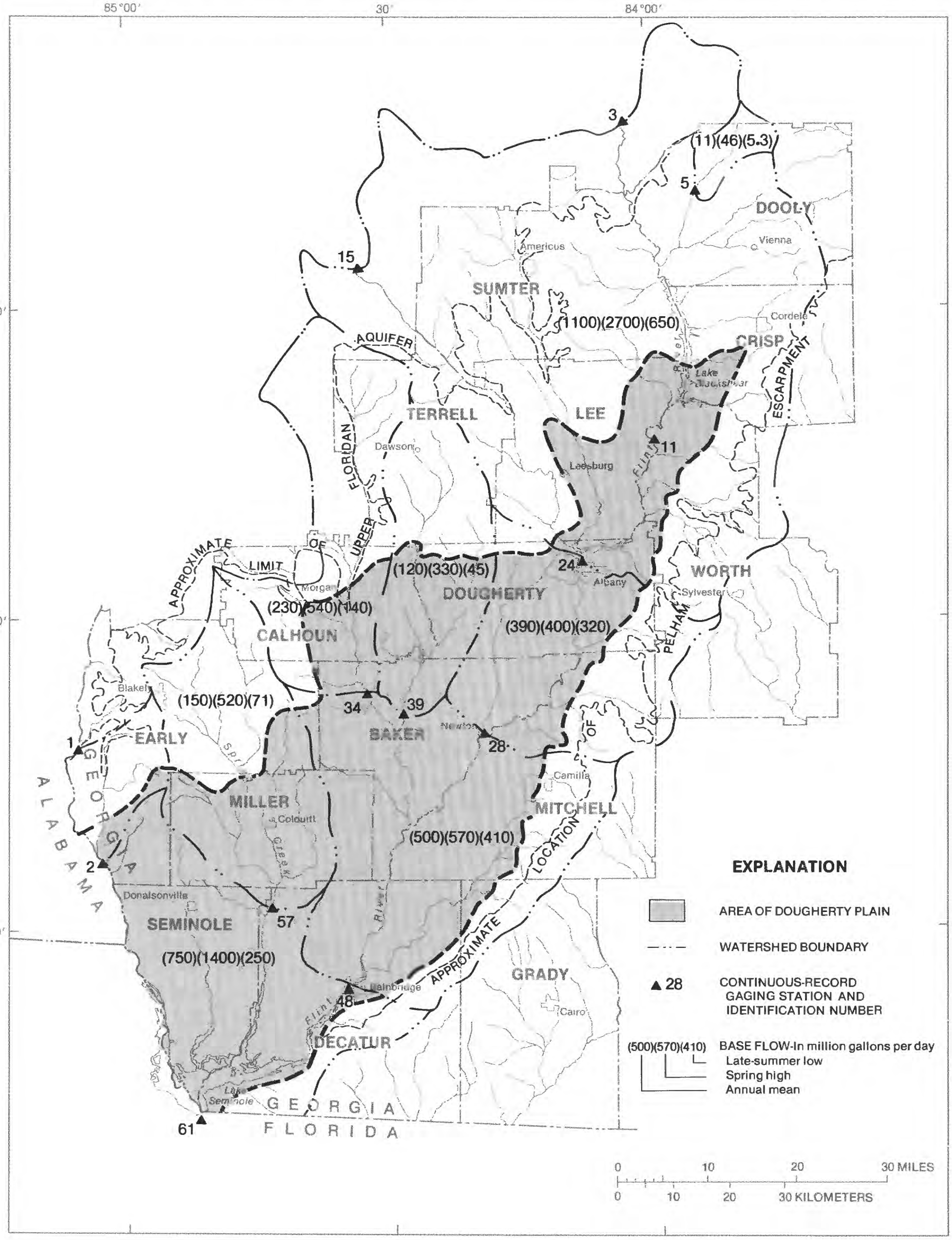


FIGURE 8.—Distribution and range of annual mean and seasonal base flows, southwest Georgia. From Hayes and others (1983).

stone, clay, and sand. Plate 2 depicts the stratigraphic and geohydrologic units of importance and their rock type, relative position, depth, and thickness in the subsurface. Note that this geohydrologic section shows that at some locations the contacts between the hydrogeologic units do not correspond to a particular geologic formation contact. For example, in southwest Georgia, the Floridan aquifer system consists of rocks of late Eocene age and, locally, of middle Eocene age, whereas, in northwest Florida, the Floridan aquifer system consists of rocks ranging in age from late Eocene to early Miocene. Professional Paper 1403-B (Miller, 1986) presents a detailed discussion of the stratigraphy and geology of the study area.

MINOR AQUIFERS AND CONFINING UNITS

SAND-AND-GRAVEL AQUIFER

The following discussion of the sand-and-gravel aquifer is based on work by Hayes and Barr (1983) and Trapp (1978). Only a brief description of the aquifer and its water chemistry will be presented in this report; for a more complete discussion, refer to the aforementioned reports.

The sand-and-gravel aquifer consists of fine to coarse sand, fine gravel, and lenses of sandy clay. The aquifer extends from land surface to the Pensacola Clay, a confining unit, which hydraulically separates the aquifer from the underlying Floridan aquifer system. The sand-and-gravel aquifer ranges in thickness from a few tens of feet in its easternmost area in Walton County, with transmissivity less than 100 ft^2/d, to more than 400 ft in western Escambia County, with transmissivity greater than 10,000 ft^2/d.

In Okaloosa and Walton Counties, differences in lithology and hydraulic properties permit separation of the aquifer into three hydrogeologic zones (Hayes and Barr, 1983): a surficial zone, which extends from land surface to depths of 20 to 60 ft and consists of fine to medium, moderately sorted sand; an intermediate zone, which ranges in thickness from less than 10 to about 65 ft, consists of sandy clay, and acts as a low-permeability confing bed; and the main water-producing zone, which makes up the bottom 10 to 85 ft of the sand-and-gravel aquifer and consists of medium to coarse sand, fine gravel, and shells. It is believed likely that these three zones could be correlated westward into Santa Rosa and Escambia Counties, Fla., and possibly northward into Alabama. Transmissivity of the main producing zone in Okaloosa County ranges from about 400 to 6,000 ft^2/d (Hayes and Barr, 1983).

Water from the sand-and-gravel aquifer generally has a dissolved-solids concentration of less than 50 mg/L and a pH of 4.5 to 6.5. With the exception of low pH and locally high iron concentration that may exceed 0.3 mg/L, water from the sand-and-gravel aquifer generally is of excellent quality and is suitable for public supply and industrial, domestic, and irrigation use. Near the coast, water from some wells may contain high concentrations of chloride and other dissolved constituents as a result of saline-water contamination. At a few sites, hydrogen sulfide, which is present in trace amounts, may cause the water to have a "rotten eggs" odor. Water from some wells that are screened opposite clayey sands may have a turbid appearance because of colloidal clay particles. Hayes and Barr (1983) have shown that dissolved-solids concentrations are generally higher in water from the surficial zone than in water from the deeper zone of the sand-and-gravel aquifer. The reason for this is that water from the surficial zone is more likely to be contaminated by saline surface water and by sewage and other pollutants resulting from human activities.

UPPER AND LOWER CONFINING UNITS

The upper confining unit of the Floridan aquifer system consists locally of the Pensacola Clay, called the Pensacola confining unit in this report, in the western Florida Panhandle, and of the residuum in southwest Georgia (fig. 9). The following discussion of the Pensacola confining unit and the residuum is limited to southern Okaloosa and Walton Counties, Fla., and to southwest Georgia, respectively.

Throughout most of the study area west of and including much of Walton County, the Floridan aquifer system is overlain by very low permeability clay, sandy clay, or clayey sand of the Pensacola confining unit. Trapp and others (1977) named these sediments the Pensacola confining unit because they correspond approximately to the lower part of the Pensacola Clay of Marsh (1966). Trapp and others (1977, p. 16) define this Pensacola confining unit as follows: "***the material of relatively low permeability between the sand-and-gravel aquifer above and the Floridan aquifer below. It may include material older, younger, or beyond the limits of the lower Pensacola Clay stratigraphic unit." The Pensacola confining unit restricts movement of water between the sand-and-gravel aquifer and the Floridan aquifer system to varying degrees, depending on its thickness and lithologic character at a particular place. The confining unit also restricts saltwater in Choctawhatchee Bay and the Gulf of Mexico from moving downward into the Floridan aquifer system.

The Pensacola confining unit dips south-southwest at about 15 ft/mi and occurs from about 140 ft above sea level in northwestern Walton County to 125 ft

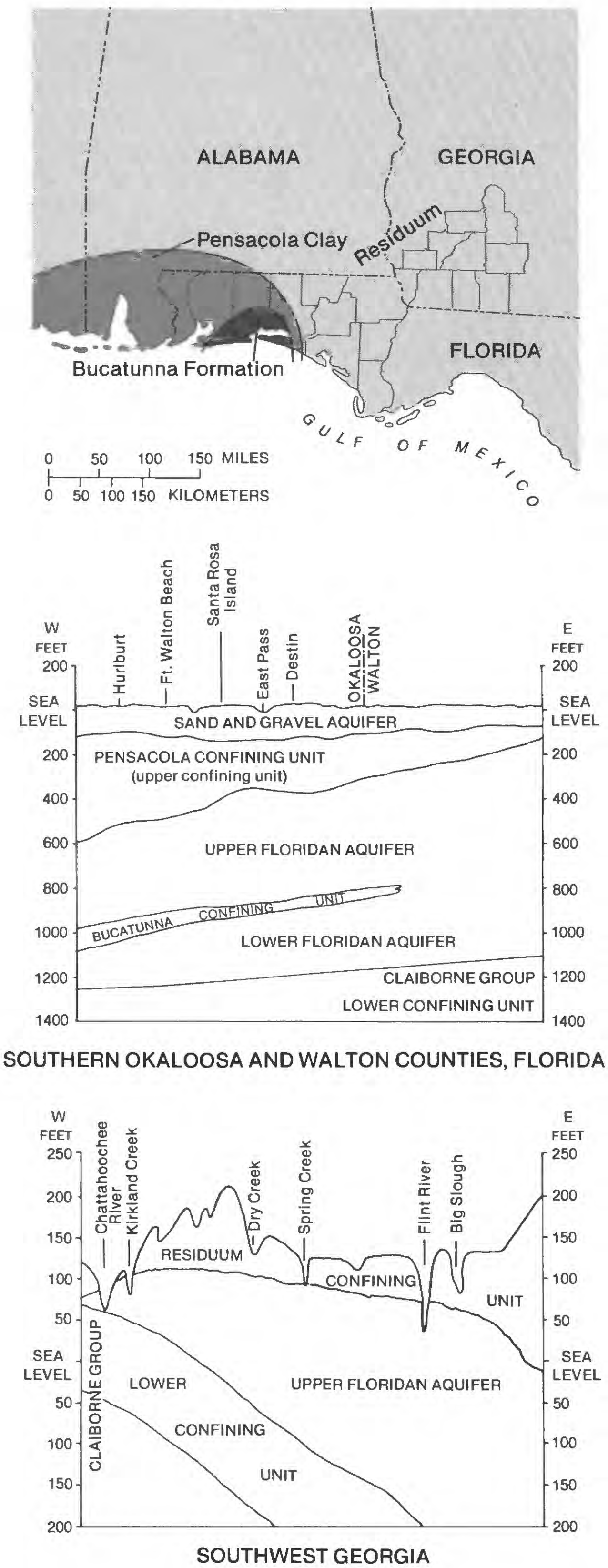


FIGURE 9.—Generalized hydrogeologic sections of the Floridan aquifer system, southern Okaloosa and Walton Counties, Florida, and southwest Georgia.

below sea level in southwestern Okaloosa County (Barr and others, 1985). The unit ranges in thickness from less than 50 ft in southeastern Walton County to more than 450 ft in southwestern Okaloosa County (Barr and others, 1985).

The Pensacola confining unit consists predominately of gray to bluish-black and light-brown carbonaceous or calcareous clay, light-gray to brown, very fine to coarse, clayey sand, coarse, angular, clayey gravel, and some limestone and shell fragments. In the study area, the confining unit grades laterally from dense clay and sandy clay in the west to sandy clay, clayey sand, and limestone in the east. On the basis of geophysical and lithologic logs, aquifer test analyses, and modeling analyses, the average vertical hydraulic conductivity of the confining unit is estimated to range from about 1×10^{-4} to 1×10^{-7} ft/d. A test of a clay core from Pensacola Clay near Milton, Santa Rosa County, indicated a vertical hydraulic conductivity of about 5×10^{-7} ft/d (F.S. Riley, U.S. Geological Survey, written commun., 1976).

In southwest Georgia where the Pensacola Clay does not exist, the upper confining unit consists of a residual layer of sand and clay derived from chemical weathering of the Ocala Limestone. The ratio of sand to clay in the residuum varies throughout the study area. Test-drilling data indicate that the residuum consists mainly of brown to red, mottled, clayey sand to slightly sandy clay (Mitchell, 1981, tables 3–46). Clay content ranges from approximately 10 to 70 percent, with samples from 45 of 50 test wells consisting of more than 25 percent clay. The residual layer ranges in thickness from a few feet to slightly more than 125 ft and has an average thickness of approximately 50 ft (Hayes and others, 1983).

The hydraulic conductivity of the residuum in southwest Georgia has been estimated from sieve analyses of drill cuttings collected at 5-foot intervals, geophysical logs, and aquifer tests (Hayes and others, 1983). The areal distribution of estimated vertical hydraulic conductivity of the residuum varies from 1×10^{-4} to 9 ft/d, with the median being 3×10^{-3} ft/d. (See Hayes and others, 1983, for a listing and location of data.) The predominant lithologic factor determining vertical hydraulic conductivity is the presence or absence of nearly impermeable clay lenses within the residuum thickness. Test drilling indicates that such clay lenses occur more commonly in the lower half of the residuum than in the upper half. Consequently, vertical hydraulic conductivities are usually considerably less in the lower half than in the upper half of the residuum.

Plate 3 illustrates a generalization of the areal range of leakage coefficients of the upper confining units in the study area estimated by model simulations after using preliminary estimated leakance values as model input. Preliminary leakance values in southwest Georgia were calculated by dividing the estimated vertical hydraulic conductivity (K'_v) by the effective thickness of the confining unit (b'), which was considered to be equivalent to the bottom half of the residuum. (See Hayes and others, 1983, for a listing and location of data.) Preliminary leakance values in southern Okaloosa and Walton Counties were calculated by dividing the estimated vertical hydraulic conductivity 1×10^{-6} ft/d by the thickness of the Pensacola confining unit. The upper confining unit outside southern Okaloosa and Walton Counties was assumed to have a leakance value of 5×10^{-4} (ft/d)/ft if it is residuum (east of Walton County) or 2×10^{-9} (ft/d)/ft if it is the Pensacola Clay (westward from Walton County). An initial leakance map was constructed using these preliminary leakance values. The final map (pl. 3) is considered reasonably accurate for southwest Georgia and southern Okaloosa and Walton Counties, Fla., because of aquifer test, core analyses, and geophysical logs. However, owing to the paucity and variability of leakance data, the regionalization is highly generalized. In areas where confining unit thickness and vertical hydraulic conductivity data were not available, the distribution of leakance is considered a "best guess" estimate only.

The lower confining unit that underlies the Floridan aquifer system consists mostly of low-permeability rocks that are part of the Lisbon and Tallahatta Formations of the Claiborne Group. However, in southwest Georgia, the uppermost part of the Lisbon Formation consists of permeable sands, and, where present, these sands are considered part of the Floridan aquifer system. In the Fort Walton Beach area, argillaceous beds that are the equivalent of the Ocala Limestone are part of the lower confining unit. These rocks consist of hard, light-gray, calcareous shale and siltstone interbedded with gray limestone, very fine to coarse sand, and some gray or brown clay (Marsh, 1966, p. 24). These relatively impermeable strata act as a confining unit and restrict the vertical movement of water into or out of the lower part of the Floridan aquifer system.

FLORIDAN AQUIFER SYSTEM

LITHOLOGY, AREAL EXTENT, AND THICKNESS

The Floridan aquifer system is a sequence of carbonate rocks of Paleocene to early Miocene age that are hydraulically connected in varying degrees. This carbonate sequence includes units of very high to low permeability that have been shown to form a regional ground-water flow system. This flow system was first identified in peninsular Florida by Stringfield (1936, p. 132, pl. 12). Later, Warren (1944, p. 17) described an extension of the system in south Georgia and applied the term "principal artesian aquifer" to the carbonate units involved. Stringfield (1966, p. 95) also used the term "principal artesian aquifer" to describe the permeable carbonate rocks from the Hawthorn Formation through the Oldsmar Limestone in Georgia, South Carolina, Florida, and Alabama (table 2). Parker (in Parker and others, 1955, p. 188–189) noted the hydrologic and lithologic similarities of the Tertiary carbonate formations in southeast Florida, concluded that they represented a single hydrologic unit, and named that unit the "Floridan aquifer." Table 2 shows the geologic formations and ages of units included by Parker and Stringfield in their aquifer definitions.

Miller (1982a, b, c, d, e) provided the first detailed regional definition of the aquifer system, presenting maps of the top, base, and thickness of the system and its major hydrogeologic components. The term "Tertiary limestone aquifer system" was applied by Miller and, in related reports, by Bush, Johnston, Miller, and Sprinkle during the first stage of the Regional Aquifer-System Analysis (RASA) study. (See Johnston, 1978; Johnston and others, 1980; Bush, 1982; Miller, 1982a–e; Sprinkle, 1982a–c.) This term was adopted because it combined the age of the rocks and their general lithology into the name of the aquifer system. However, at the final stage of the RASA study, the term "Floridan aquifer system" replaces the term "Tertiary limestone aquifer system." Professional Paper 1403–B presents a detailed regional hydrogeologic description of the Floridan aquifer system.

Throughout most of the study area, the Floridan aquifer system consists of an Upper and Lower Floridan aquifer separated by much less permeable material. The upper and lower aquifers are defined on the basis of permeability, and their boundaries locally do not coincide with either time-stratigraphic or rock-stratigraphic boundaries. (See pls. 14 and 18, Miller, 1986.) In southwest Georgia and much of northwest Florida, however, there is little permeability contrast within the aquifer system. Consequently, the Floridan aquifer system in these areas is effectively one continuous aquifer, hereafter called the Upper Floridan aquifer (fig. 9). In parts of Escambia, Santa Rosa, Okaloosa, and Walton Counties, Fla., the Floridan aquifer system is divided by the Bucatunna Formation and both the Upper and Lower Floridan aquifers are present.

In southwest Georgia, the Floridan aquifer system consists primarily of the Ocala Limestone of late Eocene age. Locally, unnamed middle Eocene lime-

TABLE 2.—*Terminology applied to the Floridan aquifer system*

[U.S. Geological Survey publications: WSP, Water-Supply Paper; PP, Professional Paper; WRIR, Water-Resources Investigations Report]

Series		Parker and others (1955) WSP 1255		Stringfield (1966) PP 517		Miller (1982b, 1982d) WRI 81-1176 WRI 81-1178		Miller (1986) PP 1403-B	
		Formation[1]	Aquifer	Formation[1]	Aquifer	Formation[1]	Aquifer	Formation[1]	Aquifer
Miocene		Hawthorn Formation	Where permeable	Hawthorn Formation		Hawthorn Formation		Hawthorn Formation	
Miocene		Tampa Limestone	Floridan aquifer	Tampa Limestone	Principal artesian aquifer	Tampa Limestone	Where present and permeable	Tampa Limestone	Where present and permeable
Oligocene		Suwannee Limestone		Suwannee Limestone		Suwannee Limestone	Tertiary limestone aquifer system	Suwannee Limestone	Floirdan aquifer system
Eocene	Upper	Ocala Limestone		Ocala Limestone		Ocala Limestone		Ocala Limestone	
Eocene	Middle	Avon Park Limestone Lake City Limestone		Avon Park Limestone Lake City Limestone		Avon Park Limestone Lake City Limestone		Avon Park Formation	
Eocene	Lower			Oldsmar Limestone		Oldsmar Limestone		Oldsmar Limestone	
Paleocene						Cedar Keys Limestone		Cedar Keys Formation	

[1]Names apply only to peninsular Florida and southwest Georgia except for Ocala Limestone and Hawthorn Formation.

stones underlying the Ocala in southwest Georgia and the eastern part of the Florida Panhandle are included in the Floridan (Claude Tindel and city of Camilla wells, pl. 2). In other parts of the study area, limestones of younger (Oligocene) age make up the upper part of the aquifer. (See Professional Paper 1403–B; Miller, 1986.) The upper surface of the aquifer system dips generally southwestward and occurs from about 300 ft above sea level in Dooly County to about sea level in Decatur County. However, the surface is highly irregular because of differential weathering (pl. 4).

The Floridan aquifer system in southwest Georgia, predominantly the Ocala Limestone, ranges in thickness from a few feet at the updip featheredge to about 700 ft in Decatur County (pl. 5). The aquifer is exposed along sections of major streams such as the Chattahoochee and Flint Rivers and Spring Creek, where erosion has removed the residuum. The aquifer is reduced in thickness at these exposures and near the updip limit may be entirely removed by a deeply incised stream.

Lying beneath the Ocala Limestone in southwest Georgia are permeable sands of the Lisbon Formation of middle Eocene age that are hydraulically connected to the Floridan. Thus, for simulation of the ground-water flow system it was necessary to include these sands as part of the Floridan aquifer system in southwest Georgia.

In the northwest Florida part of the study area, the Upper Floridan aquifer was described as a distinct geohydrologic unit by Barraclough and Marsh (1962, p. 4–18) and by Marsh (1966, p. 104). It generally consists of a white to light-gray or cream colored, highly fossiliferous, slightly dolomitic limestone. In parts of Walton County, the Upper Floridan aquifer commonly may be 10 to 25 percent sand or silty clay. The top of the aquifer ranges from about 200 ft above sea level near the updip limit to about 2,000 ft below sea level in Escambia County (pl. 4). In this part of the study area, the Floridan aquifer system ranges in thickness from a few feet at its northern updip limit in southernmost Alabama to more than 3,000 ft in Gulf County, Fla. (pl. 5).

As mentioned earlier, the Floridan aquifer system is distinguishable as two separate hydrologic units (Upper Floridan aquifer and Lower Floridan aquifer) in parts of Escambia, Santa Rosa, and southern Okaloosa Counties and in a small part of coastal Walton County, where the confining unit in the Oligocene Formation, called Bucatunna confining unit in this report, is present (fig. 9; pls. 2, 7). Except for moderately thin sections of soft brown dolomite and fine to medium quartz sand in these areas, the Lower Floridan aquifer is composed of white to gray, soft to hard limestone. Some sections, particularly in Walton County, are highly fossiliferous, being composed principally of foraminifera and shell fragments.

Where present, the Bucatunna confining unit contains a massive clay member of very low permeability that confines the water in the Lower Floridan aquifer. Cores from a well in Santa Rosa County had laboratory-measured vertical hydraulic conductivities ranging from 1.9×10^{-6} to 2.6×10^{-7} ft/d (Pascale, 1974). Data from test wells in coastal Okaloosa County show that water levels are tens of feet higher in the Lower Floridan aquifer than in the Upper Floridan aquifer. For example, in the Fort Walton Beach area, the water level in the Lower Floridan aquifer is approximately 5 ft above sea level, whereas the water level in the Upper Floridan aquifer is about 50 ft below sea level. This difference in water levels demonstrates the effectiveness of the Bucatunna confining unit in that area in separating the Upper and Lower Floridan aquifers. However, a few miles north of the Fort Walton Beach area, the water level in the Lower Floridan aquifer is only 1 to 6 ft higher than in the Upper Floridan aquifer. This suggests a lesser degree of hydraulic separation.

HYDRAULIC PROPERTIES

Permeability of the Floridan aquifer system is largely attributable to secondary porosity resulting from the dissolution of the carbonate rock. Large variations in dissolution result in regional variations in transmissivity of more than three orders of magnitude (less than 1,000 ft^2/d to greater than 1,000,000 ft^2/d). The development of solution openings is most directly related to the degree of confinement of the Floridan. Where the Upper Floridan aquifer is unconfined or thinly confined, cavities caused by dissolution are most abundant and transmissivity is greatest. Where the Floridan is thickly confined, there has been less dissolution and transmissivity is lowest. In southwest Georgia, where the Upper Floridan aquifer is covered by thin residuum that is locally breached, transmissivities are high. In contrast, the Upper Floridan aquifer in the Florida Panhandle is confined by thick Miocene clays and transmissivities are low. Also contributing to the low transmissivity of the Upper Floridan aquifer in the Florida Panhandle are thick sections of low-permeability micritic limestone.

A major assumption of the hydrologic analyses during this study is that regional flow in the Floridan can be analyzed by applying methods developed for porous media. This assumption is valid if a certain aquifer volume can be found such that within that aquifer volume there are a sufficient number of solution openings whose properties can be represented by average values. Bear (1972) defined the concept of the representative elemental volume (REV) to describe the smallest volume of rock that can be assigned a single value of any property. The dimensions of the REV have not been defined in the study area; however, aquifer-test data suggest that its dimensions are on the order of thousands of feet in southwest Georgia, and less in panhandle Florida. (See further discussion of the REV concept and aquifer-test analysis of the Nilo site in southwest Georgia in Professional Paper 1403-A; Johnston and Bush, in press.)

Plate 6 shows the estimated distribution of transmissivity and control points for the Upper Floridan aquifer. The control points are transmissivity values from aquifer tests or estimates from specific-capacity data. (See Barr and others, 1981, and Hayes and others, 1983, for a listing and expanded discussion of these tests.) The transmissivity data have been extrapolated to cover the entire study area. The distribution of transmissivity shown on plate 6 is based on aquifer tests where available, and on aquifer thickness and simulation results where tests were unavailable. Wide variations in hydraulic conductivity occur in the Upper Floridan aquifer owing to size and distribution of secondary solution openings.

Computed field values of transmissivity of the Upper Floridan aquifer range from 200 to 370,000 ft^2/d, whereas effective regional values based partly on simulation range from 250 to 600,000 ft^2/d (pl. 6). Transmissivity is lowest in panhandle Florida, just inland from the saltwater/freshwater boundary, where the Upper Floridan aquifer is thickly confined. There the flow system is stagnant and very little solutioning has occurred. Transmissivity is very high adjacent to major streams, such as the Apalachicola and Chipola Rivers in Florida and the Chattahoochee and Flint Rivers and Spring Creek in Georgia, where the Floridan is thinly confined and breached by the rivers and sinkholes. There, water flowing between the streams and the ground-water system has accelerated the development of solution channels. Transmissivity is highest in a belt extending from Decatur County, Ga., to Washington County, Fla. (pl. 6), as a result of a highly interactive surface-water and ground-water flow in the area.

The relation between transmissivity based on simulation and transmissivity derived from aquifer tests or estimated from specific-capacity data is shown in figure 10. In southwest Georgia, transmissivity values from both aquifer tests and specific-capacity data scatter considerably about the line of equality (data points would plot on the line of equality if simulated transmissivity were equal to transmissivity determined from aquifer tests or estimated from specific-capacity data). Scatter is less for the comparison of simulated transmissivity and aquifer-test transmissivity (average difference, -11,000 ft^2/d; standard deviation of difference, 52,000 ft^2/d) than for the comparison of simulated transmissivity and transmissivity estimated from specific capacities (average difference, +38,000 ft^2/d; standard deviation of difference, 119,000 ft^2/d). Some scatter is expected because a simulated value represents an average transmissivity over 1 mi^2 in the model simulation (to be discussed later), whereas transmissivity determined from aquifer tests or estimated from specific-capacity data is a point value which represents the aquifer property in the area between the pumping well and observation wells for aquifer tests, or the area near the well bore for specific-capacity data estimation. Therefore, the difference between the data determined by the different methods is expected and reasonable.

In southern Okaloosa and Walton Counties, Fla., transmissivities derived from aquifer tests and specific-capacity data plot reasonably close to the line of equality (fig. 10). Transmissivities derived from aquifer tests and those derived by simulation have a mean difference of +500 ft^2/d and a standard deviation of difference of 1,800 ft^2/d. In comparison, transmissivities derived from specific-capacity data and those derived by simulation have a mean difference of +2,000 ft^2/d and a standard deviation of difference of 5,000 ft^2/d. In this area, aquifer transmissivity does not vary abruptly.

Storage coefficients in southwest Georgia range from 3×10^{-2} to 2×10^{-4} but generally range from about 1×10^{-3} to 1×10^{-4}. Storage coefficients in southern Okaloosa and Walton Counties, Fla., range from about 6×10^{-4} to 2×10^{-5}. In theory, the storage coefficient in confined aquifers is directly proportional to aquifer thickness. However, in the Floridan aquifer system, storage coefficients bear no discernible relation to aquifer thickness on a regional basis. The values at the high end of the range, 1×10^{-2} to 1×10^{-3}, reflect the semiconfined nature of the aquifer as characterized by the southwest Georgia part of the study area. The high values indicate that some of the water from storage comes from dewatering of the aquifer rather than totally from compression of the aquifer skeleton and expansion of water. In southwest Georgia the limestone itself is not dewatered. However, the limestone, together with the sandy residuum overlying it, behaves as a single aquifer whose upper part is much less permeable than its lower part. Thus, dewatering occurs in the uppermost sands, that is, in the residuum. Because of limited storage-coefficient data, no attempt has been made to regionalize storage coeffi-

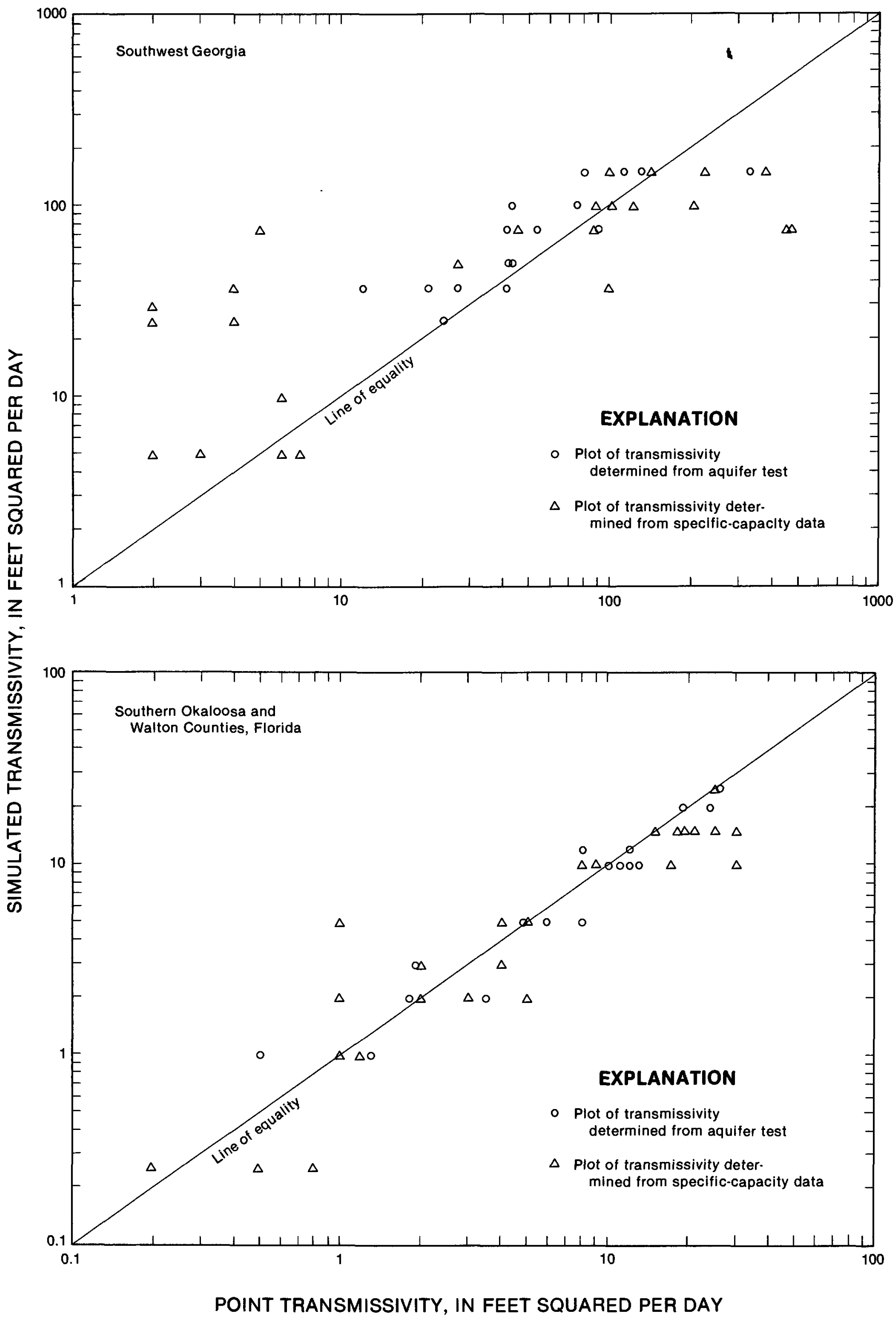


FIGURE 10.—Relation between simulated transmissivity and transmissivity derived from aquifer tests and estimated from specific-capacity data, Upper Floridan aquifer, southwest Georgia and southern Okaloosa and Walton Counties, Florida.

cients. Refer to Hayes and others (1983) for a discussion, listing, and location of storage-coefficient data for southwest Georgia; refer to Barr and others (1985) for a discussion, listing, and location of storage-coefficient data for southern Okaloosa and Walton Counties, Fla.

WATER QUALITY

The chemistry of the water in the Floridan aquifer system is described by Sprinkle (1982a, 1982b, 1982c) and is summarized briefly below. Water samples from wells open to the Upper Floridan aquifer have been collected and analyzed for concentrations of major inorganic constituents, herbicides, insecticides, and fungicides commonly used for agricultural purposes, and for the trace elements, arsenic, lead, mercury, copper, and zinc in southwest Georgia (Pollard and others, 1978; Radtke and others, 1980; Mitchell, 1981; Hayes and others, 1983) and in the northwest Florida Panhandle (Trapp and others, 1977; Wagner and others, 1980; Barr and others, 1985). These data indicate that water from the Upper Floridan aquifer generally meets U.S. Environmental Protection Agency (1976) recommended standards for drinking water.

In the study area, the pH of water from the Upper Floridan aquifer is commonly about 7.5. Dissolved-solids concentrations generally range from about 100 to 500 mg/L, and commonly range from about 150 to 250 mg/L. Hardness (as $CaCO_3$) ranges generally from about 90 to 175 mg/L but is commonly about 100 mg/L. Calcium, sodium, bicarbonate, and chloride are the major dissolved constitutents, with respective concentrations of generally about 35 to 40, 2 to 5, 120 to 250, and 2 to 10 mg/L. Regional maps showing areal distributions of these constituents are presented by Sprinkle (1982a, 1982b, 1982c). Concentrations of most other constituents are less than 10 mg/L. As will be discussed later, exceptions to these generalizations occur along coastal areas in southern Okaloosa and Walton Counties, Fla.

PESTICIDES—SOUTHWEST GEORGIA

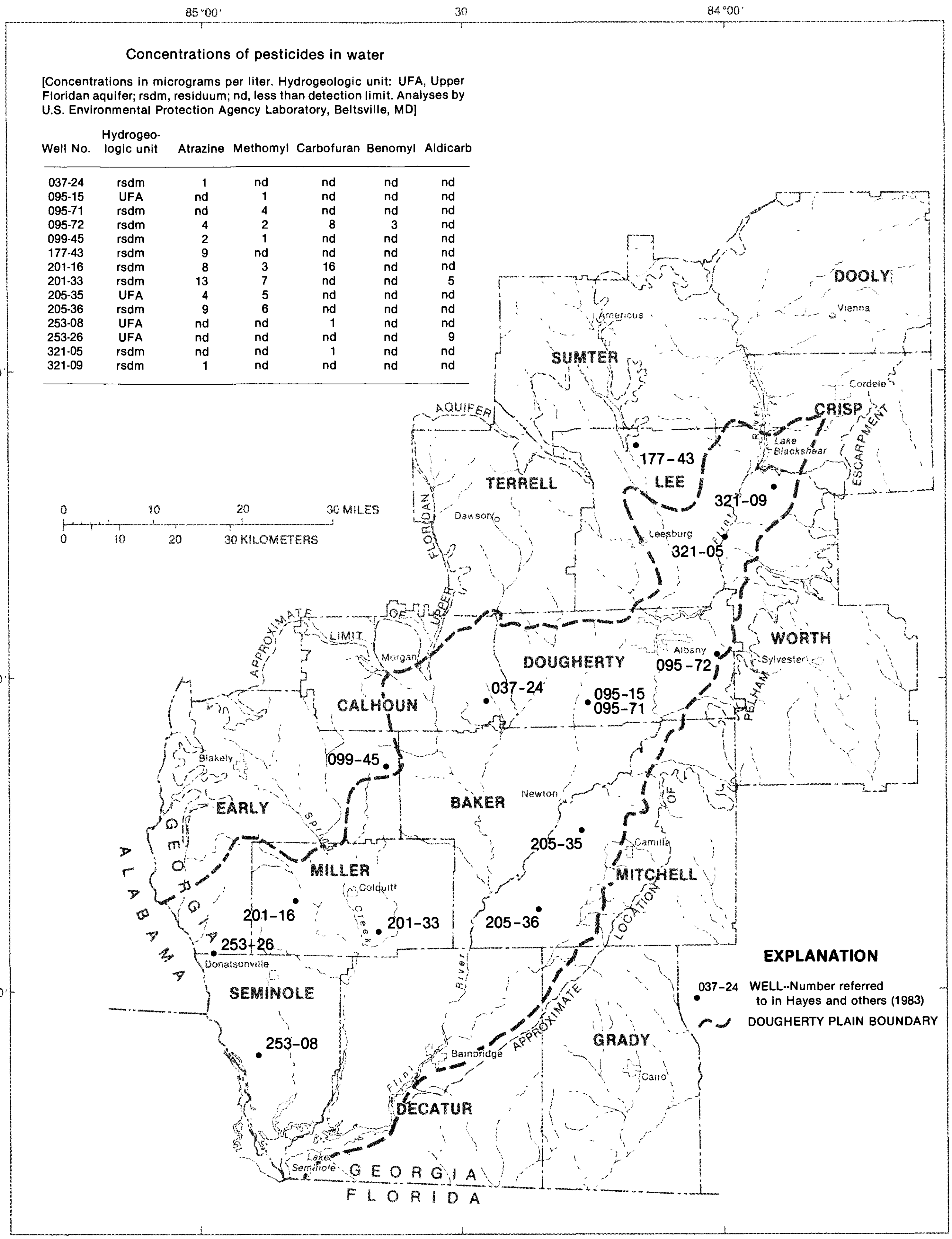
Rapid growth in agricultural use of large-acreage irrigation systems in southwest Georgia has resulted in large increases in the use of fertilizers and pesticides; some of these pesticides are highly toxic to humans, are long-lasting, and tend to accumulate in the hydrogeologic system. Water samples from 16 wells in the residuum and 16 wells in the Upper Floridan aquifer were analyzed for pesticides. Pesticides were detected in water from 10 wells in the residuum and 4 wells in the Upper Floridan aquifer. The location of these wells and pesticide concentrations are shown in figure 11. Water from two of the four wells tapping the Floridan contained pesticide concentrations only slightly above detection limits, but water from the other two wells contained concentrations considerably above detection limits. None of the water samples, however, contained concentrations of analyzed pesticides exceeding the recommended limits for drinking water (U.S. Environmental Protection Agency, 1976; National Academy of Sciences, 1977). The occurrence of pesticides in the residuum wells may be a precursor of water-quality degradation in the Upper Floridan aquifer.

The presence or absence of pesticides in water from wells in the Upper Floridan aquifer, as reported herein, is valid only for the time that the samples were taken. Concentrations of pesticides could be greater or less in samples from these same wells at other times. As will be discussed later, the aquifer is characterized by a complex flow system. Consequently, rates of pesticide movement through the aquifer may vary greatly. The areal extent, severity, and long-term effects of pesticides on quality of water from the Upper Floridan aquifer cannot be determined from the limited available data. Consequently, further studies are desirable.

SALINE WATER—COASTAL FLORIDA

The recommended limit for chloride in public drinking water supplies is 250 mg/L (U.S. Environmental Protection Agency, 1976). Water containing more than 400 mg/L of chloride tastes salty to most individuals, and water containing more than 1,500 mg/L is generally considered unfit for human consumption. Water from wells open to the Upper Floridan aquifer generally contains about 25 to 75 mg/L of chloride, but water from some wells in coastal Walton and Okaloosa Counties contains more than 500 mg/L (pl. 7). The sources of high chloride concentrations in these wells may be (1) connate saline water trapped in the aquifer at the time of its deposition, (2) relatively modern ocean water from the Gulf of Mexico or Choctawhatchee Bay moving downward into the aquifer through the overlying Pensacola confining unit, where its confinement is less effective, (3) saline water present in underlying formations and moving upward into the aquifer, (4) saline gulf water moving laterally from seaward, where the aquifer may crop out in the gulf, or (5) combinations of sources 2, 3, and 4.

Data on plate 7 indicate that chloride concentrations in water from the Upper Floridan aquifer in southern Okaloosa and Walton Counties, Fla., have remained



Concentrations of pesticides in water

[Concentrations in micrograms per liter. Hydrogeologic unit: UFA, Upper Floridan aquifer; rsdm, residuum; nd, less than detection limit. Analyses by U.S. Environmental Protection Agency Laboratory, Beltsville, MD]

Well No.	Hydrogeo-logic unit	Atrazine	Methomyl	Carbofuran	Benomyl	Aldicarb
037-24	rsdm	1	nd	nd	nd	nd
095-15	UFA	nd	1	nd	nd	nd
095-71	rsdm	nd	4	nd	nd	nd
095-72	rsdm	4	2	8	3	nd
099-45	rsdm	2	1	nd	nd	nd
177-43	rsdm	9	nd	nd	nd	nd
201-16	rsdm	8	3	16	nd	nd
201-33	rsdm	13	7	nd	nd	5
205-35	UFA	4	5	nd	nd	nd
205-36	rsdm	9	6	nd	nd	nd
253-08	UFA	nd	nd	1	nd	nd
253-26	UFA	nd	nd	nd	nd	9
321-05	rsdm	nd	nd	1	nd	nd
321-09	rsdm	1	nd	nd	nd	nd

FIGURE 11.—Locations of wells in which water was analyzed for pesticides in the residuum and the Upper Floridan aquifer, southwest Georgia.

about the same over the period of record and that saline-water contamination is not a widespread or serious problem. Nevertheless, as water levels decline in response to pumping, the potential exists for saline-water contamination of the Upper Floridan aquifer. According to Trapp and others (1977), in southern Okaloosa County upward movement of saline water from the Lower Floridan aquifer into the Upper Floridan aquifer has been largely prevented by the intervening low-permeability Bucatunna Formation. However, the Bucatunna Formation thins out a few miles eastward of the Okaloosa County–Walton County line (fig. 9; pls. 2, 7). If the cone of depression currently centered in the Fort Walton Beach area (to be discussed later) continues to expand into Walton County, upward movement of saline water may occur.

The saline water in the Lower Floridan aquifer, or in the lower part of the Upper Floridan aquifer in southern Okaloosa and Walton Counties, Fla., is believed to be seawater. As freshwater flows through the aquifer, it floats over the more saline water because of its lower density, forming an inverted wedge with freshwater in the upper part of the aquifer and more saline water at the bottom. This is illustrated by comparing water-quality data from four test wells (test wells 1–4, table 3) drilled in southern Okaloosa and Walton Counties, Fla. Mixing between the two waters takes place in a zone of diffusion.

The composite samples taken from the wells open to the Lower Floridan aquifer or to the lower part of the Upper Floridan aquifer system in the study area exceeded the U.S. Environmental Protection Agency (1976) concentration limits for chlorides and dissolved solids. Water samples taken during drilling at different depths had chloride concentrations ranging from 8.7 to 3,100 mg/L and dissolved-solids concentrations ranging from 179 to 5,830 mg/L. The only other constituent that exceeds drinking water standards is fluoride. At test wells 2 and 4 (pl. 7), fluoride concentrations of 3.1 and 2.3 mg/L, respectively, were observed. On the basis of the chloride map (pl. 7) and table 3, as well as geochemical maps presented by Sprinkle (1982a, 1982b, 1982c), it seems that the quality of water deteriorates with increasing depth and areally to the south.

GROUND-WATER FLOW

PREDEVELOPMENT FLOW SYSTEM

There are two contrasting types of flow systems for the Floridan aquifer system in the study area. In southwest Georgia and adjacent parts of Florida and Alabama, the aquifer is recharged by water moving vertically downward through the residuum, with the lower, less permeable half of the residuum acting as a leaky confining layer. The aquifer discharges water to nearby streams that are hydraulically connected to the aquifer, resulting in many local flow systems.

In contrast, the Floridan aquifer system in Walton County and westward in northwest Florida is confined from above by the thick Pensacola confining unit, resulting in a regional flow system rather than many local flow systems. In this area, part of the aquifer is recharged from above by water moving vertically downward through the Pensacola confining unit. Except for Choctawhatchee Bay, there are no surface-water bodies that have direct hydraulic connection to the aquifer. Hence, part of the aquifer discharges upward as diffuse leakage through the Pensacola confining unit into the overlying sand-and-gravel aquifer or into overlying streams, the bay, or the ocean where head differential is in an upward direction.

The rates of vertical leakage through the thin, leaky residuum are several orders of magnitude greater than the rates through the thick Pensacola confining unit. Consequently, as previously stated, recharge to the Floridan aquifer system is considerably greater where the Pensacola confining unit is absent. The lower confining unit underlying the Floridan aquifer system is assumed to be impermeable, which allows insignificant vertical flow upward or downward.

Water in the Floridan aquifer system within the study area originates almost entirely as precipitation and leaves as discharge to streams or springs, or as upward diffuse leakage to overlying sediments. The flow system within the study area is bounded on the east by a ground-water divide, on the south and west by a saltwater–freshwater interface that has been defined as the seaward lateral extent of the freshwater flow system (Bush, 1982), and on the north by the updip limit of the aquifer. As mapped by Miller (1986, p. B48), the updip limit is defined as that point where the "***clastic rocks interbedded with the limestone make up more than 50 percent of the rock column***."

The following discussion of recharge and discharge in the Floridan aquifer system is based largely on model simulations (to be discussed later) of the steady-state predevelopment flow system. The steady-state model has, in part, been tested using transient simulations of present-day (1978 and 1980) flow conditions in southern Okaloosa and Walton Counties, Fla., and in southwest Georgia. Within these areas, interpretations are considered reasonably acceptable; outside these areas, however, interpretations are considered preliminary estimates.

In areas where the altitude of the water table is higher than the altitude of the potentiometric surface of the Florida aquifer system, water moves downward

TABLE 3.—*Major chemical constituents and characteristics of water from the Floridan aquifer system, southern Okaloosa and Walton Counties, Florida*

[Units are milligrams per liter, except where noted. µg/L, micrograms per liter; µmho/cm, micromho per centimeter at 25°C; NTU, nephlometric turbidity units. See pl. 7 for well locations]

Constituent/Characteristic — Depth below land surface, in feet	Test well 1[1]		Test well 2[1]		Test well 3[2]	Test well 4[2]	
	940-1,015	940-1,380	1,020-1,060	1,020-1,200	201-900	220-420	220-820
Akalinity as $CaCO_3$, total	130	—	264	322	120	110	190
Arsenic, dissolved, µg/L	.001	0.003	.002	.001	—	—	—
Bicarbonate	158	158	322	392	146	130	230
Boron, dissolved, µg/L	.030	.570	1.100	2.100	—	—	—
Calcium, dissolved	21	26	25	25	22	36	79
Carbon, dissolved, total	3.0	—	6.1	1.0	—	—	—
Carbon dioxide	2.0	—	5.2	16	—	—	—
Carbonate	0	0	0	0	—	0	0
Chloride, dissolved	8.7	410	810	1,600	28	400	3,100
Color, platinum-cobalt units	2	5	10	5	—	2	0
Dissolved solids, calculated sum	167	816	1,760	3,000	200	834	5,360
Dissolved solids, residue at 180°C	179	925	1,070	3,160	196	861	5,830
Fluoride, dissolved	.2	.8	2.1	3.1	.2	.6	2.3
Hardness, as CaCO (Ca+Mg)	120	0	120	170	110	190	500
Hardness, noncarbonate as $CaCO_3$	0	150	0	0	0	84	320
Iron, dissolved	.010	.130	0	.280	0	—	—
Iron, suspended	.830	.580	1.9	.110	.130	—	—
Iron, total	.840	.710	1.9	.390	.130	—	—
Magnesium, dissolved	15	18	13	24	13	22	69
Nitrate, NO as N	.01	—	.00	.00	—	—	—
Nitrite, NO as N	.00	—	.00	.00	—	—	—
Nitrogen, NH as N	.06	—	1.3	2.0	—	—	—
Nitrogen, total organic as N	.09	—	.92	1.3	—	—	—
Nitrogen, total as N	.16	—	2.2	3.3	—	—	—
pH	8.1	7.9	8.0	7.6	7.9	8.1	7.7
Phosphorus, total ortho as P	.01	—	.01	.00	—	—	—
Phosphorus, total as P	.02	—	.04	.02	—	—	—
Potassium, dissolved	3.0	10	16	24	3.0	7.7	36
Silica, dissolved	15	19	21	18	19	14	17
Sodium, dissolved	14	300	700	1,100	33	260	1,900
Specific conductance, µmho/cm	295	1.760	3.510	5,700	340	1.400	10,100
Strontium, dissolved	8.000	5.300	2.600	4.700	—	9.100	20.000
Sulfate, dissolved	4.0	26	4.7	.0	9.2	21	19
Turbidity, NTU units	7.0	—	10	5.0	—	—	—
Water temperature, °C	27.5	28.5	27.5	29.5	—	—	—

[1]Lower Floridan aquifer test well.
[2]Test well open to lower part of the Upper Floridan aquifer where no effective confining unit separates the Upper and Lower Floridan aquifers.

from the surficial sand-and-gravel aquifer, or the residuum, into the Floridan aquifer system. Where the relative positions of the water table and the potentiometric surfaces are reversed (the potentiometric surface is higher than the water table), water leaves the Floridan aquifer system through upward leakage. Additionally, overlying streams that penetrate the Floridan aquifer system may act as a source of recharge or as an area of discharge, depending on hydraulic head differences between the streams and the Floridan aquifer system.

The predevelopment distribution of recharge to and discharge from the Upper Floridan aquifer is shown on plate 8. Values of recharge and discharge were obtained by model simulations and water-budget studies. Downward leakage occurs in most inland areas; upward leakage occurs along and seaward of the coastal areas and along the flood plains of many streams.

Most of the annual recharge to and discharge from the Floridan aquifer system occurs in the thinly confined areas in the eastern half of the study area (generally east of Washington County, Fla.; pl. 8). In fact, this area accounted for about 94 percent of the total mean annual discharge of 1,175 billion gallons (based on field data and model simulations), mostly as discharge to springs or streams. (Refer to section "Ground-Water Flow Models," table 8, and pl. 24 for details of spring or stream discharge.) Because under predevelopment conditions a steady-state condition has been assumed, mean annual recharge to the Floridan aquifer system in the study area was equal to mean annual discharge.

The estimated predevelopment potentiometric surface of the Upper Floridan aquifer is shown on plate 9 (modified from Johnston and others, 1980). The general direction of regional ground-water flow is from north to south (or from the updip limit of aquifer system to coastal areas). In the eastern half of the study area, the potentiometric contours are strongly influenced by major streams that are hydraulically connected to the underlying Floridan aquifer system. The closed contour domes in Jackson and Calhoun Counties, Fla., represent local areas of exceptionally high recharge (compare pls. 8 and 9). Areas of high recharge, however, are not always indicated by closed contour domes on the potentiometric surface. For example, in parts of Baker and Dougherty Counties, southwest Georgia, recharge is exceptionally high (greater than 15 in per year), yet potentiometric contour lines in these areas follow the regional trend. This is because the higher transmissivities in these areas eliminate the need for steep hydraulic gradients to move greater volumes of ground water, and no recharge domes are developed.

The generalization that widely spaced potentiometric contour lines indicate areas of high transmissivity may not always apply to the Floridan aquifer system. Potentiometric contour lines are generally more widely spaced in the western part of the study area (pl. 9), where transmissivities are generally lower than in the eastern half (pl. 6). Contour spacing in the western half of the study area simply represents an area where ground-water flow is sluggish because of limited recharge and discharge coupled with low transmissivity.

PRESENT-DAY (1980) FLOW SYSTEM

The potentiometric surface of the Upper Floridan aquifer in the study area in May 1980 (pl. 10) is from a larger map showing the potentiometric surface of the entire Upper Floridan aquifer based on more than 2,700 water-level measurements made in wells generally open to the Upper Floridan aquifer (Johnston and others, 1981). Plate 10 represents the "average head" in the Upper Floridan aquifer. Refer to Hayes and others (1983) and Barr and others (1985), respectively, for more detailed maps showing recent potentiometric surfaces of the Floridan aquifer system in southwest Georgia and northwest Florida. Except for a cone of depression centered around the Fort Walton Beach, Fla., area (pl. 10) there seems to be little difference between the estimated predevelopment and the May 1980 potentiometric surfaces of the Upper Floridan aquifer in the study area.

Plate 11 shows the changes in the Upper Floridan aquifer's potentiometric surface from predevelopment time (estimated) (pl. 9) to May 1980 (pl. 10). Water levels measured in May 1980 in parts of Santa Rosa County, most of Okaloosa County, and the southwestern part of Walton County, Fla., are more than 20 ft below the estimated predevelopment level. Near the center of the cone of depression in the area of Fort Walton Beach, Fla., water levels have declined more than 140 ft. These declines have resulted from long-term pumpage which reached 15.5 Mgal/d in March 1978 in an area where aquifer transmissivity is low (250 to 15,000 ft^2/d) and the aquifer is overlain by a thick confining zone (Pensacola confining unit), thus limiting potential for induced vertical leakage.

Comparison of plates 9 and 10 suggests that May 1980 water levels in southeastern Jackson County, Fla., are 10 to 20 ft higher than estimated predevelopment levels. This apparent area of potentiometric buildup from predevelopment time to May 1980 may be attributable to several things: (1) the precipitation in April 1980 was unusually high, (2) the May 1980 potentiometric "high" as drawn may be in error because the "high" is based on only one data point, (3) estimates of the predevelopment potentiometric surface may be in error, or (4) a combination of some or all of the above. Because the validity and the possible cause of this head buildup is uncertain, it is not shown on plate 11.

With the exception of the two areas of water-level decline and head buildup described above, the estimated predevelopment and the May 1980 water levels are similar, even in southwest Georgia, where ground-water withdrawals for irrigation purposes were about 76 billion gallons in 1980. In southwest Georgia, the aquifer has high transmissivity (generally greater than 50,000 ft^2/d), is semiconfined by about 50 ft of sandy residuum (vertical hydraulic conductivity of about 0.02 ft/d), and is hydraulically connected to streams and lakes. These characteristics, along with the seasonal nature of pumping and mean annual recharge of about 10 in/yr (Hayes and others, 1983), have prevented permanent, long-term water-level declines.

SOUTHERN OKALOOSA AND WALTON COUNTIES, FLORIDA

Development of ground water from the Floridan aquifer system in southern Okaloosa and Walton Counties, Fla., prior to 1930 was mainly for domestic purposes. One of the earlier public-supply wells was reported to have been completed in 1920 at the Miramar Apartments in Fort Walton Beach to a depth of 692 ft. This was a flowing well; the artesian head at the time of well completion was reported by local residents to be 40 ft above land surface. During the period 1930 to 1940, a few additional public-supply wells were drilled into the Floridan aquifer system in southern Okaloosa County, and all of them were flowing wells. From 1940 to 1950, large-scale development of the Floridan aquifer system took place as new public-supply systems were constructed in the Fort Walton Beach metropolitan area and on Eglin Air Force Base. Later, development spread northward but remained relatively close to the coast, where the water demand was greatest.

The predevelopment potentiometric surface (pl. 9) shows a southeasterly slope of about 2.5 ft/mi in southern Okaloosa County, Fla., with natural discharge occurring to the Gulf of Mexico and possibly to Choctawhatchee Bay. Heads were 20 to 120 ft above sea level and commonly above land surface. Trapp and others (1977, p. 49–53) show that water levels declined more than 90 ft at Fort Walton Beach between 1942 and 1968 as a result of pumping. By 1980 the greatest point of decline (more than 240 ft) occurred south of Fort Walton Beach, along the coast. Declines in the Fort Walton Beach area are generally more than 100 ft, and declines in Walton County range from about 20 to 50 ft (pl. 11). Figure 12, which shows hydrographs of wells about 1.5 mi northeast and about 13 mi north of the center of pumping, illustrates the long-term declines of water levels in southern Okaloosa County. Note that water levels are still declining but that the rate of decline away from the center of pumping has lessened in recent years.

Plate 12 shows the potentiometric surface of the Upper Floridan aquifer in March 1978, with the distribution of simulated recharge and discharge for southern Okaloosa and Walton Counties. Pumpage in this area was 385 million gallons for March 1978, and water levels at the center of the cone of depression were 100 to 130 ft below sea level. The potentiometric surface in July 1978, when about 521 million gallons were withdrawn, shows that water levels had declined 20 to 30 ft below March levels at the center of the cone of depression (Wagner and others, 1980).

The direction of ground-water flow in southern Okaloosa and Walton Counties varies greatly from predevelopment time to March 1978 (compare pls. 9 and 12). The March 1978 potentiometric surface shows ground water flowing from the northeast, north, and northwest toward the centers of pumping near Valparaiso, Niceville, and Fort Walton Beach (pl. 12). During the predevelopment period, however, ground water was generally flowing coastward (pl. 9).

The distribution of recharge–discharge and water levels in the Upper Floridan aquifer in southern Okaloosa and Walton Counties was considerably different in March 1978 than in predevelopment time (compare pls. 8 and 12). During the predevelopment period, southern Okaloosa and Walton Counties were primarily areas of discharge from the Floridan aquifer system to the overlying sand-and-gravel aquifer, Choctawhatchee Bay, and the Gulf of Mexico. By 1978, however, pumping had lowered heads in the Upper Floridan aquifer below the heads in the sand-and-gravel aquifer and below sea level throughout much of the area. As a result, recharge to the Upper Floridan aquifer now occurs where discharge occurred in predevelopment time (compare pls. 8 and 12). Note that the area of ground-water discharge has been reduced to a small coastal section of Walton County.

The source of recharge to the Upper Floridan aquifer after development is primarily leakage from the overlying sand-and-gravel aquifer. Where the aquifer is confined by thick Pensacola Clay, it is possible that a minor fraction of recharge could be supplied by consolidation of the clay associated with reduction in heads.

Table 4 summarizes changes in distribution of recharge–discharge from predevelopment time to March 1978 in the Floridan aquifer system in the study area. According to simulation results, from predevelopment (January 1941) to March 1978, about 8.6 billion gallons (1.1 billion ft^3) of water were removed from storage with pumpage of about 147 billion gallons (19.7 billion ft^3). Consequently, contribution from storage accounted for only about 5.9 percent of the total pumpage. This compares well with estimates obtained from an analytical water-budget analysis by Trapp and others (1977), who stated that from 1942 to 1968 about 6 percent of the total water pumped was from aquifer storage. As can be seen in table 4, about 85 percent of water contributed from aquifer storage occurred prior to 1970. The contribution to pumpage from other than aquifer storage occurred from decreases of vertical leakage and lateral flow. Lateral inflow includes all water entering

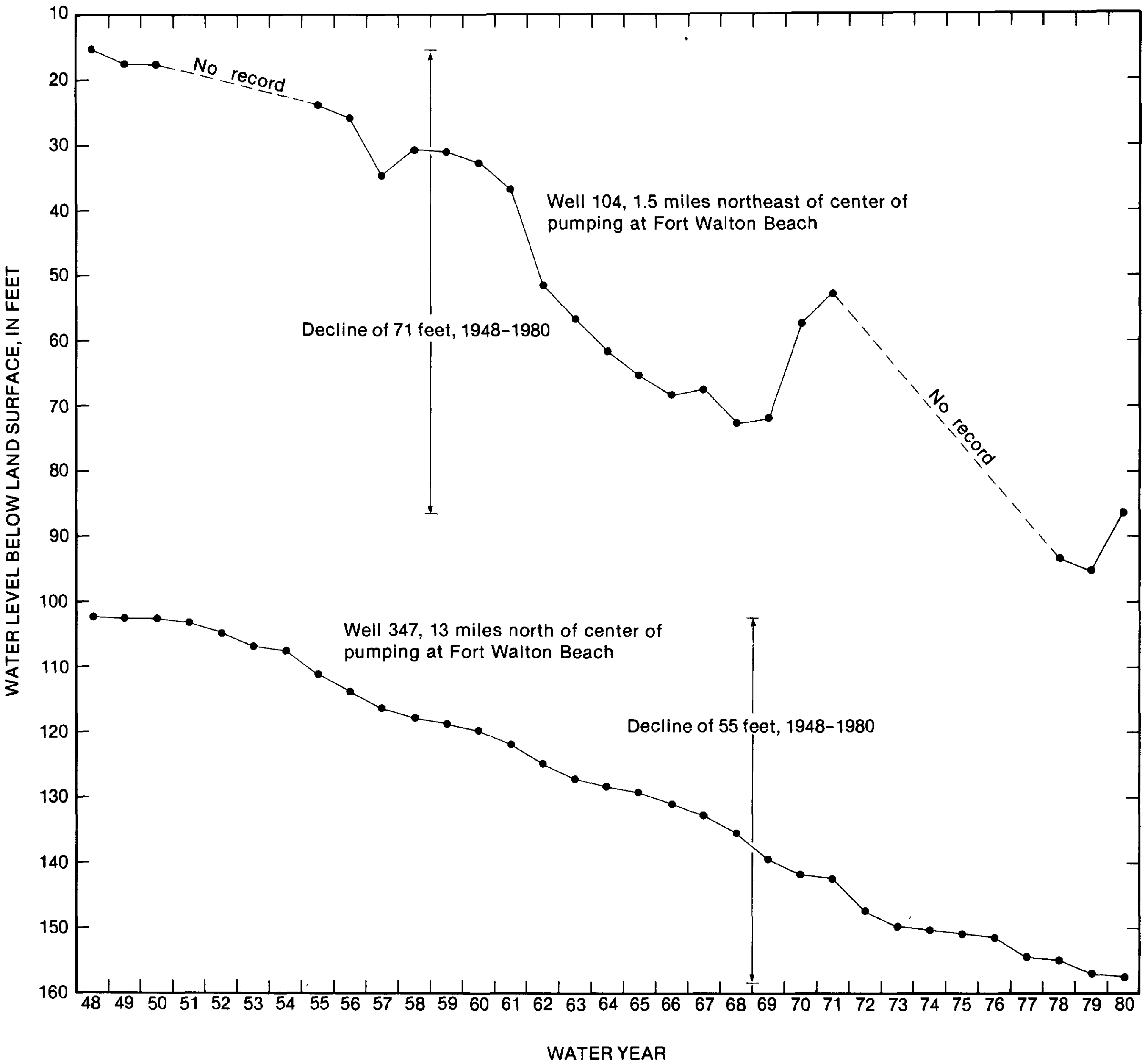


FIGURE 12.—Water-level hydrographs for water years 1948 to 1980 in the Upper Floridan aquifer, southern Okaloosa County, Florida. (See pl. 12 for location of wells.)

the aquifer and moving downgradient from the north into the study area and is a major contribution to the Floridan aquifer system study area. Lateral outflow from the study area is smaller now because of pumping.

Much of the recharge to the aquifer under present-day (March 1978) conditions is the vertical leakage from Choctawhatchee Bay through the Pensacola confining unit, which has been reduced in thickness by erosion. As discussed earlier, this poses a threat of saltwater contamination to the Upper Floridan aquifer.

SOUTHWEST GEORGIA

The 1980 potentiometric surface of the Upper Floridan aquifer in southwest Georgia (pl. 10) illustrates the major features of the flow system in the area.

TABLE 4.—*Simulated water budget of the Upper Floridan aquifer, southern Okaloosa and Walton Counties, Florida*

[Cubic feet per second]

Source terms[1]				Sink terms[1]			
Water removed from storage	Lateral inflow	Vertical leakage	Total	Lateral outflow	Pumpage	Vertical leakage	Total
January 1941 to December 1947[2]							
3.9	11.2	10.6	25.7	9.8	6.3	9.7	25.8
January 1948 to December 1970[3]							
0.4	14.4	13.8	28.6	5.1	18.0	5.6	28.6
December 1970 to March 1978[4]							
0.6	16.3	16.3	33.2	4.2	24.0	5.0	33.2

[1]Source terms and sink terms are mean values for the indicated period.
[2]Simulation period is 2,155 days.
[3]Simulation period is 8,395 days.
[4]Simulation period is 2,645 days.

Regionally, ground water within the aquifer flows from the northern part of the study area southward toward Lake Seminole. The shape of the potentiometric contours indicates, however, that major streams are principal areas of ground-water discharge. Base-runoff analyses and simulation results indicate that about 90 percent of the annual ground-water discharge occurs as discharge to streams and springs.

Except for irrigation use, very little development of ground water from the Upper Floridan aquifer has taken place in southwest Georgia. During years of average rainfall (for example, 1979), pumpage was a relatively small amount (5 to 10 percent) compared with recharge and natural discharge. Over the long term there has been little withdrawal from ground-water storage—as indicated by long-term hydrographs. However, seasonal head declines are significant owing to heavy pumpage for irrigation. The amount of the pumped water is largely balanced by reductions in ground-water discharge to streams (due to temporary reductions in head in the Upper Floridan aquifer). Ground water lost from storage during the summer pumping period is replaced during the winter recharge period.

In southwest Georgia, water level was measured in about 250 wells four times between November 1979 and April 1981. Maps showing the potentiometric surface of the Floridan aquifer system during the periods November 1-5, 1979 (Mitchell, 1981, pl. 2), May 12-16, 1980 (Hayes and others, 1983, fig. 25), November 3-7, 1980 (Watson, 1981, p. 2), and March 30-April 3, 1981 (unpublished), were constructed from these measurements. The May 1980 potentiometric surface of the aquifer reflects high water levels following late-winter through early-spring recharge. Water levels are generally about 10 ft lower in November than in May because of seasonal summer declines. March, April, and May water levels usually are about the same. However, because of a drought beginning in June 1980 and lasting through the summer of 1981, March 30-April 3, 1981, water levels were generally 10 to 20 ft lower than May 1980 levels (Hayes and others, 1983, fig. 27). The small amount of rainfall between June 1980 and April 1981 was not enough to recharge the aquifer to its normal seasonal high, and water levels remained at about the November 1980 seasonal low.

Seasonal water levels in wells in areas of high transmissivity (about 75,000 ft^2/d) normally fluctuate about 5 ft, whereas water levels in wells in areas of moderate transmissivity (about 15,000 ft^2/d) normally fluctuate about 10 ft (Hayes and others, 1983, fig. 28).

In southwest Georgia, base-flow analyses and simulation results (Hayes and others, 1983) indicate that present-day (1979-80) mean annual recharge to the Floridan aquifer system is about 2,200 Mgal/d (3,400 ft^3/s), whereas late-summer recharge is 1,400 Mgal/d (2,200 ft^3/s). Recharge to the aquifer varies considerably with location, however, because of the highly variable leakance of the residuum. For example, simulation results indicate that recharge varies from about 0.1 to 2 $(Mgal/d)/mi^2$.

Hydrograph separation techniques (discussed previously) indicate that annual mean ground-water discharge to streams from the residuum (which is very small) and the Floridan aquifer system in southwest Georgia is about 2,600 Mgal/d (4,000 ft^3/s) and that late-summer mean discharge is about 1,500 Mgal/d (2,300 ft^3/s). Annual mean ground-water discharge, which is about 950 billion gallons, is thus more than 10 times the 1980 pumpage of 82 billion gallons (76 billion gallons for irrigation and 6 billion gallons for all other uses). As with recharge, discharge varies considerably with both areal location in southwest Georgia and time of year. (See section on "Base Flow.")

WATER USE

The Floridan aquifer system is the major source of water for all uses throughout the study area except some coastal areas of northwest panhandle Florida, where the system contains saline water. Total withdrawals in the study area were about 90 billion gallons in 1980. Ground water is used primarily for irrigation, public supply, and industrial uses. Withdrawals for each type of use were inventoried for 1980 in northwest Florida by J.D. Hunn of the U.S. Geological Survey, and he prepared much of the following discussion. Water-use data for southwest Georgia were prepared by Hayes and others (1983) and by Pierce and others (1983).

NORTHWEST FLORIDA

In the northwest Florida part of the study area, the Floridan aquifer system is the principal source of water for all uses except in Santa Rosa and Escambia Counties. In Santa Rosa County, only 1 percent of the water used for public supply in 1980 came from the Floridan aquifer system. Almost all water in Santa Rosa and Escambia Counties is obtained from the sand-and-gravel aquifer that overlies the upper confining unit of the Floridan aquifer system. Okaloosa and Walton Counties use small amounts of water from the sand-and-gravel aquifer for irrigation and domestic supplies (Hayes and Barr, 1983).

The principal centers of pumping where withdrawal from the Upper Floridan aquifer is equal to or greater than 20,000 gal/d are shown on plate 13. The average rate of withdrawal for each pumping center in 1967, 1975, and 1980 is shown in table 5. The largest category of water use in 1980 was 21.5 Mgal/d for public supply. Industrial and irrigation uses in 1980 were 8.7 and 7.6 Mgal/d, respectively. Projections based on continuation of present trends indicate that water use from the Upper Floridan aquifer by the year 2000 may be about 50 Mgal/d, an increase of about 25 percent.

SOUTHERN OKALOOSA AND WALTON COUNTIES, FLORIDA

The daily average pumpage for municipal and military water systems in southern Okaloosa County increased from about 1.5 Mgal/d in 1940 to about 11.8 Mgal/d in 1968 (Trapp and others, 1977). By 1978, average water use had increased to 15.5 Mgal/d,

TABLE 5.—*Principal centers of pumping from the Upper Floridan aquifer, northwest Florida*

[J.D. Hunn, U.S. Geological Survey, written commun., 1983]

Identification No., plate 13	Type of use	Withdrawal, in million gallons per day		
		1967	1975	1980
1	Public supply	0.31	0.34	0.42
2	Industrial	.72	.30	.30
3	Public supply	.38	.46	.40
4	Industrial	.50	.50	.89
5	Public supply, Industrial.	.42	.46	.40
6	Irrigation	.11	1.02	1.33
7	Public supply, Industrial.	.31	.55	.51
8	Irrigation	.03	.23	.39
9	do.	.02	.15	.26
10	Public supply, Industrial.	1.72	1.21	1.57
11	Irrigation	.09	.65	1.10
12	do.	.14	1.05	1.77
13	do.	.14	.99	1.68
14	do.	.03	.23	.39
15	do.	.02	.12	.21
16	Public supply	.32	.35	.44
17	do.	.32	.37	.61
18	do.	.20	.15	.58
19	do.	.31	.50	.88
20	Public supply, Industrial.	2.91	1.04	.97
21	Industrial	2.80	.21	.35
22	Public supply	.51	1.25	2.11
23	Public supply, Industrial.	1.75	1.21	1.75
24	Irrigation	.27	.45	.49
25	Industrial	.26	.26	.26
26	Public supply	0	0	.29
27	do.	1.34	1.37	1.12
28	Public supply, Industrial.	4.92	6.58	5.43
29	Public supply	.16	.94	1.41
30	do.	1.00	1.96	3.76
31	do.	2.56	2.92	3.14
32	Public supply, Industrial.	1.04	1.55	1.75

representing an increase of 31 percent over the 10-year period from 1968 to 1978 (Wagner and others, 1980). Average daily water use in southern Okaloosa County can be expected to increase significantly and may exceed 20 Mgal/d by the year 2000 (Barr and others, 1981).

In southern Okaloosa County, about 95 percent of the ground-water withdrawals are made by nine public water systems: Fort Walton Beach, Okaloosa County, Eglin Air Force Base, Valparaiso, Niceville, Mary Esther, Seashore Village, Hurlburt Field, and the unincorporated area of Destin. Pumpage figures for these nine systems are given in table 6. Withdrawals vary seasonally and are generally highest in May, June, and July (the peak of the tourist season) and lowest in December, January, and February.

Okaloosa County presently operates 11 wells, 5 on Santa Rosa Island and 6 inland. All wells operated by the county withdraw water from the Upper Floridan aquifer and are the primary source of water for public supply for Santa Rosa Island and the communities of Wright, Ocean City, Shalimar, Cinco Bayou, and Longwood.

The county-operated wells on Santa Rosa Island have specific capacities of 1 to 3.5 (gal/min)/ft, the lowest of any public-supply wells in the study area, and yield about 300 to 400 gal/min. Owing to low specific capacity, the pumping drawdown in these wells would range from about 100 to 400 ft. The six inland wells have specific capacities ranging from 35.3 to 143 (gal/min)/ft and yield from 400 to 1,000 gal/min.

The city of Fort Walton Beach operates nine wells withdrawing water from the Upper Floridan aquifer, six in the main part of the city and three at the municipal golf course north of the city. Specific capacities of these wells range from about 4.4 to 72 (gal/min)/ft. Two wells in the southern part of the city have the lowest specific capacities, and wells at the golf course have the highest. Well yields range from about 600 to 900 gal/min.

The water supply for the main base and housing area of Eglin Air Force Base is supplied by 16 wells withdrawing water from the Upper Floridan aquifer. Hurlburt Field, west of Fort Walton Beach, is supplied by five wells open to the Upper Floridan aquifer.

TABLE 6.—*Summary of annual water use from the Upper Floridan aquifer, southern Okaloosa County, Florida*

[Pumpage in millions of gallons]

Location	1964	1965	1966	1967	1968	1969	1970	1971
Destin	—	—	—	—	—	—	—	—
Fort Walton Beach	777.2	854.8	880.3	965.9	1,200.0	1,010.1	1,012.0	1,079.2
Eglin Air Force Base	1,319.8	1,246.4	1,375.2	1,510.3	1,660.2	1,324.4	1,354.3	1,441.5
Hurlburt Field	247.0	237.6	259.5	237.1	265.0	252.7	269.2	268.0
Mary Esther	—	—	116.3	124.6	140.0	131.3	143.1	127.7
Niceville	—	—	—	—	—	—	—	—
Okaloosa County	—	—	—	—	—	—	—	—
Seashore Village	—	—	—	—	—	—	11.4	—
Valparaiso	—	—	—	—	—	—	—	—
Total	2,344.0	2,338.8	2,631.3	2,836.9	3,265.2	2,718.5	2,790.0	2,916.4

Location	1972	1973	1974	1975	1976	1977	1978
Destin	—	—	342.7	319.2	383.5	437.9	499.4
Fort Walton Beach	1,125.7	1,086.6	1,126.8	1,063.9	1,115.8	1,169.2	1,176.9
Eglin Air Force Base	1,859.1	1,761.1	1,652.8	1,701.5	1,537.4	1,442.3	1,205.2
Hurlburt Field	267.5	227.1	—	—	—	369.7	292.0
Mary Esther	133.0	109.3	122.6	139.7	163.0	187.7	181.9
Niceville	—	443.4	331.3	302.7	389.2	419.4	492.0
Okaloosa County	—	609.3	761.7	716.9	1,141.3	1,296.5	1,359.1
Seashore Village	—	45.6	94.3	160.5	—	107.6	92.9
Valparaiso	135.2	110.0	146.9	142.5	162.8	206.4	200.5
Total	3,520.5	4,392.4	4,579.1	4,546.9	4,892.8	5,636.7	5,499.7

All the auxiliary fields, except one in Santa Rosa County, and most of the miscellaneous test ranges and sites obtain all their water from the Upper Floridan aquifer. Specific capacities of the main-base and housing-area wells range from 19 to 56 (gal/min)/ft, but most of the wells are in the 30 to 40 (gal/min)/ft range. Well yields range from about 500 to 1,000 gal/min (A.N. Southard, U.S. Air Force, written commun., 1978).

Niceville, Valparaiso, Destin, Mary Esther, and Seashore Village (all of which obtain their water from the Upper Floridan aquifer) withdraw considerably less water than the three systems discussed above. Niceville currently operates five wells; Valparaiso has three wells; Destin has three wells; Mary Esther has two wells; and Seashore Village has two wells. Specific capacities range from about 3 to 25 (gal/min)/ft. Well yields range from about 150 to 800 gal/min.

SOUTHWEST GEORGIA

Ground-water withdrawals from the Upper Floridan aquifer in southwest Georgia for irrigation use increased from 47 billion gallons per year in 1977 to about 76 billion gallons in 1980 (H.E. Gill, U.S. Geological Survey, written commun., 1981). Pumping in southwest Georgia is not localized as it is in southern Okaloosa and Walton Counties, Florida. Rather, it is spread throughout a 15-county area of southwest Georgia (pl. 13). Because of constantly increasing irrigation use and the hydrologic drought that occurred from the summer of 1980 through the summer of 1981, irrigation withdrawals were estimated to have increased to about 107 billion gallons in 1981 during an extended 154-day irrigation season from May through October (Hayes and others, 1983). Ground-water use for irrigation is expected to continue to increase throughout the area as additional land is converted to farm use and farmers become more and more dependent on supplemental irrigation to ensure successful multicropping. Average yearly water use for all purposes other than irrigation is about 6 billion gallons. In the Dougherty Plain area of southwest Georgia, measured well yields range from about 40 to 1,600 gal/min (Hayes and others, 1983, table 11). Where transmissivity is high, well yields of 1,000 to 2,000 gal/min are common. Measured specific capacity of wells range from 4 to 1,000 (gal/min)/ft (Hayes and others, 1983, table 11).

GROUND-WATER FLOW MODELS

Three digital models were used to simulate ground-water flow in the study area: (1) a relatively coarse-mesh model of the entire study area intended to simulate major features of the flow system, (2) a fine-mesh model of the Dougherty Plain in southwest Georgia intended to simulate large-scale irrigation pumping, and (3) a fine-mesh model intended to simulate pumping in the Fort Walton Beach area. The coarse-mesh model is a subregional model related to a regional model of the entire Floridan aquifer system, as shown in figure 13. The regional model is discussed in Professional Paper 1403–C (Bush and Johnston, in press) as well as by Bush (1982), and the Dougherty Plain model is described by Hayes and others (1983). The coarse-mesh subregional model and the Fort Walton Beach model are described for the first time in this report. Although local differences in hydrogeology occur, all three models simulate the ground-water flow within the Floridan aquifer system.

CONCEPTUAL MODEL OF THE FLOW SYSTEM

A first step in designing a ground-water-flow model is developing a conceptual flow model. In this study, the Floridan aquifer system in southwest Georgia, northwest Florida, and southernmost Alabama was conceptualized as having two flow systems corresponding to the two areas of major pumping stress in the study area (pls. 10, 13). The flow system of the Upper Floridan aquifer that occurs in the area of the Dougherty Plain of southwest Georgia is semiconfined above by the weathered residuum and confined below by the impermeable lower part of the Lisbon Formation of the Claiborne Group (discussed previously). As shown in figure 14, the Upper Floridan aquifer is recharged by water moving vertically downward through the residuum semiconfining layer. Even without pumping, there is a vigorous flow system with high rates of inflow and outflow. Ground water is discharged to streams that are hydraulically connected to the aquifer, and to pumping wells.

In contrast, the Upper Floridan aquifer in southern Okaloosa and Walton Counties is confined above by the thick Pensacola confining unit, which allows some vertical water movement, and below by sediments of the upper part of the Claiborne Group, through which no significant vertical movement of water occurs (fig. 14). In comparison with southwest Georgia, the Upper Floridan aquifer here had very little ground-water inflow and outflow prior to the introduction of pumping. No major streams penetrate the Upper Floridan aquifer and, with the exception of Choctawhatchee Bay, little flow takes place between the surface-water-flow system and the Upper Floridan aquifer. Consequently, the major mechanism for aquifer discharge is pumping.

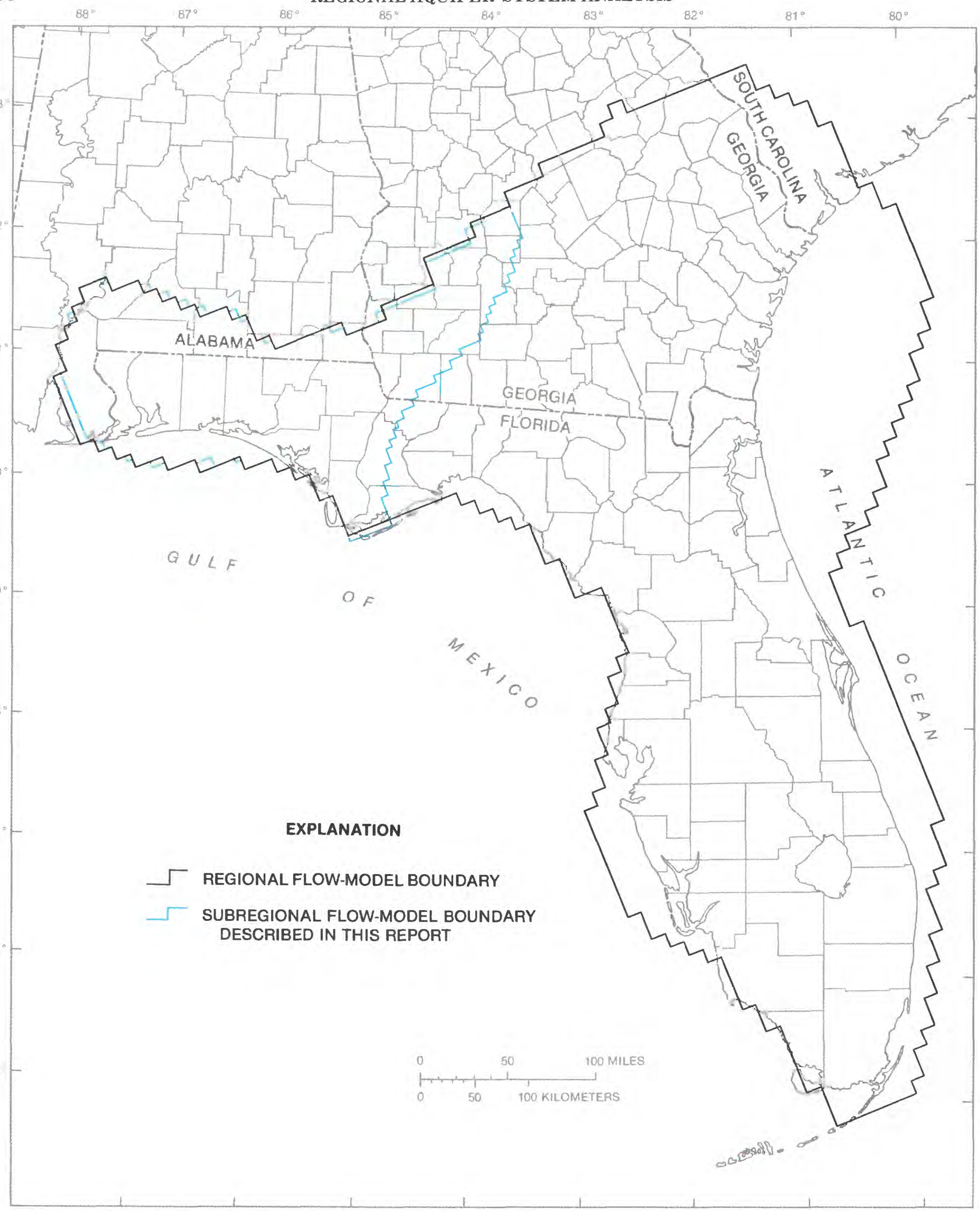


FIGURE 13.—Relation between subregional and regional flow models.

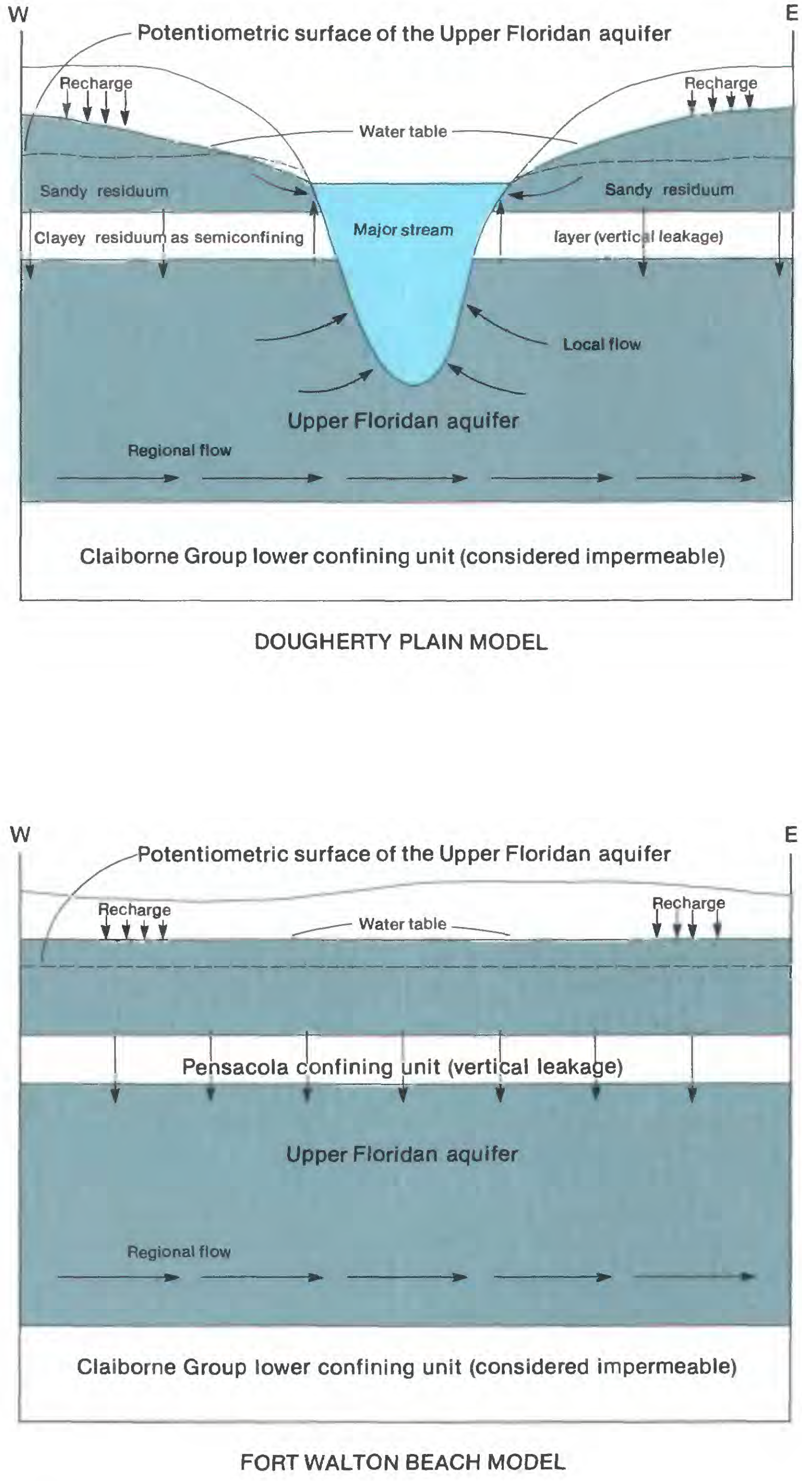


FIGURE 14.—Conceptual flow models of the Floridan aquifer system, southwest Georgia and southern Okaloosa and Walton Counties, Florida.

The rates of vertical leakage through the upper confining unit in southwest Georgia and southern Okaloosa and Walton Counties, Fla., may vary by several orders of magnitude. Leakance rates of the southwest Georgia residuum confining unit are much greater than corresponding rates in the Pensacola confining unit in southern Okaloosa and Walton Counties, Fla. For simulation, the aquifer is assumed to be isotropic and homogeneous in an individual cell block.

The lower confining unit is assumed to be impermeable in all models. In southern Okaloosa and Walton Counties, Fla., the Upper Floridan aquifer is separated from the Lower Floridan aquifer by the Bucatunna confining unit (fig. 9), which is considered impermeable. Therefore, in this area the Lower Floridan aquifer was not simulated. Elsewhere, the Upper and Lower Floridan act as a single aquifer hydrologically. Therefore, in these areas the Upper and Lower Floridan aquifers are grouped and termed the Upper Floridan aquifer.

NUMERICAL MODEL

MODEL DESCRIPTION

The numerical model used to simulate predevelopment, present, and future water levels in the Floridan aquifer system is a two-dimensional finite-difference model developed by Trescott and others (1976). The model uses a finite-difference approximation to evaluate the governing partial differential equations for two-dimensional (areal) ground-water flow. The mathematical and numerical development of the model is described in detail by Pinder and Bredehoeft (1968) and Trescott and others (1976). A detailed explanation of the calibration and application of the model in the Dougherty Plain area of southwest Georgia is described in Hayes and others (1983).

A two-dimensional-model approach was justified because lithologic and hydraulic data show that the Floridan, in both southwest Georgia and most of panhandle Florida, can be considered one limestone aquifer in which lateral flow predominates. During an extended drought, increased pumping in southwest Georgia causes a change from confined to unconfined conditions in the Upper Floridan aquifer. Therefore, the two-dimensional Trescott model, which simulates a change in aquifer status from confined to unconfined conditions, was used.

Three digital models were calibrated and subsequently used for evaluation of water-level declines due to stresses. The subregional model (SRM) of southwest Georgia, northwest Florida, and southernmost Alabama covers an area of approximately 20,000 mi^2 (pl. 14). The model is bounded on the east in southwest Georgia by the Pelham Escarpment (Hayes and others, 1983), on the west and north in southernmost Alabama by the updip limit of the Floridan aquifer system (Miller, 1986, pl. 25), and on the south by the Gulf of Mexico at the assumed intersection of the freshwater–saltwater interface with the top of the Floridan aquifer system (Bush, 1982). Additionally, the SRM boundaries were selected, in part, to coincide with the other subregional model boundaries (fig. 1). Within the SRM, more detailed flow models were developed for the two areas of major ground-water withdrawals: the Dougherty Plain model (DPM) for southwest Georgia and the Fort Walton Beach model (FWBM) for southern Okaloosa and Walton Counties, Fla.

The Dougherty Plain model extends over a 13-county area of southwest Georgia, covering an area of approximately 4,400 mi^2 (fig. 15). This model is bounded on the east by the Pelham Escarpment (coinciding approximately with the eastern boundary of the SRM), on the west by the Chattahoochee River, on the north by the updip limit of the Floridan aquifer system (coinciding approximately with part of the northern boundary of the SRM), and on the south by Lake Seminole, which is formed by impoundment of the Chattahoochee River by Jim Woodruff Dam. The discrepancies between the eastern and northern boundaries of the SRM and the DPM (pl. 14) occur because the DPM boundaries are based on a refined model scale justified by availability of more test-drilling data in the Dougherty Plain (Mitchell, 1981; Hayes and others, 1983).

The Fort Walton Beach model was developed to simulate ground-water flow in southern Okaloosa and Walton Counties in northwest Florida and covers an area of about 1,700 mi^2 (fig. 16). The model boundaries are not located along any physiographic or hydrologic boundaries as are the other model boundaries, except to the south, where the boundary coincides with part of the southern boundary of the SRM (pl. 14).

FINITE-DIFFERENCE GRIDS AND BOUNDARY CONDITIONS

The areal extent of the Upper Floridan aquifer modeled by the subregional model (SRM) was discretized using a 49-row by 69-column finite-difference grid with block-centered nodes, as shown on plate 14. Each side of a cell block throughout the grid has a length of 4 mi, with the node of the cell being located at the center of the block. For the SRM, the following boundary condition (pl. 14) was imposed:

On the eastern boundary, the Pelham Escarpment, which is a physiographic boundary, is assumed to approximate a ground-water divide generally based

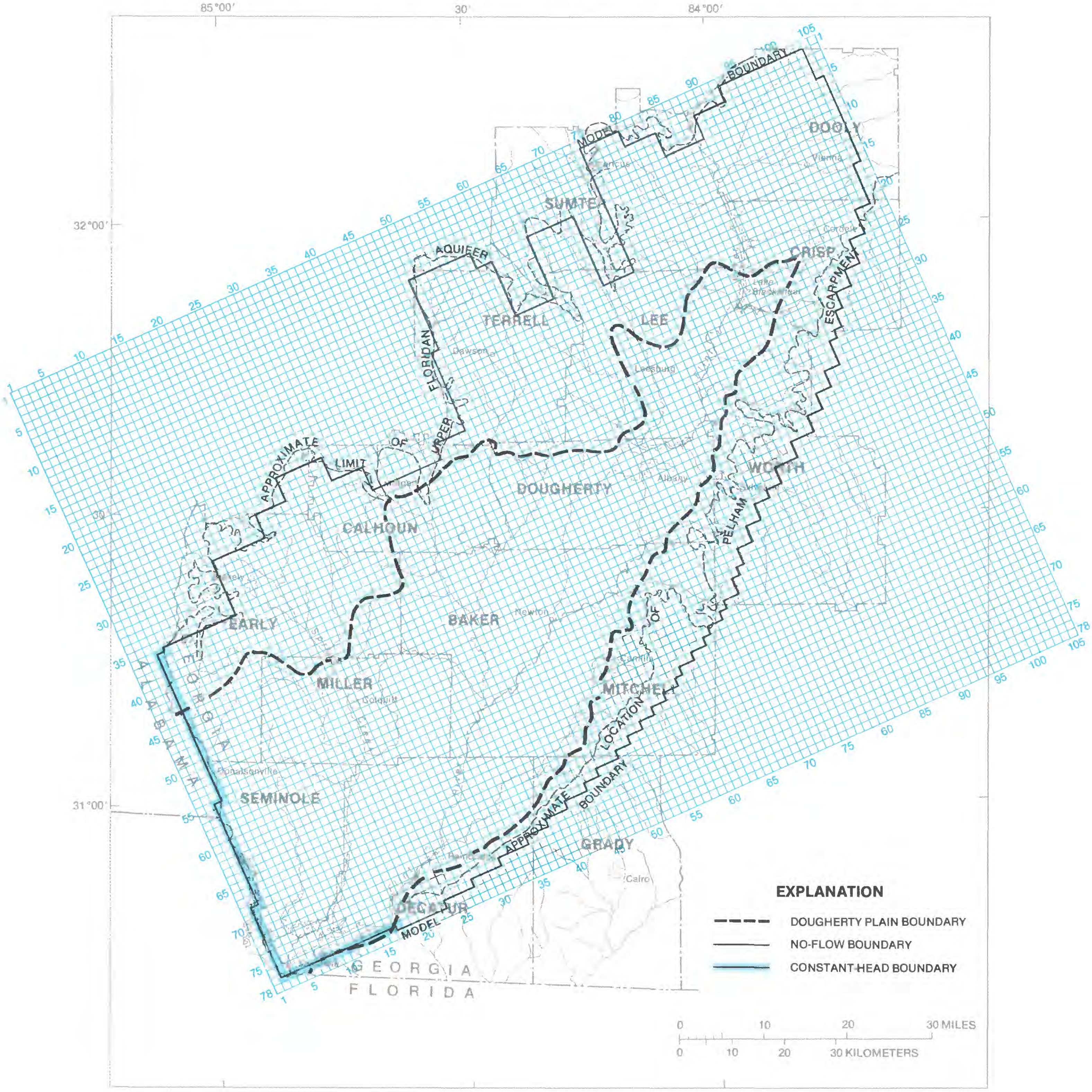


FIGURE 15.—Finite-difference grid and model boundary conditions for the Dougherty Plain model, Upper Floridan aquifer, southwest Georgia. From Hayes and others (1983).

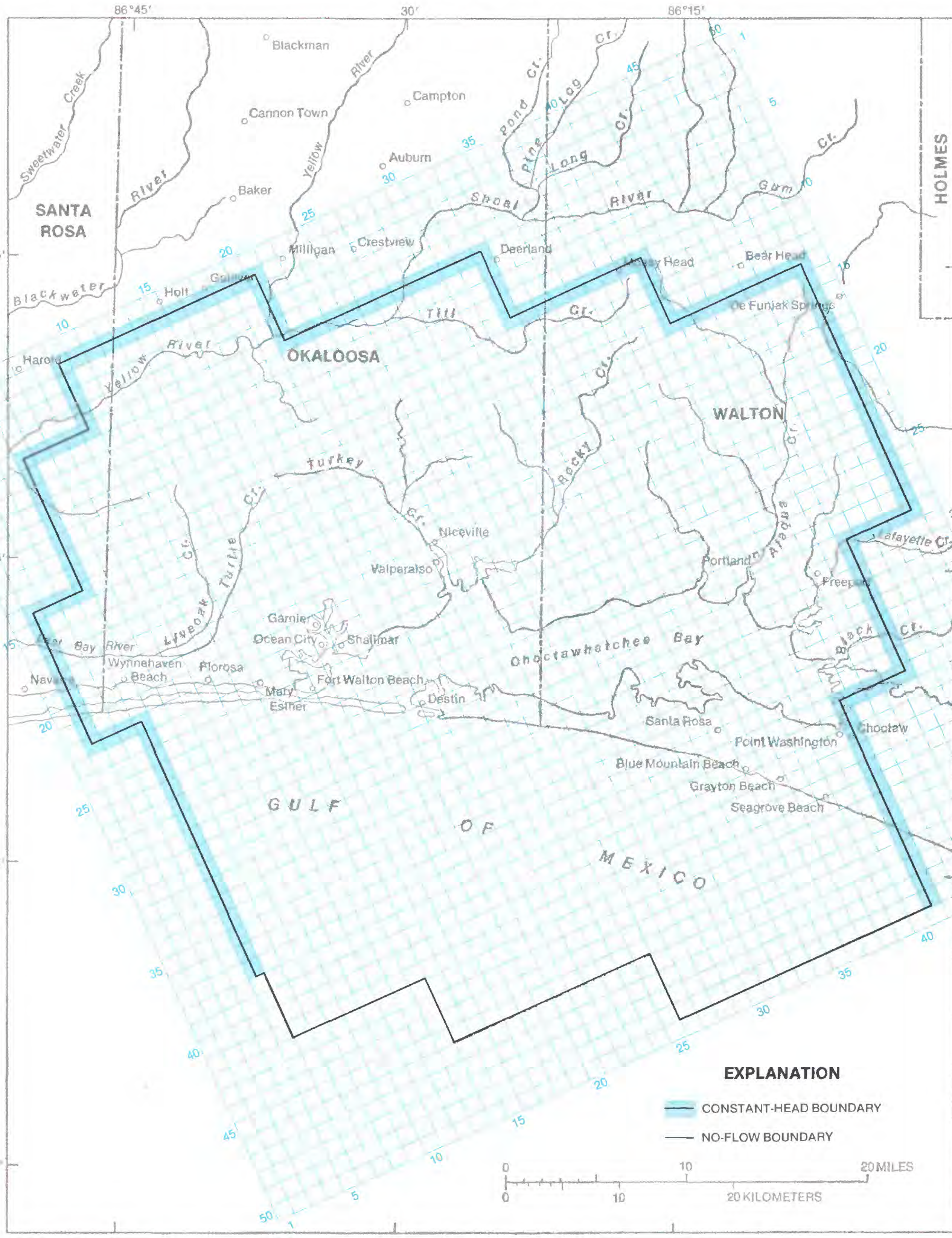


FIGURE 16.—Finite-difference grid and model boundary conditions for the Fort Walton Beach model, Upper Floridan aquifer, southern Okaloosa and Walton Counties, Florida.

on estimated predevelopment (Johnston and others, 1980) and existing potentiometric-surface maps (Johnston and others, 1981; Hayes and others, 1983) of the Upper Floridan aquifer. To the south of the Pelham Escarpment (but still on the eastern boundary of the SRM), the model boundary coincides with the surface-water divide and the coincident ground-water divide (based on potentiometric-surface maps of the Upper Floridan aquifer) between the Apalachicola and Ochlockonee Rivers. The northern boundary of the SRM coincides with the updip limit of the Upper Floridan aquifer. Finally, the western and southern boundaries of the model (which generally follow the coastal area of northwest Florida) are at the assumed intersection of the freshwater–saltwater interface and the top of the Upper Floridan aquifer and, thus, are assumed to be no-flow boundaries (Bush, 1982). Therefore, all the model boundaries of the SRM are no-flow boundaries.

The Dougherty Plain model (DPM) was constructed using a 78-row by 105-column grid, as shown in figure 15. Each cell block of the grid occupies an area of 1 mi^2 (1 mi in length per block side) throughout the grid. The following boundary conditions (fig. 15) were imposed on the DPM:

1. Constant-head boundary—In the DPM, the model boundaries coinciding with the Chattahoochee River (western boundary) and Lake Seminole (southern boundary) were assigned the water-level altitude in the water bodies as the constant-head values (pl. 14, fig. 15). These values ranged from 75 ft above sea level near Lake Seminole to 144 ft above sea level at the intersection of the Chattahoochee River and the northern boundary of the DPM. Analysis of historical stage levels for the Chattahoochee River coinciding with the western boundary and with Lake Seminole coinciding with the southern boundary indicate that the surface-water system and the Upper Floridan aquifer are in direct hydraulic connection, thus justifying a constant-head boundary.
2. No-flow boundary—The eastern boundary of the DPM coincides with the Pelham Escarpment (pl. 14, fig. 15), which is a physiographic and approximate ground-water divide that represents a no-flow line. The northern boundary of the DPM approximately coincides with part of the northern boundary of the SRM and is the updip limit of the Upper Floridan aquifer. Therefore, no-flow boundaries were assigned to the eastern and northern boundaries of the DPM.

The Fort Walton Beach model (FWBM) was constructed using a 50-row by 50-column grid, as shown in figure 16. Each cell block of the FWBM occupies an area of 1 mi^2 (1 mi in length per block side). The following boundary conditions (fig. 16) were imposed on the model:

1. Constant-head boundary—Constant-head values were imposed on the northern boundary (nodes 2,9 to 14,49 in fig. 16), the eastern boundary (nodes 15,49 to 49,41), and the western boundary (nodes 3,9 to 37,9). Head values along these boundaries were derived from March 1978 measured and estimated water levels of the Upper Floridan aquifer in southern Okaloosa and Walton Counties. Values ranged from 43 to 120 ft above sea level on the northern boundary, from 14 to 112 ft above sea level on the eastern boundary, and from 6 ft below to 42 ft above sea level on the western boundary.

   The reason for imposing the constant-head values along the model boundaries is that well data from about 1970 to March 1978 indicate that heads remained about constant near the boundary areas of the model. Admittedly, the application of a constant-head boundary condition may be inaccurate for the period of predevelopment to about 1970; however, the FWBM has been calibrated in a transient analysis against the March 1978 water levels (to be discussed later). Therefore, it is hoped that the apparent errors introduced in the early time periods of the simulation by imposing the constant-head boundaries (by assigning the head values derived from the March 1978 measured and estimated water levels) would be insignificant.

   Analysis of several water-level measurements from wells open to the Upper Floridan aquifer indicates the existence of approximate constant-head conditions—even in the interior of the modeled area—from 1970 to March 1978. For example,

- well 347 (reported by Wagner and others, 1980, p. 14) north of the headwaters of Turtle and Turkey Creeks in southern Okaloosa County (pl. 12) has maintained a water level of about 25 ft above sea level since about 1973;
- near the eastern boundary at Freeport in Walton County (pl. 12), well 270 (Wagner and others, 1980, p. 13) has maintained a water level of approximately 21 ft above sea level since 1974; and
- along the coast and eastern boundary in Walton County (pl. 12), well 10 (Wagner and others, 1980, p. 16) has maintained an approximately constant water level of 16 ft above sea level since 1968.

2. No-flow boundary—The southern boundary of the FWBM (pl. 14, fig. 16) is in the Gulf of Mexico at the assumed intersection of the freshwater-saltwater interface and the top of the Upper Floridan aquifer (Bush, 1982). At this boundary, ground-water movement is assumed to be negligible and a no-flow boundary was assigned along the southern boundary of the model.

These boundary conditions are reasonable on the basis of the conceptual viewpoint and are supported by the simulation results. They reflect current hydrogeologic conditions. At the time of the study, there were no known centers of major pumping near no-flow boundaries.

DATA REQUIREMENTS

Input data needed for model simulations are aquifer hydraulic properties and initial head conditions. For steady-state and transient simulations, aquifer transmissivity (*T*), vertical hydraulic conductivity of confining units (K'_v), thickness of confining units (b'), heads in the surficial aquifer above the upper confining unit, and stages of streams must be specified for each active cell block. (An active cell block is one in which transmissivity is greater than zero.) Initial head values (starting heads) must also be specified for each active cell block. Storage coefficients (*S*) or specific yield (*Sy*) values (for unconfined conditions) are required for each active cell block during transient simulations.

HYDRAULIC PROPERTIES

Hydraulic properties required for the SRM, DPM, and FWBM included aquifer transmissivity, confining unit leakance values, and altitude of water table in the overlying surficial aquifers. For simulating unconfined conditions (which may occur in southwest Georgia), data required were lateral hydraulic conductivity of the Upper Floridan aquifer, altitudes of the top and base of the Upper Floridan aquifer, and the specific yield of the aquifer materials. Hydraulic properties presented in this section and used in the models were derived by using regionalized field values (discussed in the section on Floridan aquifer system "Hydraulic Properties"; also see pls. 3–6), which were used as the initial input values. These values were adjusted during model calibrations (to be discussed in section on "Calibration Procedures"). These adjusted values then became the final calibrated values representing the regional hydraulic properties of the Upper Floridan aquifer. That is, where available, field data were used as initial input in deriving model-simulated values. Where field data were unavailable, lithologic data or even estimates derived on the basis of knowledge of the hydrogeology of the area were used to simulate the best calibrated hydraulic properties by the models. Where field data were of high quality and provided sufficient areal coverage, regionalized field values are very similar to the values obtained by model simulations (for example, compare the field transmissivity with the model-simulated transmissivity shown on pl. 6). For hydraulic properties for which field data were scanty (leakance data, pl. 3), regionalized field values and model-simulated values may differ. It should be noted that a cell block of the SRM contains 16 cell-block areas represented by the DPM and the FWBM. Therefore, the hydraulic properties in a cell block of the SRM are the averaged sums of the hydraulic properties of the 16 cell blocks of the DPM and the FWBM contained in the single cell block of the SRM.

Transmissivity values for the Upper Floridan aquifer used in the SRM ranged from 250 to 600,000 ft^2/d and were derived from aquifer-test data where available and aquifer thickness and model simulations where data were unavailable. Values are generally within acceptable limits of the aquifer-test data discussed previously. Transmissivity values in excess of 400,000 ft^2/d had to be used in the SRM in areas of known aquifer discharge to streams in order to simulate the measured or estimated amount of discharge from the Upper Floridan aquifer to the streams. Model cell blocks having an assigned value of transmissivity greater than 400,000 ft^2/d were few. Seepage-run measurements, as well as heads in the aquifer near the streams, generally agreed with the simulated values.

In the DPM, model transmissivity values ranged from 3,000 ft^2/d near the updip limit of the Upper Floridan aquifer at the northern end of the Dougherty Plain to 300,000 ft^2/d at the southern end of the Dougherty Plain (pl. 15). Model-simulated transmissivities (pl. 15) are similar to corresponding regionalized field transmissivity values (pl. 6).

In the FWBM, model transmissivity values ranged from 250 ft^2/d along the coast to 25,000 ft^2/d in the northwest part of the study area (pl. 16). Model-simulated transmissivity values in southern Okaloosa and Walton Counties, Fla., along with transmissivity values derived from aquifer-test values and specific-capacity data, are shown on plate 6. Model-simulated values closely agree with regionalized field values.

The SRM was not used to simulate transient conditions. Therefore, storage coefficients were not needed. Transient simulations were conducted only for areas of major pumping stress—southwest Georgia and southern Okaloosa and Walton Counties, Fla., areas using the DPM and the FWBM, respectively. In the

Dougherty Plain, point values of storage coefficients estimated from aquifer tests ranged from 2×10^{-4} to 3×10^{-2} but generally ranged from 1×10^{-4} to 1×10^{-3} (Hayes and others, 1983). For the DPM, an average value of 5×10^{-4} was used throughout the study area. A specific yield value of 2×10^{-1} was used when water levels in the Upper Floridan aquifer declined below the top of the aquifer owing to pumping during an extended drought period.

Point values of storage coefficients in southern Okaloosa and Walton Counties, Fla., estimated from aquifer tests ranged from 2×10^{-5} to 6×10^{-4} (Barr and others, 1981). For the FWBM, storage coefficient values were determined by using the product of specific storage and aquifer thickness (DeWeist, 1967, p. 185; Barr and others, 1984). Assuming a constant specific-storage value of 1×10^{-6} ft^{-1} (the compressibility of water), the storage coefficients used in the FWBM ranged from 5×10^{-4} to 9×10^{-4}, which are within an acceptable range in comparison with available data.

The vertical hydraulic conductivity and the thickness of the upper confining units in the SRM, DPM, and FWBM were combined into one parameter, called leakance and defined as

$$L' = K'_v/b',$$

where L' is the leakance (T^{-1}), K'_v is the vertical hydraulic conductivity of the confining unit (LT^{-1}), and b' is the thickness of the confining unit (L). Leakance used in the SRM was obtained from the averaged leakance values used in the DPM (Hayes and others, 1983, fig. 20) and the FWBM. In some cell blocks, the leakance used in the SRM had to be increased above the average values obtained from the DPM and the FWBM in order to simulate the measured or estimated amount of aquifer discharge to streams. The need to do this is attributed to the increased cell-block area of the SRM over that of the DPM and the FWBM. (See discussion of calibration of the SRM.) Leakance used in the SRM (pl. 3) ranged from 5×10^{-7} (ft/d)/ft in the southern Okaloosa and Walton Counties area, where the confining unit is thick and clayey, to greater than 5×10^{-4} (ft/d)/ft in southwest Georgia, where the confining unit is thin and sandy.

Data representing the altitude of the water table in the weathered residuum in southwest Georgia and the sand-and-gravel aquifer in southern Oklaloosa and Walton Counties, Fla., were obtained from data gathered by Hayes and others (1983, fig. 22) and by Hayes and Barr (1983, fig. 9). These data were used as model input for the DPM and the FWBM. Values of water-table altitude in the area of southwest Georgia and southern Okaloosa and Walton Counties, Fla., of the SRM were obtained from the averaged water-level values simulated by the DPM and the FWBM, respectively. In cell blocks simulating the aquifer/surface-water interactions (referred to as "river nodes"), the input head values were the mean water-surface altitudes of the stream obtained from 1:24,000-scale topographic maps and from stream-gage data.

In the predevelopment calibration of the SRM as well as in the steady-state calibration of the DPM, estimated "late-summer" water-table altitudes occurring under average annual rainfall conditions (Hayes and others, 1983, fig. 22) were used as input head data. In transient simulations, estimated water-table values used in the DPM were varied seasonally to approximate conditions at the beginning, middle, or end of irrigation periods. A detailed description of the values of water-table altitude and the method used to vary them during a transient simulation in the DPM is given by Hayes and others (1983).

In the southern Okaloosa and Walton Counties, Fla., area of the SRM and in the FWBM calibrations, the mean 1978 water-table altitudes in the sand-and-gravel aquifer were used as input data (Hayes and Barr, 1983, fig. 9). The mean 1978 water-table altitudes were used in the Fort Walton Beach area because the water-table altitudes have not varied significantly over time (Barr and others, 1985). Thus, the water-table values in the Fort Walton Beach area were not varied in transient and steady-state simulations using the FWBM and the SRM.

Values of water-table altitudes used in the SRM ranged from sea level in the coastal areas of northwest Florida to greater than 300 ft above sea level at the updip limit of the Upper Floridan aquifer in southwest Georgia. In the Dougherty Plain area of the SRM, the averaged cell-block values of the 1979 water-table altitudes used in the DPM (steady-state conditions) were input to the SRM (which was calibrated under steady-state conditions). In the Fort Walton Beach area of the SRM, the averaged cell-block values of the 1978 water-table altitudes used in the FWBM were used as input. For detailed discussions of water-table altitudes in the Dougherty Plain and Fort Walton Beach areas, refer to Hayes and others (1983) and Hayes and Barr (1983), respectively.

During periods of drought and heavy withdrawals from the Upper Floridan aquifer in the Dougherty Plain area, the potentiometric surface locally declines below the top of the Upper Floridan aquifer and an unconfined condition occurs. To simulate an unconfined aquifer in the model, four additional parameters were needed as input data:

1. lateral hydraulic conductivity of the Upper Floridan aquifer in the Dougherty Plain—These

values were determined by dividing the transmissivity by the estimated thickness of the Upper Floridan aquifer for each cell block.
2. altitude of the top of the Upper Floridan aquifer—These values were obtained from a structure contour map of the top of the Upper Floridan aquifer in the Dougherty Plain by Watson (1981).
3. altitude of the base of the Upper Floridan aquifer—These values were obtained from a structure contour map of the top of the Lisbon Formation in the Dougherty Plain area (Watson, 1981).
4. specific yield of the Upper Floridan aquifer—Because of the large solution channels occurring in the Dougherty Plain, a value for specific yield of 0.2 was assigned to each active cell block.

INITIAL CONDITIONS

Initial head values are required as input data for each active cell block in all models. A predevelopment potentiometric surface map of the Upper Floridan aquifer developed by Johnston and others (1980) provided initial heads used in the SRM. Initial heads in the DPM were based on a November 1979 potentiometric surface map of the Upper Floridan aquifer in southwest Georgia (Mitchell, 1981, pl. 2). These heads represent average late-summer hydrologic conditions. Hydrographs indicate that approximate steady-state conditions persist for some time following cessation of the water-level declines in summer (Hayes and others, 1983, figs. 39, 40).

Initial heads in the FWBM were estimated from a few pre-1941 head values. Prior to the start of large-scale ground-water withdrawals at Fort Walton Beach in 1941, steady-state conditions prevailed. Outside the pumping center, quasi-steady-state conditions prevailed into the late 1940's (fig. 12). These heads are acknowledged to be inaccurate on a node-by-node basis in southern Okaloosa and Walton Counties, Fla. Nevertheless, because the model was being calibrated against March 1978 water levels by using a transient simulation, a regional estimate of the initial head values prior to 1941 was considered reasonable for the transient calibration processes.

CALIBRATION PROCEDURES

The purpose of model calibrations is to adjust and refine data on hydrologic properties within acceptable limits until estimated flow conditions can closely approximate observed field conditions. Principal factors affecting model calibration include the distribution and quality of input data. During model calibrations a decision must be made as to whether sufficient calibration can be achieved in steady-state simulations or whether the flow model needs to be further calibrated by transient simulation if pumping data are available. In this study, the predevelopment calibration of the SRM was obtained through a steady-state simulation. However, to improve the calibration in areas of major pumping stress, the southern Okaloosa and Walton Counties, Fla., area of the SRM was improved through a transient simulation (January 1941–March 1978) using the FWBM. Additionally, the southwest Georgia area of the SRM was further improved by a steady-state calibration (November 1979) using the DPM. The DPM calibration was further tested by a transient simulation (May–November 1980). Refined data on hydrologic properties resulting from calibrations of the DPM and the FWBM were averaged and then used as input data for the SRM to obtain a better predevelopment steady-state calibration. The calibration process is shown graphically in figure 17 and is discussed below.

1. Initial estimates of hydrologic properties were input to the SRM.
2. Hydrologic properties in areas of major pumping stress were modified and refined by simulations using the DPM and the FWBM.
   - In southwest Georgia data on hydrologic properties were improved through the assumed steady-state conditions reflected by the potentiometric surface obtained in November 1979 using the steady-state calibration of the DPM. Without revision of the calibrated hydrologic-property data, the DPM was tested by a transient simulation from May to November 1980.
   - In southern Okaloosa and Walton Counties, Fla., estimates of hydrologic properties were improved through a transient calibration from January 1941 to March 1978 using the FWBM.
3. The refined hydrologic parameters obtained from calibration of the DPM and the FWBM were averaged and input into the SRM.
4. The predevelopment steady-state calibration of the SRM was then completed.

In all of the models, an acceptable calibration required the mean head difference between the simulated heads and the heads derived from potentiometric surface maps based on measured or estimated water levels (absolute head difference) to approach zero. Henceforth, this will be referred to simply as "difference." Further, a standard deviation of ±5 ft of the head difference was assumed. Assuming that the head difference is a normal distribution function (for example, see Hayes and others, 1983, fig. 35), then the described calibration conditions would ensure that 95

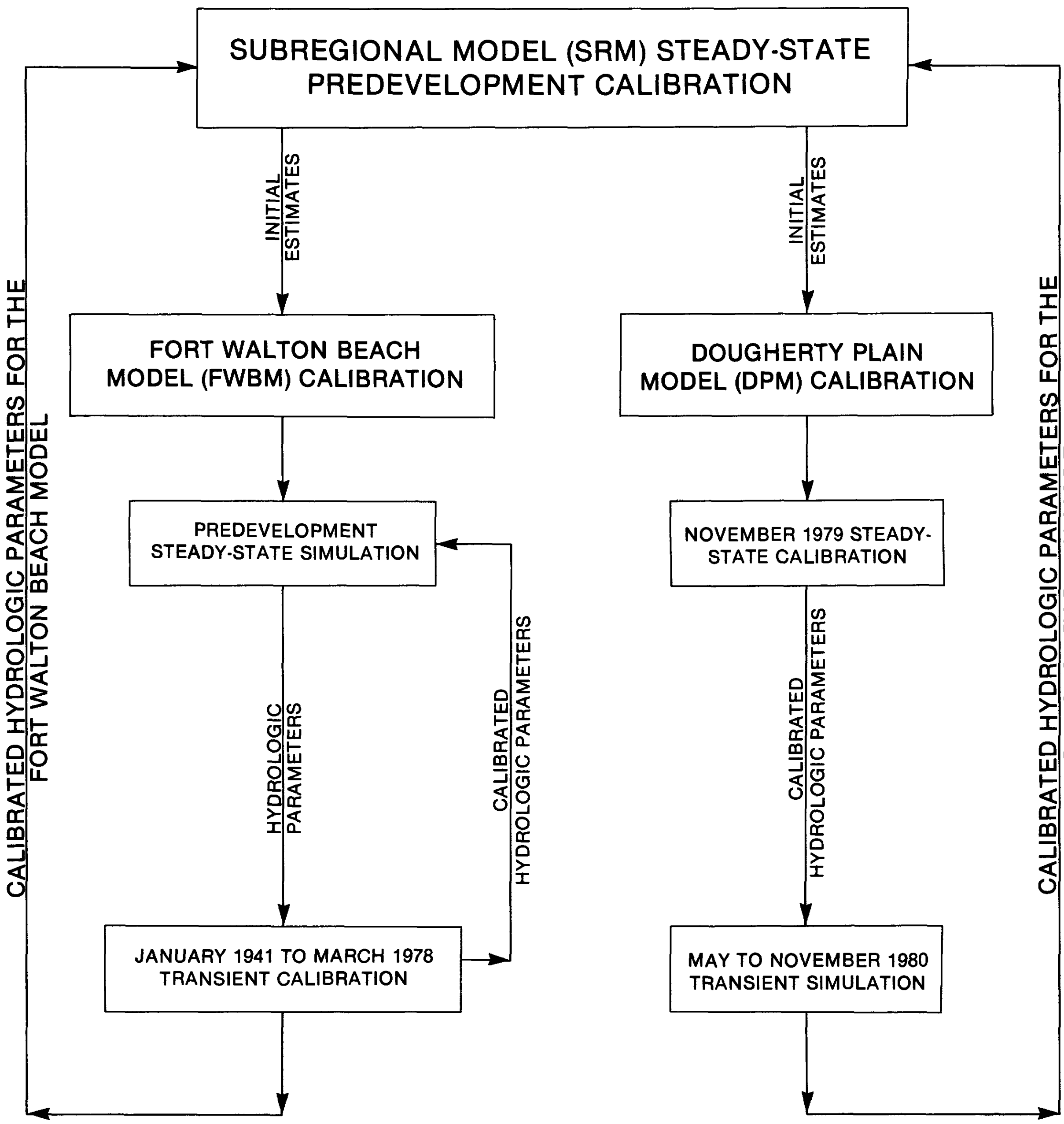


FIGURE 17.—Predevelopment calibration process for the subregional model.

percent of the simulated heads would be within ±10 ft of the heads described by the potentiometric maps. In areas where head data were unknown or could not be extrapolated from the potentiometric maps with any degree of confidence (such as in the Gulf of Mexico offshore from Fort Walton Beach), simulation differences were not used in the computation of mean head difference and standard deviation.

DOUGHERTY PLAIN MODEL CALIBRATION

The Dougherty Plain model was calibrated for the assumed steady-state conditions reflected by the potentiometric surface of the Upper Floridan aquifer obtained in November 1979. The calibrated parameters were further tested by a transient simulation for the irrigation season of May 15–November 5, 1980.

Because no adjustments were made in the steady-state calibrated hydrologic-property data during the transient simulation (with the exception of residuum water-table altitudes, which fluctuate seasonally, as explained in the section on "Hydraulic Properties"), the steady-state calibrated hydrologic-property data were believed to be acceptable within the limits of the model. The calibration of the DPM is summarized below and is described in detail in Hayes and others (1983).

NOVEMBER 1979 STEADY-STATE CALIBRATION

Aquifer transmissivity, confining unit leakance, and the altitude of the water table in the residuum were adjusted during the calibration. Calibrated transmissivities (pl. 15) were not varied much from the initial values estimated from aquifer tests (pl. 6). Leakance was varied more than transmissivity during the calibration. However, a check was conducted to ensure that simulated leakance values were in general agreement with leakance values derived from lithologic data. Additionally, input leakance values were checked to ensure that unrealistic values of areal recharge were not being simulated by the model. Based on the areal coverage and the availability of data, water-table altitude (Hayes and others, 1983, fig. 22) was the least accurately known aquifer parameter. Therefore, this parameter was adjusted the most. In the calibrated model, water-table-altitude data were checked to ensure that they were below land surface and above the top of the Upper Floridan aquifer and that they generally agreed with stream stages.

A map comparing measured water levels for November 1979 and the simulated steady-state potentiometric surface is shown on plate 17. The average simulation difference was computed to be 0.6 ft and the standard deviation of the head difference was computed as 4.6 ft. This was within the assumed calibration limits, which required 95 percent of all simulated heads to be within ±10 ft of the heads derived from measured water levels.

The distribution of the absolute head difference over the DPM area (difference between input heads and simulated heads) is shown on plate 18. The areas of greatest difference are at points of aquifer discharge along the Flint River and other streams. Because of the model requirement of having to dedicate an entire cell-block area as a discharge point in order to simulate the aquifer discharge to a stream, although less than 5 percent of the cell-block area may actually be discharging to the stream, the head difference in the discharging cell blocks and in some adjacent cell blocks could not meet the established calibration limits. However, these cell blocks were few and did not distort the overall calibration.

The flow model also was used to simulate ground-water discharge to streams. Ground-water discharge to streams in the Dougherty Plain was simulated as 2,200 ft^3/s for the November 1979 simulation. Late-summer (September–November) base runoff for water years 1959–70 for the Floridan aquifer system in southwest Georgia was estimated by hydrograph separation techniques as about 2,300 ft^3/s. (See section on "Base Flow.") Consequently, the simulated discharge compares well with the estimated discharge.

MAY-NOVEMBER 1980 TRANSIENT SIMULATION

The transient simulation analyzed the effects of municipal, industrial, and agricultural pumping on water levels in the Upper Floridan aquifer. The time period was simulated in three stages: (1) May 15–31, 1980, 17 days; (2) June 1–September 15, 1980, 107 days; and (3) September 16–November 5, 1980, 51 days. Municipal and industrial pumpage of 6 billion gallons per year was simulated during all three time periods. Agricultural withdrawals of 76 billion gallons were simulated during the second time period (the main irrigation period in southwest Georgia for 1980). All pumping within a 1-square-mile cell block was assumed to take place at the center of the cell block. Thus, several irrigation systems within a 1-square-mile cell block were aggregated and represented as one pumping center in the cell block. A detailed discussion of digital simulation of the agricultural pumping in southwest Georgia is presented in Hayes and others (1983).

Measured water levels for November 1980 compared with the simulated potentiometric surface at the end of the transient simulation are shown on plate 19. The average head difference for the November 1980 simulation was computed as 0.2 ft, with a standard deviation of head difference of 3.4 ft. Since this was within the assumed limits established for the DPM, the transient simulation indicated that the hydrologic parameters derived during the steady-state calibration were acceptable. Simulated water-level fluctuations for four wells in the Dougherty Plain, from May 15 to November 5, 1980, compare acceptably with measured water levels for the same period (fig. 18).

SENSITIVITY OF CALIBRATED AQUIFER PARAMETERS

Transmissivity (*T*), confining-unit leakance (*L*), and water-table altitude (*W*) were varied from the steady-state calibration values to determine the sensitivity of

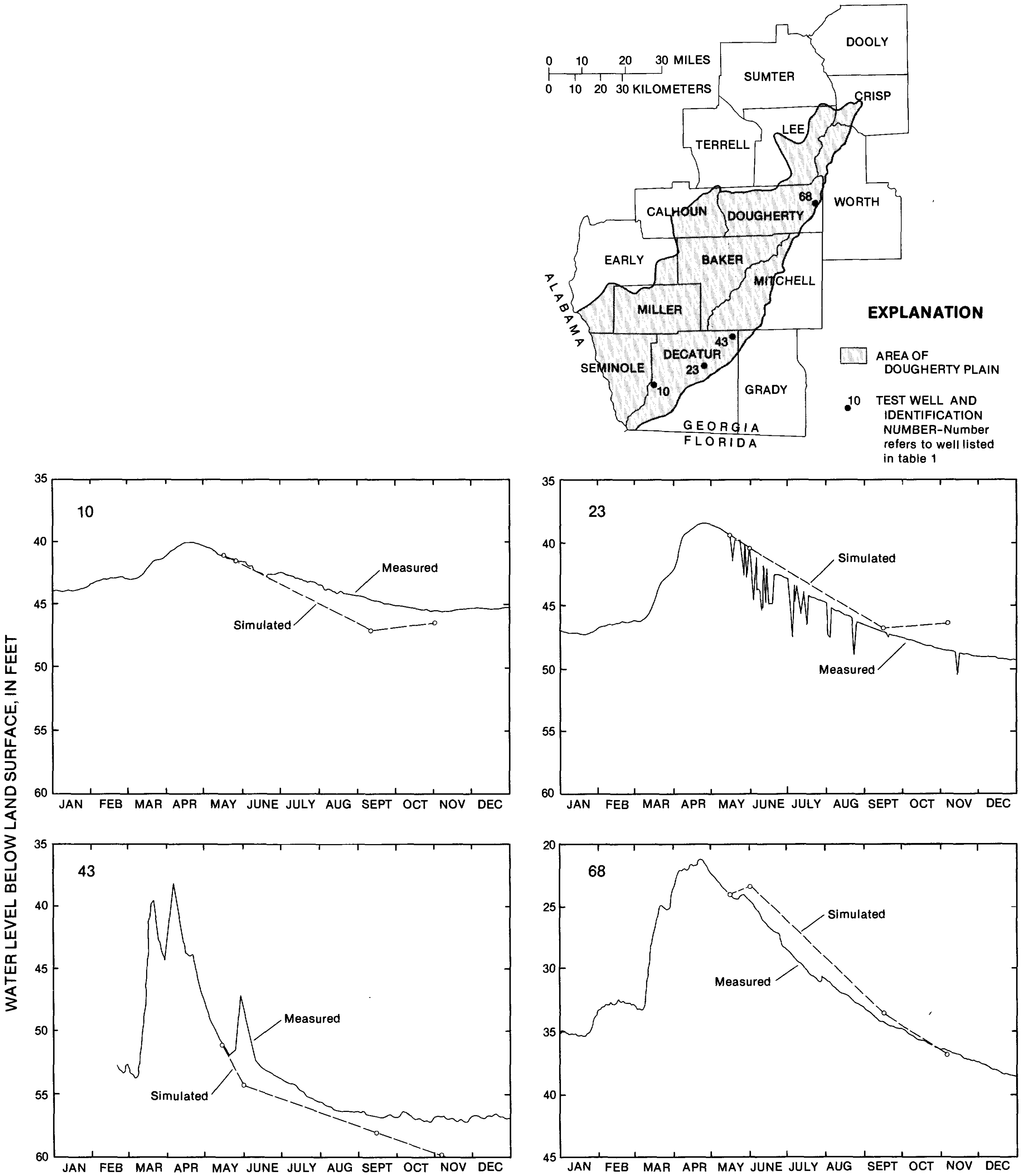


FIGURE 18.—Measured and simulated water levels for selected wells, Upper Floridan aquifer, southwest Georgia. From Hayes and others (1983).

the digital model to variations in each aquifer parameter (table 7). After each simulation, by using the varied parameters, the average head difference and standard deviation of the head difference were computed. Table 7 shows average simulated head difference, standard deviation of the head difference, and ground-water discharge for the calibrated and the varied aquifer parameters. Although several of the sensitivity runs were within the assigned limits of head differences, only the calibrated aquifer parameters simulated an accurate water budget. Thus, it has been shown that to duplicate flow conditions in southwest Georgia within the assigned error limit, the digital model must be able to duplicate the observed heads and discharge to streams.

The hydrologic parameter most sensitive to change is water-table altitude, as shown in table 7. This indicates that to further refine the calibrated hydrologic parameters, additional water-table data are needed. Further, it is an indication of the effect changes in the water-table altitude have on the potentiometric surface of the Upper Floridan aquifer in southwest Georgia. By changing water-table altitudes, the model could be used to simulate drought conditions (lowered water-table altitude and, hence, reduced recharge to the Upper Floridan aquifer) in southwest Georgia. This will be discussed in the section on "Potential for Ground-Water Development Based on Simulations."

FORT WALTON BEACH MODEL CALIBRATION

To calibrate the FWBM for predevelopment steady-state conditions, a potentiometric surface existing prior to 1941—the time when large-scale ground-water withdrawals were initiated at Eglin Air Force Base—was required. Initially, the hydrologic parameters of the FWBM were calibrated against the estimated regional predevelopment potentiometric surface (prior to 1941) of the Upper Floridan aquifer (Johnston and others, 1980). However, during the subsequent transient simulation for January 1941 to March 1978, when pumping was increased to the 1978 level of 15.5 Mgal/d, it became apparent that the hydrologic parameters of the FWBM calibrated on the basis of the estimated regional predevelopment potentiometric surface (prior to 1941) needed further refinement. After the hydrologic parameters of the FWBM were calibrated for transient conditions, the model was used to simulate the predevelopment potentiometric surface prior to 1941 by removing all pumping stresses. The final predevelopment potentiometric surface shown on plates 9 and 22 is based on additional head data (1942 and 1947) as well as on simulation.

TABLE 7.—*Response of the Dougherty Plain model to changes in transmissivity* (T), *confining-unit leakance* (L), *and water-table altitude* (W)

Run number	Hydrologic parameter	Average head difference,[1] in feet	Standard deviation of head difference in feet	Simulated ground-water discharge, in cubic feet per second (inches per year)	
C[2]	*T, L, W*	+0.6	4.6	2,207[3]	(6.4)
1	0.25*T, L, W*	-2.0	4.4	934	(2.7)
2	0.50*T, L, W*	-.9	4.2	1,458	(4.2)
3	2.0T, *L, W*	+2.6	5.7	3,213	(9.3)
4	4.0*T, L, W*	+5.4	7.7	4,491	(13.0)
5	*T,* 0.25*L, W*	+5.4	7.7	1,127	(3.3)
6	*T,* 0.50*L, W*	+2.7	5.7	1,610	(4.6)
7	*T,* 2.0*L, W*	-.8	4.2	2,817	(8.1)
8	*T,* 4.0*L, W*	-2.0	4.4	3,700	(10.7)
9	*T, L,* 0.8*W*	+38.2	18.0	3,056	(8.8)
10	*T, L,* 1.2*W*	-37.0	18.0	3,943	(11.4)

[1]Head difference between the simulated heads and heads of November 1979.
[2]Calibrated hydrologic parameters for November 1979 head conditions.
[3]Estimated ground-water discharge, 2,300 ft^3/s (Hayes and others, 1983).

JANUARY 1941 TO MARCH 1978 TRANSIENT CALIBRATION

To accurately simulate water levels of the Upper Floridan aquifer in southern Okaloosa and Walton Counties, Fla., information on location of pumping wells and pumpage was needed. These data were obtained from U.S. Air Force records and from municipal records of towns in the Fort Walton Beach area (Wagner and others, 1980; A.N. Southard, U.S. Air Force, written commun., Aug. 1982).

Transient calibration for the period January 1941 to March 1978 was conducted by using three pumping periods. The number and duration of the pumping periods were determined after analysis of pumping records. The first pumping period was from January 1941 to December 1947 (2,155 days). The average pumping rate was estimated to be 4.1 Mgal/d during this period. Most of the ground-water withdrawals occurred at Eglin Air Force Base, beginning with the onset of World War II. Toward the end of 1947, however, significant withdrawals were taking place in Fort Walton Beach, Mary Esther, Shalimar, and other locations throughout Okaloosa County. As with the DPM, all pumpage from wells located within a 1-square-mile cell block was summed and represented as a single pumping well located at the center of the cell block.

The second pumping period began in January 1948 and ended in December 1970 (8,395 days). For this period, an average pumping rate of 11.6 Mgal/d was used. Pumpage during this period was generally constant at Eglin Air Force Base but increased at Fort Walton Beach, Mary Esther, Niceville, and Okaloosa

County and was initiated at Sea Shore Village, Valparaiso, Destin, and Freeport.

The third pumping period began in January 1971 and ended in March 1978 (2,645 days). During this period, the major increases in pumpage took place in Niceville, Fort Walton Beach, and Destin. These increases were due primarily to the seasonal and expanding tourist industry in these cities. Other increases in withdrawals occurred at selected locations in Okaloosa County and at the cities of Freeport, Sea Shore Village, Mary Esther, and Valparaiso. An average pumping rate of 15.5 Mgal/d was used for this pumping period.

Transmissivity, confining unit leakance, and the altitude of the water table in the sand-and-gravel aquifer were adjusted during calibration. Calibrated transmissivities (pl. 16) were in good agreement with values obtained from aquifer tests (compare pls. 6 and 16). Leakance values were varied more than transmissivity during calibration. On the basis of water-level data presented in Hayes and Barr (1983), the average yearly altitude of the water table in the sand-and-gravel aquifer is believed to have remained almost constant from predevelopment time to 1978. Therefore, the altitude of the water table derived from measurements made during 1978 was used for the transient calibration.

A map comparing measured water levels and the simulated potentiometric surface for March 1978 is shown on plate 20. The average simulated head difference and the standard deviation of the head difference were computed to be 0.2 ft and 3.3 ft, respectively. This difference was within the established calibration criteria that required 95 percent of all simulated heads to be within ±10 ft of the measured March 1978 heads. A histogram showing the distribution of head differences between measured water levels and simulated heads as well as the number of nodes in which the head difference occurs (fig. 19) indicates that the simulated head difference is approaching a normal distribution with a slight skew.

The areal distribution of the absolute head differences between the March 1978 potentiometric surface constructed from measured water levels and simulated heads of the FWBM is shown on plate 21. The areas of greatest head difference are at cell blocks in or near the pumping centers in the Fort Walton Beach, Mary Esther, Niceville, and Valparaiso areas. The greatest absolute head difference computed was 11 ft. The absolute head difference is the difference between the simulated head and an average head value in a 1-square-mile cell block derived from measured water levels for March 1978. Water levels measured at or near a pumping well undoubtedly vary significantly

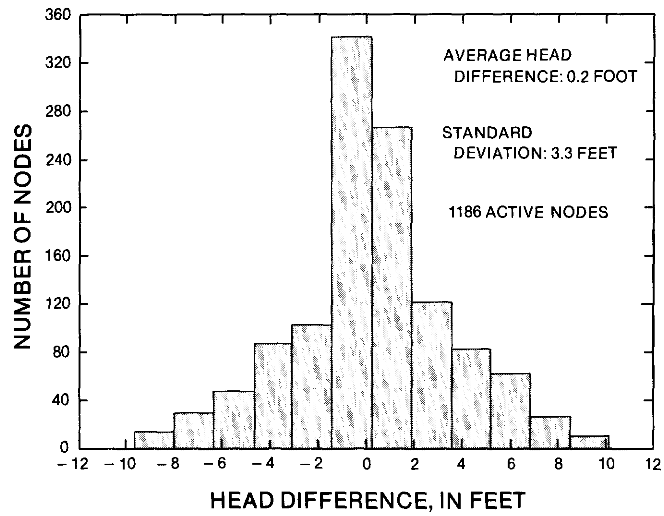


FIGURE 19.—Head difference between the March 1978 measured water levels and simulated heads, Upper Floridan aquifer, southern Okaloosa and Walton Counties, Florida.

from the cell block average value. For example, a water level of 130 ft below sea level was measured at the center of the Fort Walton Beach cone. However, the average cell block value was 70 ft below sea level. In this cell block the simulated head is 73 ft below sea level, which results in an absolute head difference of 3 ft (pls. 20, 21). To simulate the pumping cones and the measured values more accurately, a finer grid would be required for the areas of greatest pumping stress. With the current cell-block size of 1 mi^2, the gradients resulting from pumping stress cannot be represented precisely. However, even with the 1-square-mile cell blocks, the simulated potentiometric surface near the pumping center seems reasonable.

PREDEVELOPMENT STEADY-STATE SIMULATION USING THE TRANSIENT CALIBRATED HYDROLOGIC PARAMETER VALUES

After the FWBM was calibrated by using a transient simulation from January 1941 to March 1978, a steady-state simulation was made again, with all pumping stresses removed (predevelopment conditions). Although water-level measurements made before 1941 were not available, a few water-level measurements made between 1942 and 1947 were available for the Fort Walton Beach area. The simulated predevelopment heads should be equal to or higher than the measured water levels for 1942 and 1947. The simulated predevelopment potentiometric surface and water-level measurements for 1942 and 1947 at selected locations are shown on plate 22. Simulated results compare well with the available data. Generally, simulated heads are equal to or greater than the measured data. In Fort Walton Beach and at a well near Valparaiso, the simulated potentiometric surface is lower than the available water-level measurements. This may be due to ground-water withdrawals prior to 1941 in these areas, although there is no documentation indicating either the quantity or the location of such pumping. Even with the differences between the simulated and the estimated predevelopment heads in these areas (pl. 22), the simulated potentiometric surface is considered reasonable.

Simulated head declines between predevelopment time and March 1978 (compare pls. 20 and 22) in Mary Esther and Fort Walton Beach range from 90 ft to more than 120 ft, in Niceville and Valparaiso from 70 to 80 ft, and in Destin from 40 to 50 ft. The observed declines in Fort Walton Beach increased to more than 140 ft by 1980, as shown on plate 11.

Sensitivity of Calibrated Aquifer Parameters

Transmissivity (*T*), confining-unit leakance (*L*), and storage coefficient (*S*) were varied in a series of sensitivity simulations to evaluate the sensitivity of the model to the hydrologic parameters. Because of the comparative abundance of transmissivity data derived from aquifer-test and specific-capacity data for southern Okaloosa and Walton Counties, Fla., transmissivity values in the sensitivity tests were one-half and twice the calibrated transmissivity values. With the relatively few field data pertinent to storage coefficient and confining-unit leakance, the reliability of these data was estimated to be within plus or minus an order of magnitude. Hence, in the sensitivity analyses, calibrated confining-unit leakance and storage-coefficient values were varied by plus or minus an order of magnitude. As previously discussed, water-table altitudes have not changed significantly since predevelopment time. In addition, with the relatively low confining-unit leakance values (on the order of 10^{-9} (ft/d)/ft in the area of the FWBM, compared with 10^{-4} (ft/d)/ft in the area of the DPM), varying input water-table-altitude values (within the reliability limits of the data) would not produce significant changes in the potentiometric surface or the water budget simulated by the FWBM. Therefore, the water-level altitudes used in the sensitivity analyses were not changed from the calibrated values.

Changes in parameter values, and the resulting simulated head differences, are shown in figure 20. Head difference is computed as the head simulated in the sensitivity run minus the head simulated using the calibrated hydrologic parameters. Thus, a positive head difference indicates a head buildup and a negative head difference indicates a head decline, as compared with heads using the calibrated values.

Because the sensitivity of parameters in the areas of heavy pumping was of greatest interest, the sensitivity analyses results are reported for cell blocks in the digital model representing Fort Walton Beach, Niceville, and Destin, Fla. (nodes 24,14; 20,24; and 27,20, respectively, in fig. 16). Furthermore, all sensitivity runs were conducted as transient analyses for the period beginning in January 1941 and ending in March 1978. Results are reported for December 1947, December 1970, and March 1978 (fig. 20).

Decreasing the calibrated transmissivity values by 50 percent (0.5*T*, *L*, *S* in fig. 20) resulted in simulated head deficits at Fort Walton Beach, Niceville, and Destin, Fla., for December 1947, December 1970, and March 1978. This is due to the reduction in lateral flow as a result of lower transmissivity used in the sensitivity analyses. Thus, as pumping increases, water levels in the Upper Floridan aquifer begin to decline. A point of interest is that by March 1978, the largest head decline occurred in Fort Walton Beach, whereas the smallest head decline was in Destin (18 ft). This can be attributed to the values of transmissivity used at these locations. Pumping at Fort Walton Beach (node 24,14) was simulated using a transmissivity of 1,000 ft^2/d (50 percent of the calibrated value of 2,000 ft^2/d). Corresponding transmissivities at Niceville and Destin were 1,000 and 7,500 ft^2/d, respectively. Furthermore, even though Fort Walton Beach and Niceville have the same value of transmissivity, Fort Walton Beach is on the coast and is surrounded by a zone of lower transmissivity (125 ft^2/d), whereas Niceville is surrounded by a zone of higher transmissivity (2,500 ft^2/d, or 50 percent of the calibrated value of 5,000 ft^2/d). Thus, Fort Walton Beach had greater simulated head declines. Because vertical leakage is extremely low, movement of water to the pumping centers is due entirely to lateral inflow. Consequently, transmissivity is the controlling factor in water-level response to pumping.

Increasing transmissivity by 200 percent (2*T*, *L*, *S* in fig. 20) resulted in head surpluses at Fort Walton Beach, Niceville, and Destin. The simulated transmissivity of 4,000 ft^2/d (200 percent of the calibrated value of 2,000 ft^2/d) at Fort Walton Beach and Niceville and 30,000 ft^2/d at Destin allowed enough water flowing laterally to the pumping centers to compensate for the withdrawals.

Decreasing confining-unit leakance values by an order of magnitude (*T*, 0.1*L*, *S* in fig. 20) during the sensitivity analyses resulted in simulated head differences of +3 ft at Fort Walton Beach and Niceville and +8 ft at Destin for December 1947. Because heads in the Upper Floridan aquifer were higher than heads in the sand-and-gravel aquifer and higher than sea level

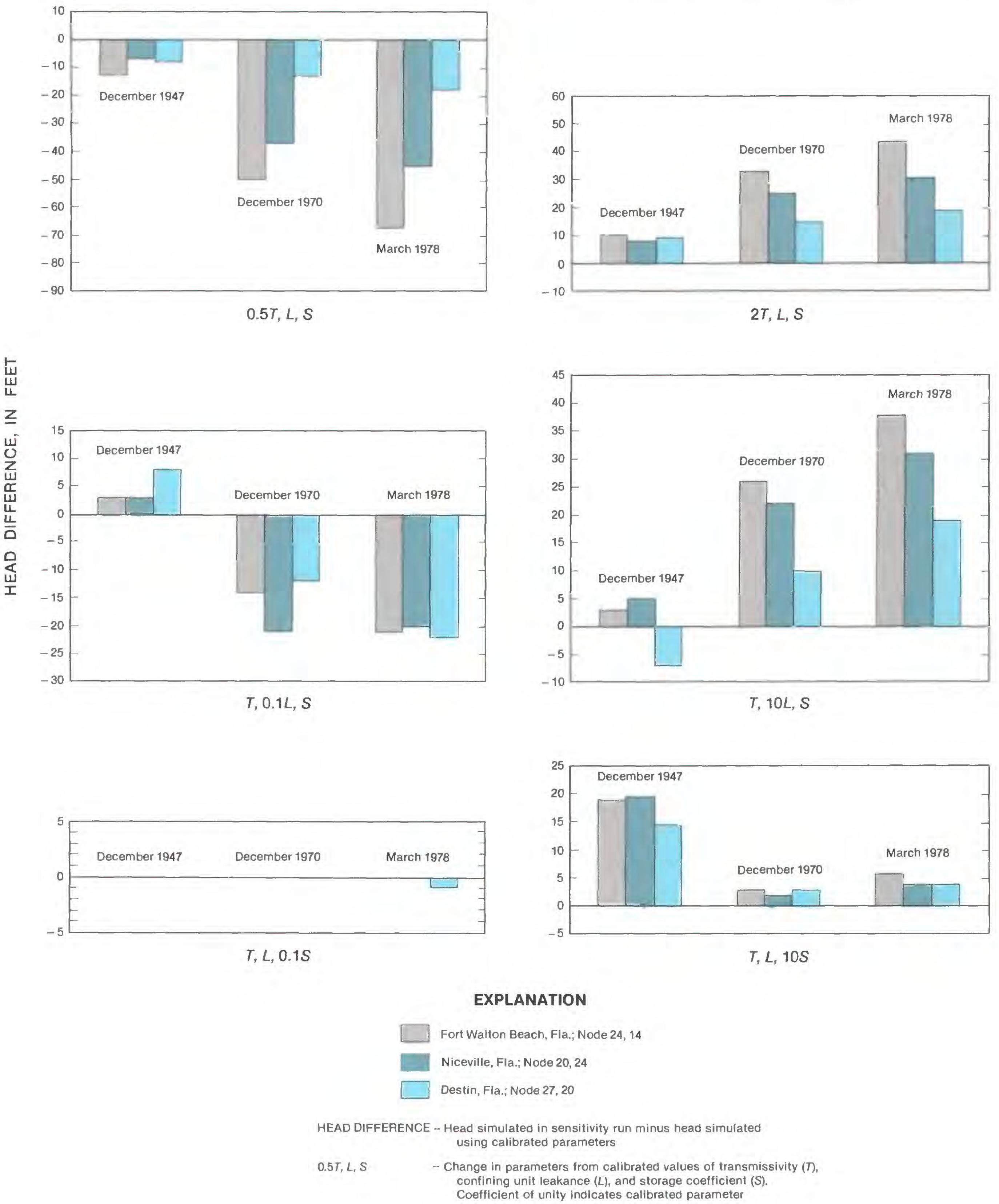


FIGURE 20.—Sensitivity of the calibrated Fort Walton Beach model to changes in hydrologic parameters in the area of Fort Walton Beach, Niceville, and Destin, Florida.

prior to development, water in the Upper Floridan aquifer discharged upward through the upper confining unit diffusively into the sand-and-gravel aquifer and into the ocean. Decreasing the confining-unit leakance rate reduced upward discharge, resulting in higher simulated heads. By December 1947, after the introduction of large-scale pumping, heads in the Upper Floridan aquifer had not lowered enough to reverse the direction of the hydraulic gradient; thus, water in the Upper Floridan aquifer was still leaking upward. At Destin (node 27,20), pumping was not initiated until January 1948. Therefore, reducing leakance resulted in simulated head buildups of 8 ft in December 1947.

By December 1970, heads in the Upper Floridan aquifer had been reduced below heads in the sand-and-gravel aquifer and below sea level. Therefore, reducing confining-unit leakance an order of magnitude resulted in less water leaking downward from the sand-and-gravel aquifer and recharging the Upper Floridan aquifer. This, combined with increased pumping, resulted in greater simulated head declines in the Upper Floridan aquifer.

Increasing the confining-unit leakance by an order of magnitude (*T*, 10*L*, *S* in fig. 20) allowed greater movement of ground water out of the Upper Floridan aquifer by upward diffuse leakage during predevelopment time (pl. 8). Because of large-scale pumping that started in 1941, heads in the Upper Floridan aquifer were lowered below those of the sand-and-gravel aquifer. By December 1947, ground water from the sand-and-gravel aquifer was recharging the Upper Floridan aquifer at a higher rate because the confining-unit leakance was increased; thus, higher heads were simulated in the sensitivity analyses (+3 ft at Fort Walton Beach and +5 ft at Niceville). Because pumping did not begin at Destin until 1948, heads in the Upper Floridan aquifer there were still greater than heads in the sand-and-gravel aquifer. The increased leakance rate allowed more water to discharge from the Upper Floridan aquifer to the sand-and-gravel aquifer and to the sea through upward diffuse leakage. As a result, a simulated head decline of 7 ft for Destin by December 1947 was indicated by the sensitivity analyses.

By March 1978, heads in the Upper Floridan aquifer were lowered even farther by increased pumping, and a larger head gradient occurred between the sand-and-gravel aquifer and the Upper Floridan aquifer as a result of increasing confining-unit leakance. Increasing the calibrated values of leakance an order of magnitude allowed more water to leak from the sand-and-gravel aquifer to the Upper Floridan aquifer. This increased recharge attenuated the effects of increased pumping, resulting in water-level declines less than those measured in March 1978.

Decreasing the values of the storage coefficient (*T*, *L*, 0.1*S* in fig. 20) did not produce any appreciable effects on simulated water levels in the Upper Floridan aquifer. This is because steady state was reached in each time step of the simulation and the aquifer transmissivity was sufficient to supply required water for pumping. Thus, for the pumping-period durations used (years), the reduction in the storage factor probably has an insignificant effect on water levels.

Increasing values of the storage coefficient by an order of magnitude (*T*, *L*, 10*S* in fig. 20) had the effect of simulating erroneously higher heads by December 1947 of +18, +19, and +14 ft, respectively, at Fort Walton Beach, Niceville, and Destin. In this sensitivity analysis, more water per unit volume is available to be released from the aquifer material in a given time period, thus resulting in a head buildup. Additionally, the simulation indicated that the flow system was still in a transient state in December 1947, thereby indicating the importance of the storage coefficient at that time. In December 1970 and March 1978, the sensitivity analyses indicated a small head buildup with additional pumpage. However, the flow system approached steady-state conditions rapidly. Therefore, the storage coefficient is insignificant during these simulation periods.

In summary, the results of the sensitivity analyses show that

1. The ground-water flow system is sensitive to the parameters of transmissivity and confining-unit leakance. Therefore, the data bases of these parameters need further refinement by additional field measurements.
2. If wells can be located in zones of higher transmissivity, water-level declines resulting from pumping can be reduced.
3. Changes in the storage coefficient do not significantly affect the flow system in southern Okaloosa and Walton Counties for simulation periods of more than several years, because the flow system reaches steady-state conditions rapidly.

SUBREGIONAL MODEL CALIBRATION

Having obtained acceptable calibrations for the DPM and the FWBM, the calibrated hydrologic parameters from these models were summed and averaged over 16 cell-block areas and used as input to the SRM. In parts of the study area covered by the SRM and not modeled by the DPM or the FWBM (such as southernmost Alabama and the Apalachicola Bay area of northwest Florida), field data were not available. Transmissivity and leakance values were estimated on the basis of available hydrogeologic information. These values were then input into the model as the initial values and later were adjusted by calibration. Surface altitudes of streambeds of important streams in the area were derived from 7½-minute topographic maps. All estimated values of leakance and transmissivity were checked for agreement with areas of similar hydrogeologic characteristics in southwest Georgia and southern Okaloosa and Walton Counties, Fla.

PREDEVELOPMENT STEADY-STATE CALIBRATION

The estimated regional predevelopment potentiometric surface constructed by Johnston and others (1980) was modified in southwest Georgia and southern Okaloosa and Walton Counties, Fla., on the basis of recently acquired data and simulated heads as a result of the DPM and the FWBM simulations. The modified potentiometric surface was then discretized and used as the starting head input for the SRM calibration. All boundaries around the SRM were designated no-flow boundaries.

The modified predevelopment potentiometric surface and the simulated steady-state predevelopment potentometric surface are shown on plate 23. As with the FWBM and the DPM, the input predevelopment heads and simulated predevelopment heads in each cell block of the SRM represent the average head of the Upper Floridan aquifer over the area of a cell block (16 mi^2 for the SRM). The areas of greatest head difference occur near nodes having ground-water discharge to springs and streams, such as points along the Flint River in southwest Georgia and the Apalachicola River and springs in northwest Florida. The average head difference is -0.6 ft and the standard deviation of the head difference is 4.9 ft. The distribution of head differences generally follows a normal distribution pattern (fig. 21) but is less defined than the head distribution computed from the calibration of the DPM (Hayes and others, 1983) and the FWBM (fig. 19). This may be due, in part, to a lack of measured hydrologic data and uncertainty about the predevelopment potentiometric surface in areas outside southwest Georgia and southern Okaloosa and Walton Counties, Fla.

In the DPM, constant-head boundary conditions were imposed on the Chattahoochee River and on Lake Seminole (fig. 15), and in the FWBM, constant-head boundary conditions were imposed on all boundaries except the southern boundary (fig. 16). Upon removing these boundary conditions for the calibration of the SRM, no adjustments or changes in hydrologic parameter values were made in the cell blocks corresponding to the nodes for which constant-head boundaries of the DPM and the FWBM were assigned. The simulated head differences still were within the established limits of calibration. This indicates that the use of constant-head boundaries in the calibration of the DPM and the FWBM is probably correct.

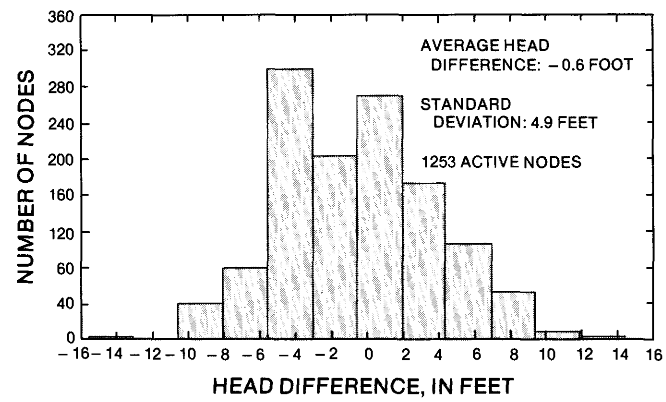


FIGURE 21.—Head difference between the estimated and simulated predevelopment potentiometric surfaces, Upper Floridan aquifer, southwest Georgia, northwest Florida, and southernmost Alabama.

Surface-water and ground-water discharge relations, hydraulic parameters, and head differences along streams, lakes, and springs are shown in table 8. To simulate aquifer discharge in a cell block to a stream penetrating the Upper Floridan aquifer, the water-table altitude value of the cell block was set equal to the mean annual surface-water altitude of the stream that coincides with the location of the cell block (river node). However, for some of the smaller streams and tributaries in the Dougherty Plain, aquifer discharge was simulated in the SRM by using a pumping well at the center of the cell block and assuming that the small tributary did not penetrate the Upper Floridan aquifer modeled by the SRM. The quantity of discharge assigned to the pumping well was determined from the aquifer discharge for the stream simulated by the DPM. This method was used because the relatively large cell-block size of the SRM (16 mi^2) did not justify the dedication of the entire cell block to the smaller streams. The location of cell blocks identified as having aquifer discharge to streams (river nodes) and the location of the pumping wells representing the discharge to the smaller streams are shown on plate 24 and listed in table 8.

In the Dougherty Plain, mean annual discharge from the Upper Floridan aquifer to the Flint River, to Lake Seminole, and to small streams was simulated as 2,380 ft^3/s. Results from hydrograph separation (Hayes and others, 1983) indicate that mean annual ground-water discharge to streams in southwest

TABLE 8.—*Comparison of surface-water and ground-water discharge relations, hydraulic parameters, and head differences along selected streams, lakes, and springs, southwest Georgia, northwest Florida, and southernmost Alabama*

Identification number[1]	Node (row/column) (see pl. 24)	Estimated or measured flow[2] (ft^3/s)	Node type and value assigned (stage, in ft, to river node; flux, in ft^3/s, to well node)	Net simulated flow[3] (ft^3/s)	Water-table altitude (ft)	Transmissivity (1,000 ft^2/d)	Leakance (1×10^{-4} (ft/d)/ft)	Head difference[4] (ft)
			SOUTHWEST GEORGIA					
			Chattahoochee River					
1	28,43	---		-31	77	25	40	1
2	27,43	---		-26	77	20	40	2
3	26,43	---		-37	77	25	40	0
4	25,43	---		-37	77	37	40	0
5	24,43	---	River node, 77 ft	-43	77	45	40	0
6	23,43	---		-66	77	75	40	-2
7	22,43	---		-52	77	75	40	-2
8	21,43	---		-36	77	150	40	-1
9	20,43	---		-2	77	300	2	-2
10	19,43	---		+8	77	300	40	0
11	18,43	---	River node, 70 ft	-20	70	300	40	4
			Lake Seminole					
12	19,44	---		-1	77	300	40	-1
13	19,45	---		+2	77	300	40	1
14	19,46	---	River node, 77 ft	-6	77	300	40	1
15	19,47	---		-22	77	200	40	1
16	19,48	---		-37	77	150	40	1
			Sawhatchee Creek					
17	27,44	---	[5]Well, -8 ft^3/s	[6]+6.6	180	20	1	8
			Dry Creek					
18	29,49	---	Well, -7 ft^3/s	+.2	217	15	2	5
19	29,47	---	do. -7 ft^3/s	+2.0	224	15	2	0
20	28,47	---	do. -6 ft^3/s	-.2	203	27	2	1
21	28,48	---	do. -2 ft^3/s	+2.9	200	20	3	1
22	28,49	---	do. -3 ft^3/s	-3.1	196	15	2	4
23	27,47	---	do. -20 ft^3/s	-.8	191	37	3	-4
24	27,48	---	do. -5 ft^3/s	+1.0	180	37	2	-6
			Spring Creek					
25	26,48	---	Well, -20 ft^3/s	-20.0	140	37	.2	3
26	25,48	---	do. -15 ft^3/s	-13.8	141	37	.2	5
27	24,48	---	do. -19 ft^3/s	-7.7	128	37	.2	7
28	23,47	---	do. -20 ft^3/s	-19.1	110	60	.2	3
29	23,48	---	do. -15 ft^3/s	-11.4	126	50	.3	9
30	22,46	---	do. -24 ft^3/s	-22.5	107	75	.2	-2
31	21,46	---	do. -35 ft^3/s	-34.2	90	150	.2	-3
			Ichawaynochaway Creek					
32	29,52	---	Well, -5 ft^3/s	+.4	200	5	8	1
33	28,52	---	do. -10 ft^3/s	-2.4	180	13	5	5
34	27,52	---	do. -15 ft^3/s	-8.5	171	37	1	4
35	26,51	---	do. -50 ft^3/s	-43.1	160	37	19	0
36	26,52	---	do. -5 ft^3/s	-3.7	158	75	.2	1
37	25,52	---	do. -30 ft^3/s	-22.6	143	75	1	6
38	24,52	---	do. -7 ft^3/s	+19.1	135	100	3	6

TABLE 8.—*Comparison of surface-water and ground-water discharge relations, hydraulic parameters, and head differences along selected streams, lakes, and springs, southwest Georgia, northwest Florida, and southernmost Alabama*—Continued

Identification number[1]	Node (row/column) (see pl. 24)	Estimated or measured flow[2] (ft^3/s)	Node type and value assigned (stage, in ft, to river node; flux, in ft^3/s, to well node)	Net simulated flow[3] (ft^3/s)	Water-table altitude (ft)	Transmissivity (1,000 ft^2/d)	Leakance (1×10^{-4} (ft/d)/ft)	Head difference[4] (ft)
			Chickasawhatchee Creek					
39	29,54	---	Well, -0.5 ft^3/s	-.9	203	5	.5	0
40	28,54	---	do. -5 ft^3/s	-2.4	186	15	.5	4
41	27,54	---	do. -5 ft^3/s	-4.1	169	37	.5	5
42	27,53	---	do. -2 ft^3/s	+6.0	190	55	.6	-1
43	26,53	---	do. -2 ft^3/s	-.9	162	75	.2	-1
			Cooleewahee Creek					
44	27,56	---	Well, -10 ft^3/s	-.8	173	75	38	-3
45	26,55	---	do. -10 ft^3/s	+12.6	162	120	25	-2
46	25,55	---	do. -3 ft^3/s	+4.0	142	200	6	8
			Kinchafoonee Creek					
47	32,59	---	Well, -3 ft^3/s	-2.4	255	5	.2	1
48	31,58	---	do. -6 ft^3/s	-5.9	228	5	.2	-2
49	30,59	---	do. -10 ft^3/s	-3.6	221	20	3	8
50	29,58	---	do. -22 ft^3/s	-21.2	203	48	.2	7
51	29,59	---	do. -11 ft^3/s	+39.8	214	75	30	-1
			Muckalee Creek					
52	32,60	---	Well, -3 ft^3/s	-2.0	261	5	.2	-1
53	31,60	---	do. -10 ft^3/s	-7.4	252	13	.2	-7
54	30,60	---	do. -20 ft^3/s	-17.9	234	31	.2	-1
55	29,60	---	do. -5 ft^3/s	+63.1	220	75	25	2
			Turkey Creek					
56	36,66	---	Well, -6 ft^3/s	-1.3	319	5	.5	2
57	35,65	---	do. -2 ft^3/s	+6.8	300	8	2	-6
			Gum Creek					
58	32,66	---	Well, -3 ft^3/s	+6.3	301	5	.5	0
59	32,65	---	do. -4 ft^3/s	+.6	264	5	8	-6
			Cedar Creek					
60	31,66	---	Well, -5 ft^3/s	+4.3	301	15	1	3
61	31,65	---	do. -5 ft^3/s	-1.4	269	15	1	2
			Swift Creek					
62	30,65	---	Well, -7 ft^3/s	+4.1	286	37	1	4
63	30,64	---	do. -7 ft^3/s	-1.7	271	37	.5	3
			Jones Creek					
64	29,63	---	Well, -7 ft^3/s	+6.3	266	37	1	2
65	29,62	---	do. -1 ft^3/s	+22.5	220	60	25	-1
			Abrams Creek					
66	28,63	---	Well, -9 ft^3/s	+6.6	267	75	1	1
67	28,62	---	do. -5 ft^3/s	+28.7	255	75	2	3

Footnotes at end of table.

TABLE 8.—*Comparison of surface-water and ground-water discharge relations, hydraulic parameters, and head differences along selected streams, lakes, and springs, southwest Georgia, northwest Florida, and southernmost Alabama*—Continued

Identification number[1]	Node (row/column) (see pl. 24)	Estimated or measured flow[2] (ft³/s)	Node type and value assigned (stage, in ft, to river node; flux, in ft³/s, to well node)		Net simulated flow[3] (ft³/s)	Water-table altitude (ft)	Transmissivity (1,000 ft²/d)	Leakance (1x10⁻⁴ (ft/d)/ft)	Head difference[4] (ft)
			Spring Creek-Flint River						
68	20,45	---	River node,	77 ft	-34	77	150	100	1
69	20,49	---	do.	77 ft	-63	77	200	100	2
70	21,49	---	do.	78 ft	-54	78	200	100	4
71	21,50	---	do.	79 ft	-49	79	200	100	6
72	22,50	---	do.	80 ft	-91	80	200	100	5
73	23,51	---	do.	85 ft	-104	85	200	100	11
74	23,52	---	do.	90 ft	-75	90	200	100	15
75	23,53	---	do.	100 ft	-79	100	200	100	18
76	24,54	---	do.	117 ft	-63	117	200	100	2
77	24,55	---	do.	120 ft	-62	120	200	100	8
78	24,56	---	do.	130 ft	-49	130	200	100	9
79	25,57	---	do.	135 ft	-100	135	200	100	12
80	26,58	---	do.	145 ft	-106	145	200	100	4
81	27,58	---	do.	155 ft	-72	155	200	800	10
82	28,59	---	do.	182 ft	-45	182	200	100	12
83	28,60	---	do.	185 ft	-58	185	200	100	19
84	28,61	---	do.	190 ft	-69	190	200	100	19
85	29,61	---	do.	195 ft	-82	195	200	100	23
86	30,62	---	do.	200 ft	-105	200	100	100	-2
87	31,63	---	do.	236 ft	-21	236	50	100	0
88	32,64	---	do.	236 ft	-14	236	50	100	0
89	33,64	---	do.	236 ft	-20	236	50	100	0
90	34,64	---	do.	236 ft	-29	236	50	1,000	0
91	35,64	---	do.	245 ft	-13	245	35	100	15
			NORTHWEST FLORIDA						
			Apalachicola River						
92	17,41	---	River node,	47 ft	-175	47	2,000	80	11
93	17,42	---	do.	49 ft	-134	49	2,000	80	7
94	16,40	---	do.	43 ft	-131	43	2,000	80	9
95	15,39	---	do.	42 ft	-114	42	2,000	80	9
96	13,37	-8	do.	13 ft	-9	13	300	.5	-10
97	12,37	-8	do.	10 ft	-11	10	300	.7	-9
98	11,35	-5	do.	7 ft	-30	7	300	3	3
			Choctawhatchee River						
99	24,30	---	River node,	45 ft	-27	45	300	60	5
100	24,29	---	do.	31 ft	-84	31	300	60	19
101	23,28	-18	do.	30 ft	-20	30	300	20	5
102	22,28	---	do.	24 ft	-32	24	300	40	2
103	21,28	-169	do.	17 ft	-77	17	300	40	5
104	20,27	---	do.	18 ft	-20	18	300	20	4
			Econfina Creek						
105	18,21	-276	River node,	42 ft	-113	42	600	40	5
			Blue, Williford, Gainer, Pitts, Springs[7]						
106	17,31	-208	River node,	14 ft	-116	14	600	10	-4
			Holmes Creek						
107	22,29	---	River node,	25 ft	-64	25	600	30	-1
108	22,30	---	do.	27 ft	-104	27	600	30	-5
109	22,32	-185	do.	30 ft	-162	30	600	15	-7

TABLE 8.—*Comparison of surface-water and ground-water discharge relations, hydraulic parameters, and head differences along selected streams, lakes, and springs, southwest Georgia, northwest Florida, and southernmost Alabama*—Continued

Identification number[1]	Node (row/column) (see pl. 24)	Estimated or measured, flow[2] (ft^3/s)	Node type and value assigned (stage, in ft, to river node; flux, in ft^3/s, to well node)	Net simulated flow[3] (ft^3/s)	Water-table altitude (ft)	Transmissivity (1,000 ft^2/d)	Leakance ($1x10^{-4}$ (ft/d)/ft)	Head difference[4] (ft)
			Jackson, Ponce de Leon					
110	26,29	-50	River node, 60 ft	-28	60	50	10	15
			Vortex Blne Springs					
111	25,29	---	River node, 50 ft	-11	50	50	10	18
			Morrison Spring					
112	24,28	-82	River node, 32 ft	-50	32	50	60	22
			Bazemore Springs[8]					
113	25,40	-10	River node, 130 ft	-7	130	25	6	7
			Hayes Springs					
114	23,39	-18	River node, 85 ft	-35	85	50	6	24
			Bosel Springs					
115	22,39	-73	River node, 75 ft	-46	75	300	10	1
			Blue Springs					
116	21,40	-190	River node, 46 ft	-181	46	300	15	8
			Blue Hole Springs					
117	22,38	-57	River node, 77 ft	-43	77	300	8	-2
			Double Spring, Gadsen Spring					
118	21,37	-89	River node, 54 ft	-92	54	300	7	-2
			Mill Pond Spring, Black Spring					
119	20,37	-73	River node, 53 ft	-59	53	300	5	-6
			Springboard Spring					
120	20,38	-17	River node, 52 ft	-37	52	300	3	-17
			Chipola River					
121	24,39	-5	River node, 115 ft	-2	115	25	1	12
122	21,38	-12	do. 60 ft	-20	60	300	2	-2
123	19,38	-40	do. 50 ft	-3	50	600	.2	8
124	18,38	-40	do. 40 ft	-87	40	300	5	5
125	17,37	-35	do. 40 ft	-50	40	600	3	-4
126	16,37	-10	do. 39 ft	-22	39	600	1.5	-18
127	15,37	-15	do. 38 ft	-33	38	300	3	-5
128	14,36	-10	do. 37 ft	-18	37	100	2.5	-7
129	13,36	-9	do. 27 ft	-18	27	100	2.5	-8
130	12,35	-8	do. 10 ft	-12	10	200	1	-4

[1]See plate 24 for location of identification numbers.
[2]+, recharge to aquifer; -, discharge to streams; 1 ft^3/s per 16 mi^2 cell block = 0.8481 in/yr.
[3]Net simulated flow: +, recharge to aquifer; -, discharge to stream.
[4]Input head-simulated head: +, head decline; -, head buildup.
[5]Simulated flow rate of well using Dougherty Plain model (DPM).
[6]Value determined by summing discharge of pumping well and simulated ground-water flow at node: (-8 ft^3/s+14.6 ft^3/s + 6.6 ft^3/s).
[7]Estimated or measured discharges and locations of Florida springs, from Rosenau and others (1977).
[8]Southernmost Alabama.

Georgia—including discharge from both the residuum and the Upper Floridan aquifer—should be about 4,000 ft^3/s. Mean annual ground-water discharge from the Upper Floridan aquifer simulated by the DPM, as well as the value reported by Hayes and others (1983), is about 3,400 ft^3/s. The discharge simulated by the SRM is about 1,000 ft^3/s less than the discharge simulated by the DPM and that reported by Hayes and others (1983). The reduced aquifer discharge in the coarser mesh indicated by the simulations of the SRM is due solely to model grid size. The larger cell-block area of the SRM grid (16 mi^2) in comparison with the DPM grid (1 mi^2) results in a discrepancy of aquifer discharges. That is, in a 16-square-mile area, the DPM has 16 cell blocks, some of which simulate discharge from the aquifer and some of which simulate recharge to the aquifer. In the SRM, these 16 cell blocks are represented by only one cell block, and this makes it necessary to show ground water moving in one direction only (either discharge from or recharge to the aquifer), thus creating discrepancies.

For the Dougherty Plain, where aquifer discharge to streams is occurring, calibrated leakance and transmissivity values derived from the DPM had to be increased slightly to accurately simulate aquifer discharge to streams with the coarse mesh (16-square-mile cell block) SRM grid. The increased transmissivity values may be seen by comparing transmissivities in the Upper Floridan aquifer (pl. 6) with the DPM transmissivity values (pl. 15).

In summary, three conclusions can be drawn:

1. The SRM results in a poorer simulation than the DPM and the FWBM, because less hydrologic data in areas outside southwest Georgia and southern Okaloosa and Walton Counties, Fla., are available for calibration.
2. Because in many areas covered by the SRM the predevelopment potentiometric surface was constructed or inferred from a few sparsely located data points, the potentiometric surface may be in error, as suggested by the simulated heads.
3. A more effective method of determining the hydrogeologic nature of a region stressed by pumping is to develop and calibrate several finer grid models (like the DPM and the FWBM) rather than a large-grid-size model.

SENSITIVITY OF CALIBRATED AQUIFER PARAMETERS

In the SRM, the two areas of principal interest, the Dougherty Plain in southwest Georgia and the Fort Walton Beach area of southern Okaloosa and Walton Counties, Fla., currently are incurring large pumping stresses. Sensitivity analyses of hydrologic parameters in these areas have been made using the finer grid models (DPM and FWBM). In areas outside southwest Georgia and southern Okaloosa and Walton Counties, Fla., no hydrologic data were available to improve the SRM calibration. The SRM calibration outside the DPM and FWBM areas is a "best guess" and may, in fact, be in error. Therefore, conducting a sensitivity analysis using questionable values of parameters in areas outside southwest Georgia and southern Okaloosa and Walton Counties, Fla., was not considered worthwhile.

POTENTIAL FOR GROUND-WATER DEVELOPMENT BASED ON SIMULATIONS

The calibrated flow models for southwest Georgia (DPM) and southern Okaloosa and Walton Counties, Fla. (FWBM) were used in a series of simulations to evaluate the effects of changes in recharge and pumpage on the potentiometric surface of the Upper Floridan aquifer. Simulation results from the DPM and the FWBM are summarized in this section and are presented as a series of maps showing the projected net water-level changes in the Dougherty Plain and Fort Walton Beach areas.

EVALUATION OF POTENTIAL DEVELOPMENT IN THE DOUGHERTY PLAIN AREA

EFFECTS OF IRRIGATION PUMPAGE DURING A CONSECUTIVE THREE-YEAR DROUGHT

There was a significant increase in the use of ground water for irrigation in southwest Georgia from 1975 to 1980 (Hayes and others, 1983). During a hydrologic drought (reduced soil moisture and recharge conditions), pumpage for irrigation from the Upper Floridan aquifer in the Dougherty Plain area likely would greatly increase. Consequently, simulations were conducted to simulate water-level declines for a consecutive 3-year drought beginning with initial water levels of November 1979. During each year of the drought, an irrigation season of 154 days (May 15 to October 15) was simulated. Water levels in the residuum would be affected by the drought. Therefore, recharge conditions during the drought were simulated as follows:

1. Recharge for year 1 of the drought was the estimated recharge of 1981—a drought year in the Dougherty Plain,
2. Recharge for year 2 of the drought was assumed to be 80 percent of the 1981 recharge, and
3. Recharge for year 3 of the drought was assumed to be 60 percent of the 1981 recharge.

Although actual recharge conditions are unknown, the assumed recharged conditions probably are reasonable, judging from water-table (residuum) data available before and during the 1980-81 drought (Hayes and others, 1983).

Projected potential increase in agricultural land use within the Dougherty Plain area was estimated from county land-use maps prepared by the Soil Conservation Service of the U.S. Department of Agriculture (R.R. Pierce, U.S. Geological Survey, written commun., 1981). Projected pumpage was based on the number of acres of potential agricultural land available in a county for new or additional irrigation and an average application rate per acre. Potential irrigation pumpage was not assigned to urban or urbanizing areas, to areas not suitable for irrigation by center-pivot systems, or in counties mostly outside of the Dougherty Plain.

Two drought scenarios (each drought lasting 3 irrigation seasons, as above) were simulated using the DPM. In the first scenario, pumpage at the 1981 rate was assumed, and in the second scenario, pumpage nearly four times the 1981 pumpage was used. Pumpage in the first scenario (a total of 339 billion gallons for the 3-year drought) consisted of municipal and industrial pumpage of 6 billion gallons per year and irrigation pumpage of 107 billion gallons per year and is shown graphically in figure 22. Pumpage during the first year of the simulated drought (113 billion gallons) was the 1981 estimated pumpage in the Dougherty Plain area. Pumpage in the second scenario (a total of 1,224 billion gallons for the 3-year drought) also included 6 billion gallons per year of municipal and industrial pumpage. However, in this scenario, annual irrigation pumpage was increased to 402 billion gallons. This figure was calculated by assuming that 100 percent of available agricultural land in the Dougherty Plain was under cultivation and being irrigated (fig. 22). The derivation of all quantities of pumpage for the drought scenarios are described in detail in Hayes and others (1983).

PUMPAGE AT 1981 WITHDRAWAL RATES (ASSUMED DROUGHT CONDITION)

Simulated mean declines in the potentiometric surface of the Upper Floridan aquifer in the Dougherty Plain area for a consecutive 3-year drought in years 1, 2, and 3 were 18, 22, and 26 ft below the starting potentiometric surface (low water levels in November 1979), respectively. Simulated water-level declines at the end of the hypothetical 3-year drought were generally less than 50 ft (fig. 23) but ranged from 50 to 60 ft in about 15 percent of the modeled area. In some of the area, water levels declined from 1 to 10 ft below the top of the Upper Floridan aquifer, as shown in figure 24.

During the hypothetical 3-year drought, about half of the total pumpage of 339 billion gallons (321 billion gallons for irrigation and 18 billion gallons for all other uses) was derived from aquifer storage and about half from recharge. Simulated aquifer discharge to streams was significantly reduced, and all streams originating within the Dougherty Plain stopped flowing. Simulated flow of the Flint River at the end of the 3-year drought declined to about 800 ft^3/s, whereas measured flow in August 1980 was about 1,200 ft^3/s. Simulated flows of Ichawaynochaway, Kinchafoonee, and Muckalee Creeks were about 50, 100, and 40 ft^3/s, respectively, with most of the flow being derived from outside the Dougherty Plain. In comparison, measured flows of the Ichawaynochaway, Kinchafoonee, and Muckalee Creeks were 268, 105, and 77 ft^3/s in August 1980, respectively, and 144, 83, and 37 ft^3/s in July 1981, respectively. The effects of stream diversion for irrigation were not simulated. Consequently, quantitative comparisons of streamflow measurements with simulated streamflows should not be made in areas where stream diversion is significant.

PUMPAGE INCREASED TO IRRIGATE ALL POTENTIAL AGRICULTURAL LAND IN THE DOUGHERTY PLAIN (ASSUMED DROUGHT CONDITION)

Simulated mean declines in the potentiometric surface of the Upper Floridan aquifer in the Dougherty Plain area for a hypothetical 3-year drought in years 1, 2, and 3 were 25, 29, and 33 ft, respectively, below the low water levels of the November 1979 potentiometric surface. Simulated head declines at the end of the hypothetical 3-year drought were generally less than 50 ft but ranged from 50 to 75 ft in about 15 percent of the area (fig. 25). Water levels declined from 1 to 10 ft below the top of the aquifer in about 30 percent of the modeled area and from 10 to 50 ft in some interstream tracts, as shown in figure 26.

During the hypothetical 3-year drought simulation, of the total pumpage of 1,224 billion gallons (1,206 billion gallons for irrigation and 18 billion gallons for others), 634 billion gallons was supplied by aquifer storage, 410 billion gallons was induced recharge from surface water, and 180 billion gallons was recharge from the residuum. Most of the surface-water recharge to the aquifer was from the Flint River (water entering the Flint River upstream of the Dougherty Plain) and from Lake Seminole (from lake storage and inflow from the Chattahoochee River). Mean flows of the Chattahoochee and Flint Rivers and

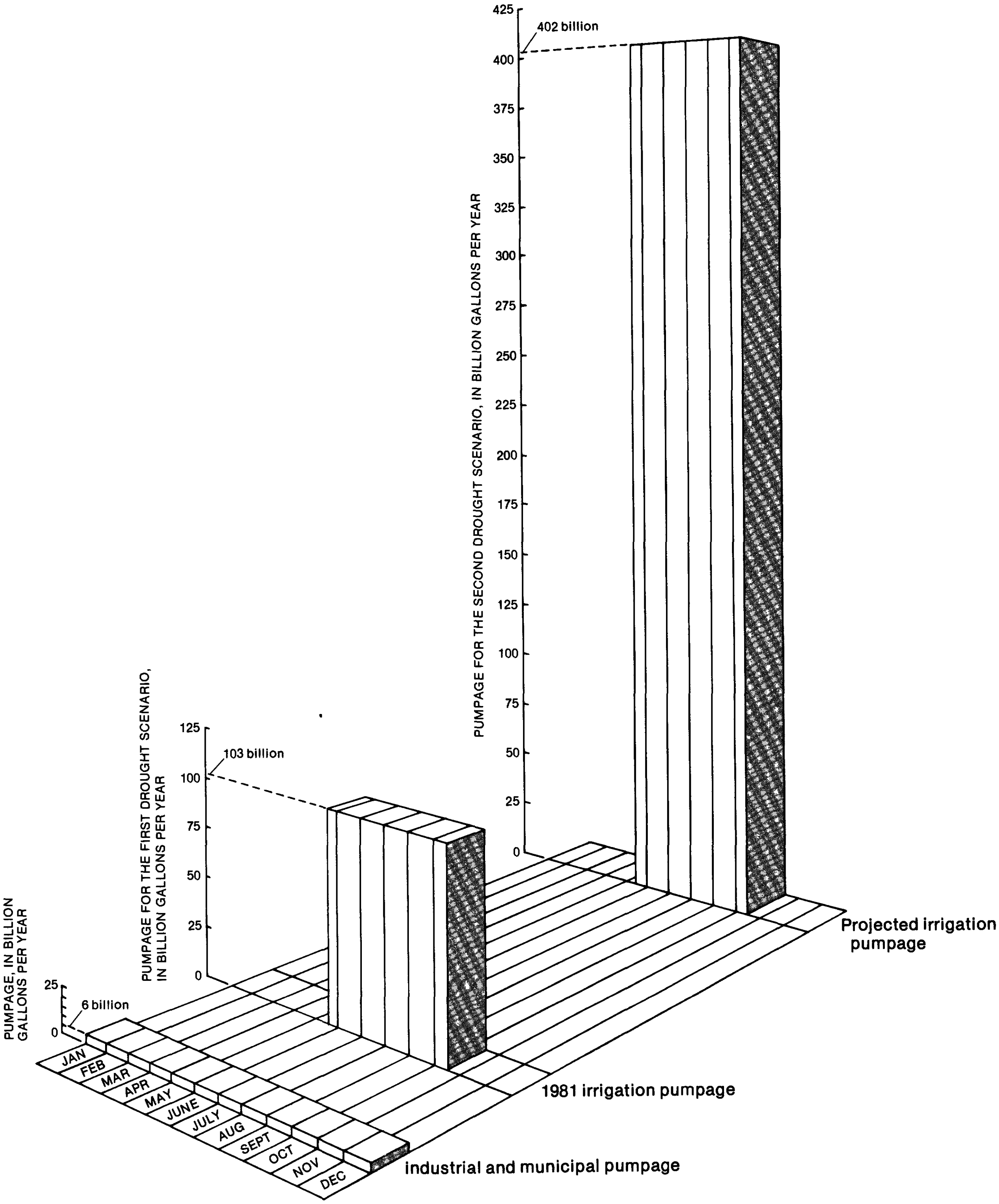


FIGURE 22.—Distribution of pumpage for a hypothetical hydrologic drought, Upper Floridan aquifer, southwest Georgia.

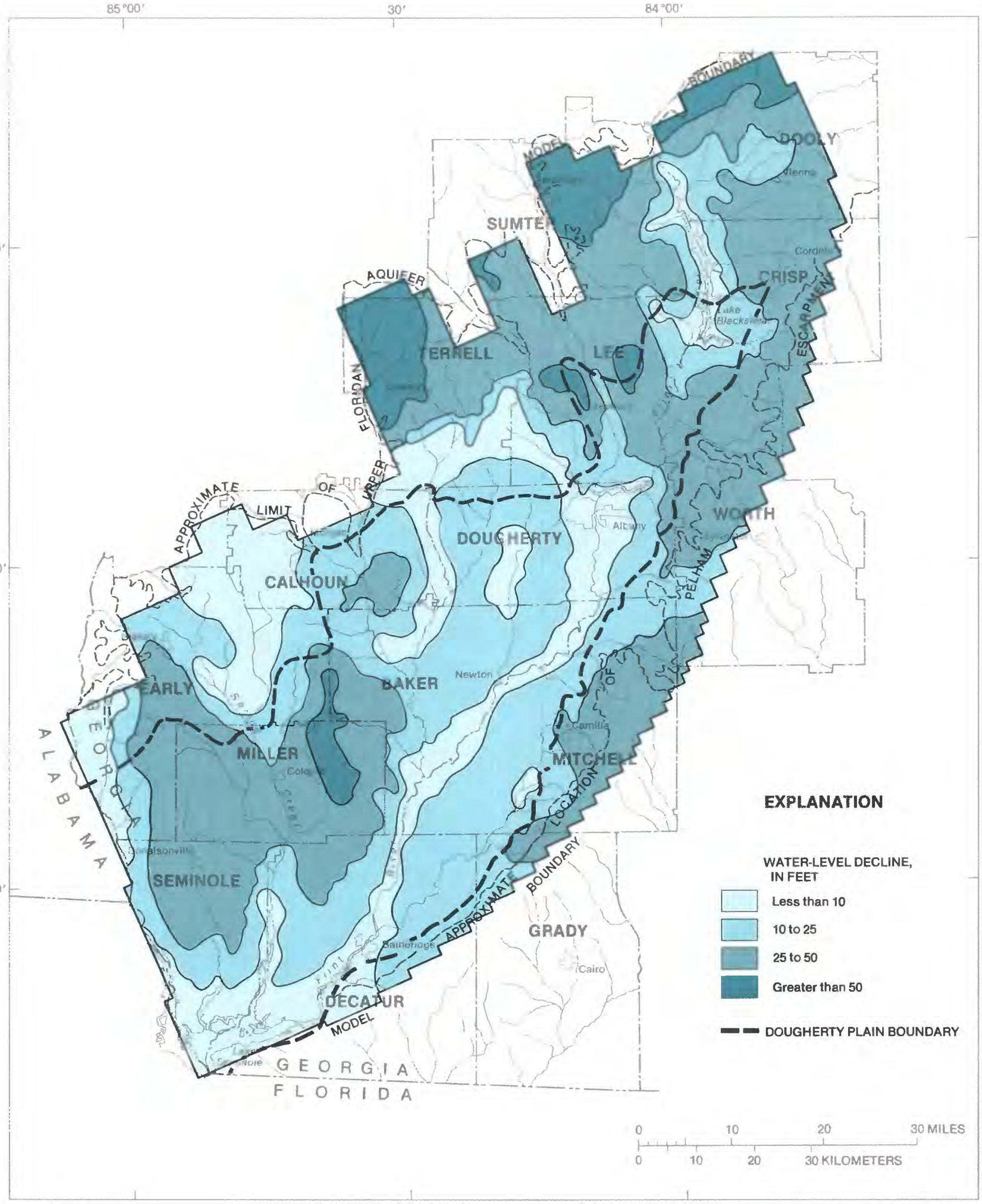


FIGURE 23.—Simulated water-level declines during a hypothetical 3-year drought, with an assumed total pumpage of 339 billion gallons in 3 years, Upper Floridan aquifer, southwest Georgia. From Hayes and others (1983).

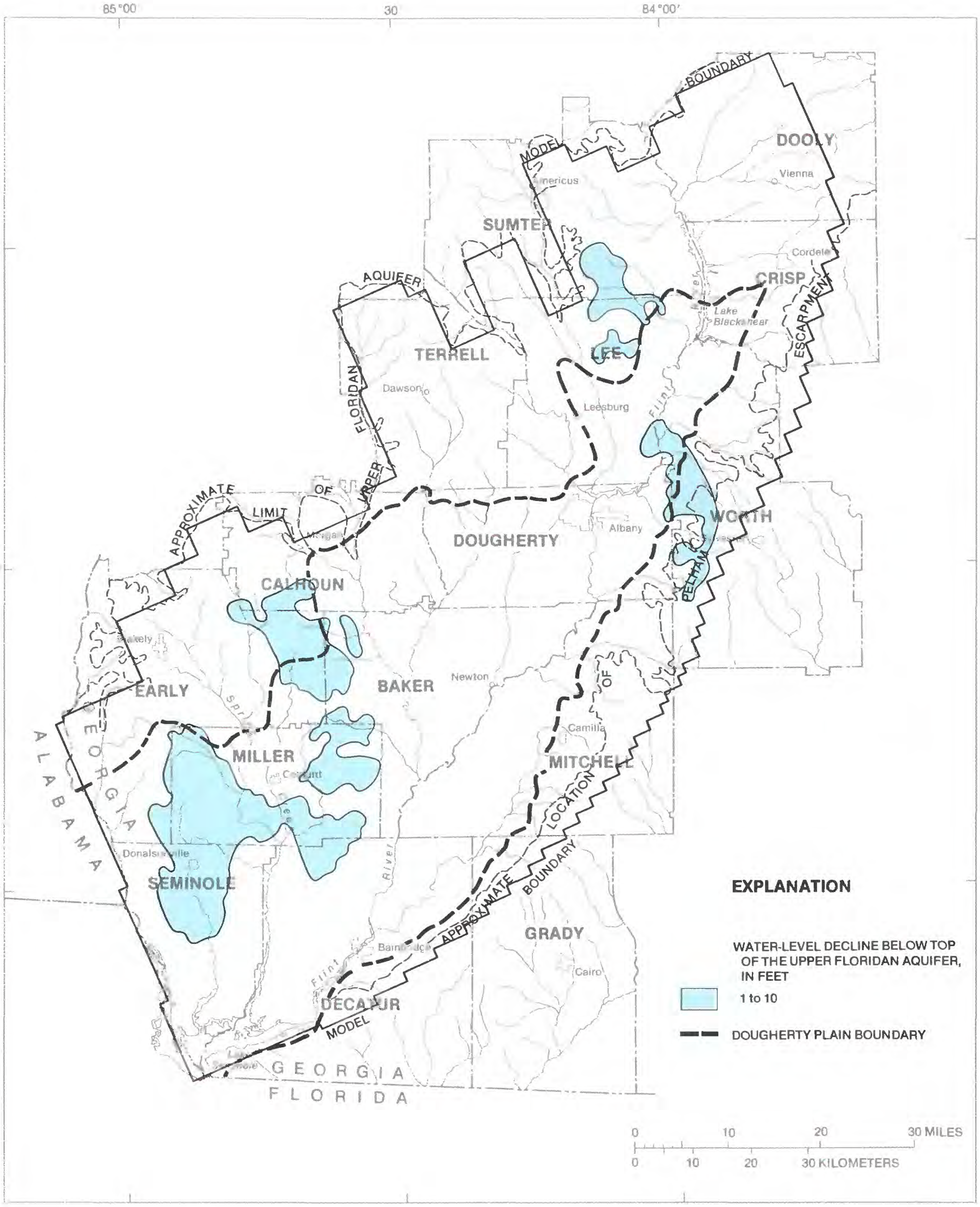


FIGURE 24.—Simulated water-level declines below the top of the Upper Floridan aquifer during a hypothetical 3-year drought, with an assumed total pumpage of 339 billion gallons in 3 years, southwest Georgia. From Hayes and others (1983).

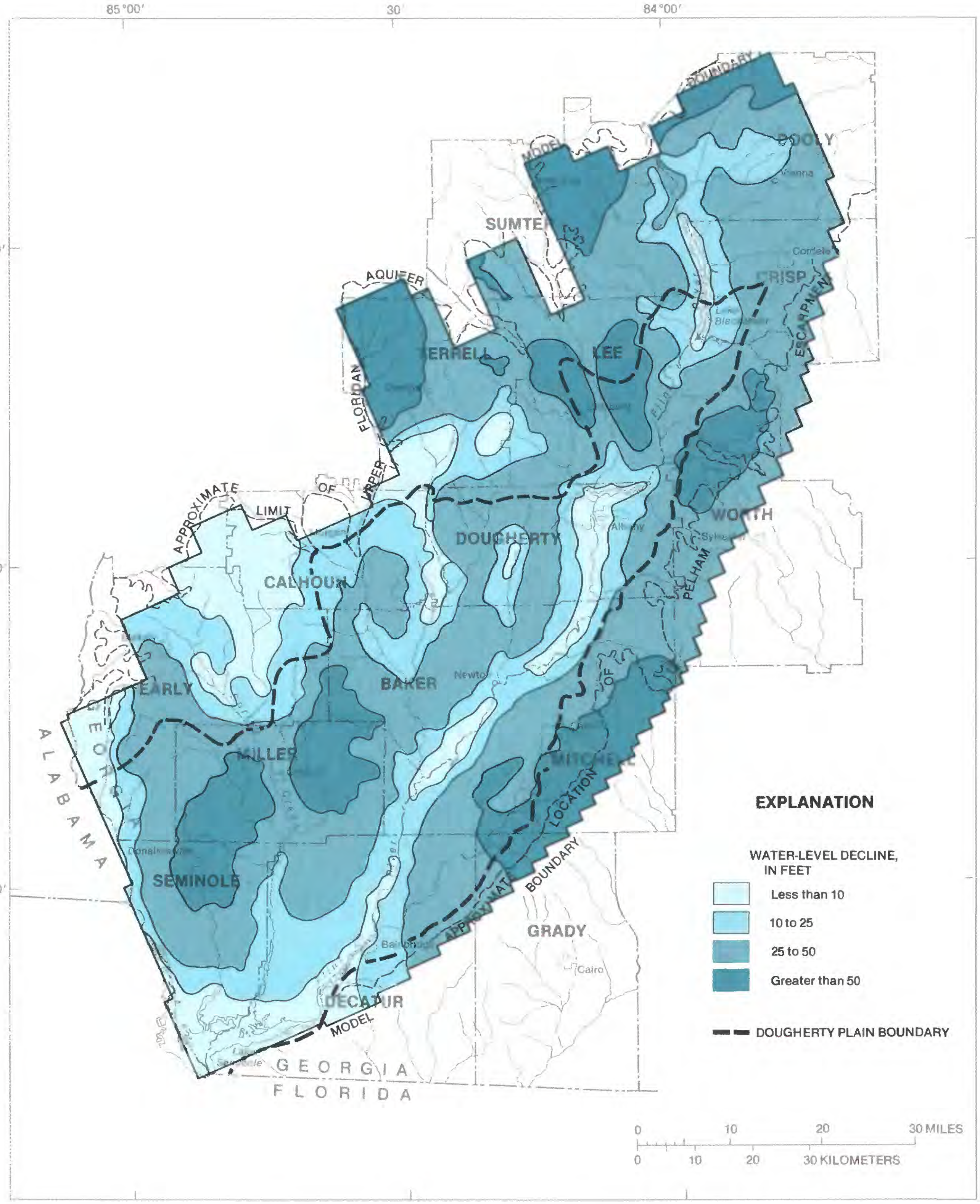


FIGURE 25.—Simulated water-level declines during a hypothetical 3-year drought, with an assumed total pumpage of 1,224 billion gallons in 3 years, Upper Floridan aquifer, southwest Georgia. From Hayes and others (1983).

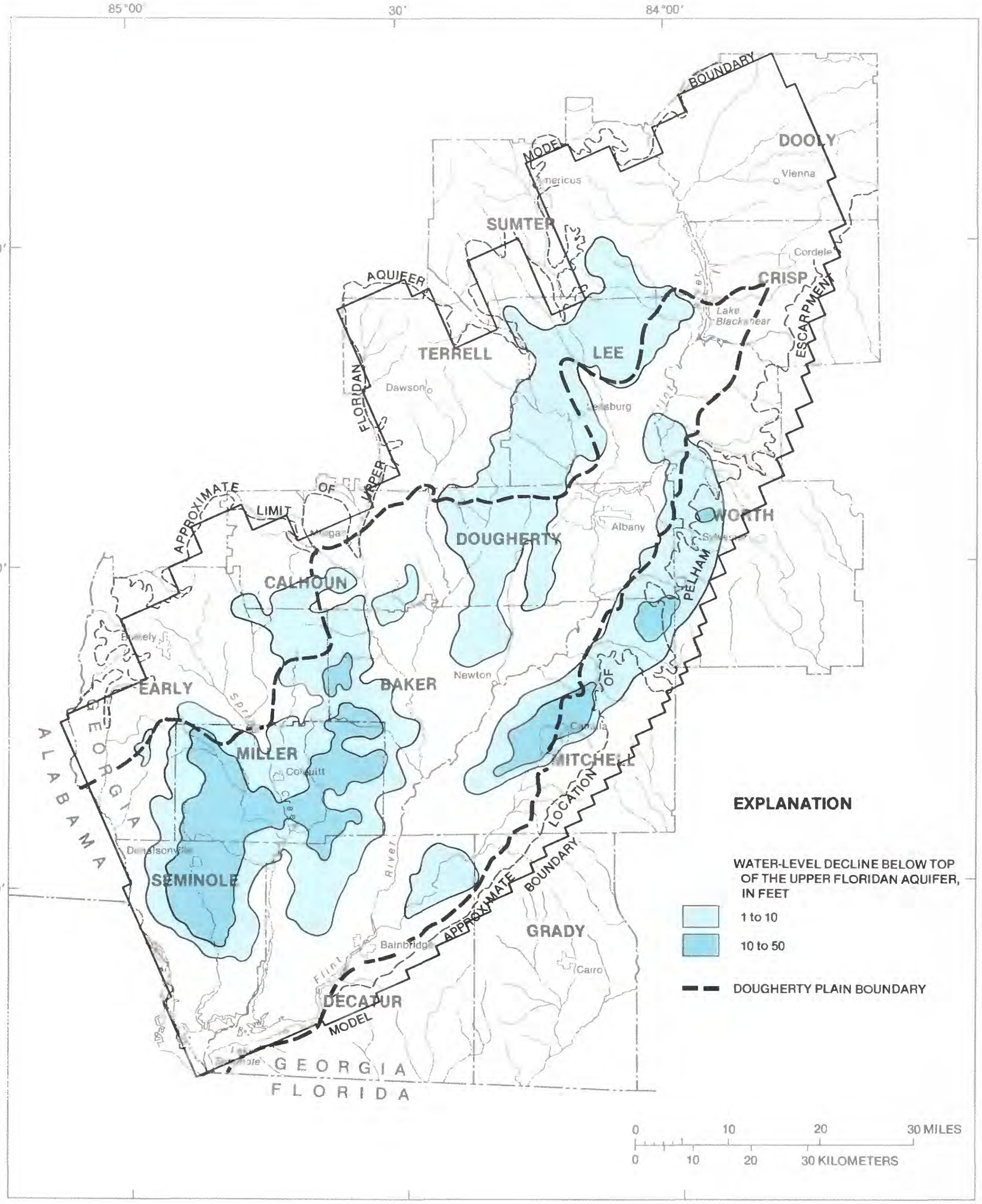


FIGURE 26.—Simulated water-level declines below the top of the Upper Floridan aquifer during a hypothetical 3-year drought, with an assumed total pumpage of 1,224 billion gallons in 3 years, southwest Georgia. From Hayes and other (1983).

Kinchafoonee Creek were severely reduced. All other streams ceased flowing.

EFFECTS OF INCREASE IN IRRIGATION PUMPAGE FOR TEN YEARS (ASSUMED AVERAGE HYDROLOGIC CONDITION)

A 10-year simulation based on mean annual hydrologic conditions and using the calibrated hydraulic parameters was made to determine the effects of long-term irrigation pumping on water levels in the Dougherty Plain area of the Upper Floridan aquifer. Head declines were computed as the difference between simulated water levels at the end of the 10-year simulation and yearly average water levels, which were calculated from the November 1979 low levels and the May 1980 high levels. Pumpage of 287 billion gallons per year was input to the model, as shown in figure 27. (The pumpage of 287 billion gallons consisted of 6 billion gallons of municipal and industrial pumpage and 281 billion gallons of irrigation pumpage during an average irrigation season of 107 days (the duration of the 1980 estimated irrigation season). The 281 billion gallons of irrigation pumpage consisted of 1980 pumpage of 76 billion gallons plus projected pumpage of 205 billion gallons (fig. 27).

The mean decline in the potentiometric surface at the end of the 10-year period was 4 ft, with the general range of decline being 0 to 9 ft. Maximum declines of 9 to 15 ft occurred in less than 15 percent of the modeled area. On a yearly mean basis, 2 billion gallons was removed from storage—less than 1 percent of the 287 billion gallons pumped. The remaining 285 billion gallons came primarily from intercepted discharge to streams. Consequently, the main result of increased irrigation pumping from the Upper Floridan aquifer in the Dougherty Plain area would be slightly lowered water levels and about a 30-percent reduction in aquifer discharge to streams, resulting in significantly reduced streamflow throughout the Dougherty Plain area.

EVALUATION OF POTENTIAL DEVELOPMENT IN THE FORT WALTON BEACH AREA

EFFECTS OF PUMPAGE IN THE YEAR 2000

Pumping centers in the Fort Walton Beach area were evaluated for the potential of expanding pumping capacities through the year 2000. This evaluation suggests that the cities of Fort Walton Beach and Niceville should be able to increase 1978 pumping capacities by 25 percent. Simulations also suggest that Destin and pumping locations throughout Okaloosa County could increase 1978 pumping capacities by 100 percent. The hypothetical increase in pumpage was added to pumpage existing in March 1978. The total projected ground-water withdrawal by the year 2000 is estimated as 20.5 Mgal/d.

To simulate future water levels in southern Okaloosa and Walton Counties using the FWBM, the values of the heads in the year 2000 along the northern, eastern, and western model boundaries needed to be known at the start of the simulation. The SRM was used to simulate the required boundary head values, with the following conditions:

1. The average of 1978 pumpage of 15.5 Mgal/d used in the FWBM was input to the SRM in the Fort Walton Beach area, and a steady-state simulation was made.
2. The projected pumpage of 20.5 Mgal/d in the year 2000 was input to the SRM, and a steady-state simulation was conducted.
3. The simulated heads using the pumpage for the year 2000 were subtracted from the simulated heads using the average 1978 pumpage, yielding a net head decline from 1978 to 2000 due to the increase in pumpage.
4. The heads along the northern, eastern, and western model boundaries of the FWBM were adjusted by the projected net water-level declines from 1978 to 2000 simulated by the SRM.

After insertion of the adjusted boundary heads in the FWBM, two simulations—projected pumpage allocated at existing pumping centers and projected pumpage allocated at relocated pumping centers—were conducted, each having a time period of 8,275 days (March 1978 to the year 2000) and an average projected pumping rate of 20.5 Mgal/d.

PROJECTED PUMPAGE AT EXISTING PUMPING CENTERS

The decline in potentiometric surface from March 1978 to the year 2000 for the first simulation—projected pumpage allocated to existing pumping centers—is shown in figure 28. The input starting heads were obtained by using the derived heads based on measured water levels for March 1978 in the land areas and the simulated heads obtained from the FWBM transient calibration in the ocean areas. Further, all pumping was located in cell blocks that were simulating the pumping wells in the FWBM as of March 1978. Simulated head declines of 40 to 60 ft occur in the vicinity of Fort Walton Beach. Destin, Valparaiso, Niceville, and Mary Esther exhibit an average of 20 to 30 ft of simulated head declines. Because the rate of pumping was an average value, the

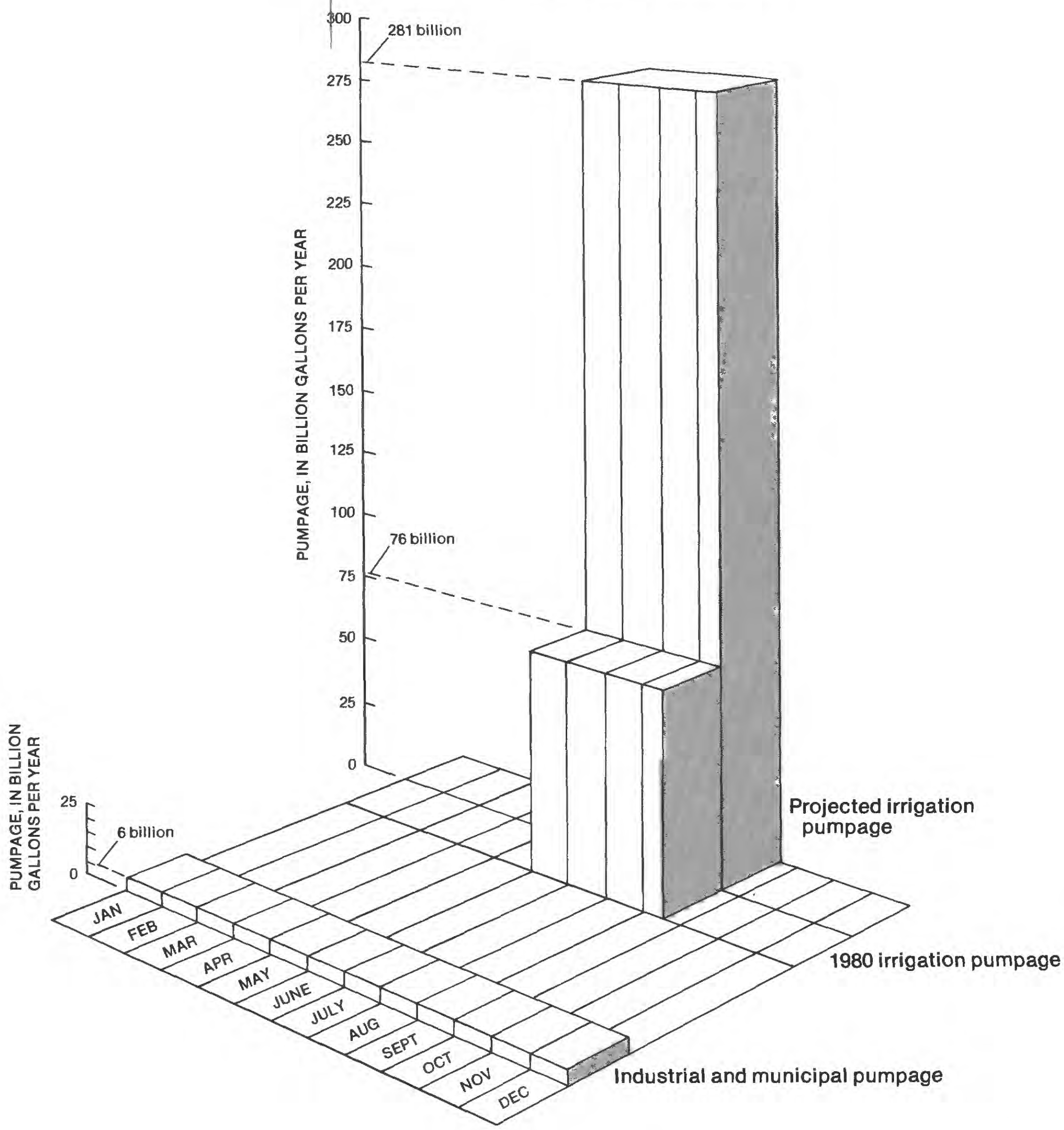


FIGURE 27.—Distribution of pumpage for simulation under mean annual hydrologic conditions, Upper Floridan aquifer, southwest Georgia.

head declines should also be interpreted as average values. Thus, during the peak tourist season, when pumping is significantly higher than at other times of the year, head declines could be expected to be greater than those simulated by the model.

PROJECTED PUMPAGE AT RELOCATED PUMPING CENTERS

In the second simulation—projected pumpage allocated to relocated pumping centers—the same pumping rate of 20.5 Mgal/d was used. However, four wells on Santa Rosa Island were aquifer transmissivity is less than 1,000 ft^2/d (nodes 24,13; 25,15; 26,16; and 26,17 in fig. 16 and on pl. 16) were moved to a newly proposed well field located west of Valparaiso and Niceville at Eglin Air Force Base where transmissivity is 5,000 ft^2/d (nodes 17,19; 18,19; and 19,19 in fig. 16 and on pl. 16).

Simulated declines in the potentiometric surface from March 1978 to the year 2000 are shown in figure 29. The results of this simulation indicate that relocating the pumping centers from an area of low transmissivity to an area of high transmissivity would significantly reduce the large head declines form March

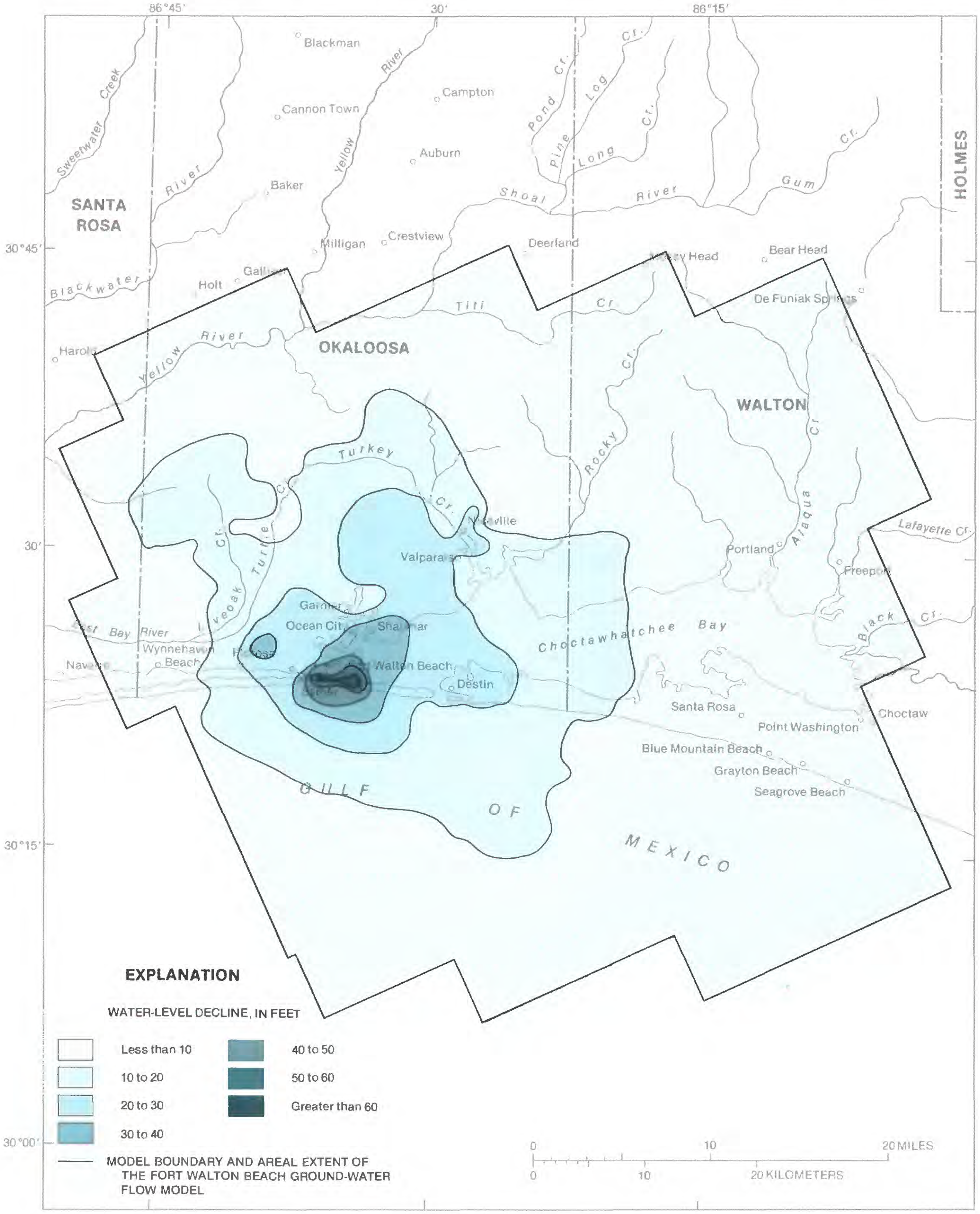


FIGURE 28.—Simulated water-level declines from 1978 to 2000 for pumpage of 20.5 million gallons per day allocated to existing pumping centers, Upper Floridan aquifer, southern Okaloosa and Walton Counties, Florida.

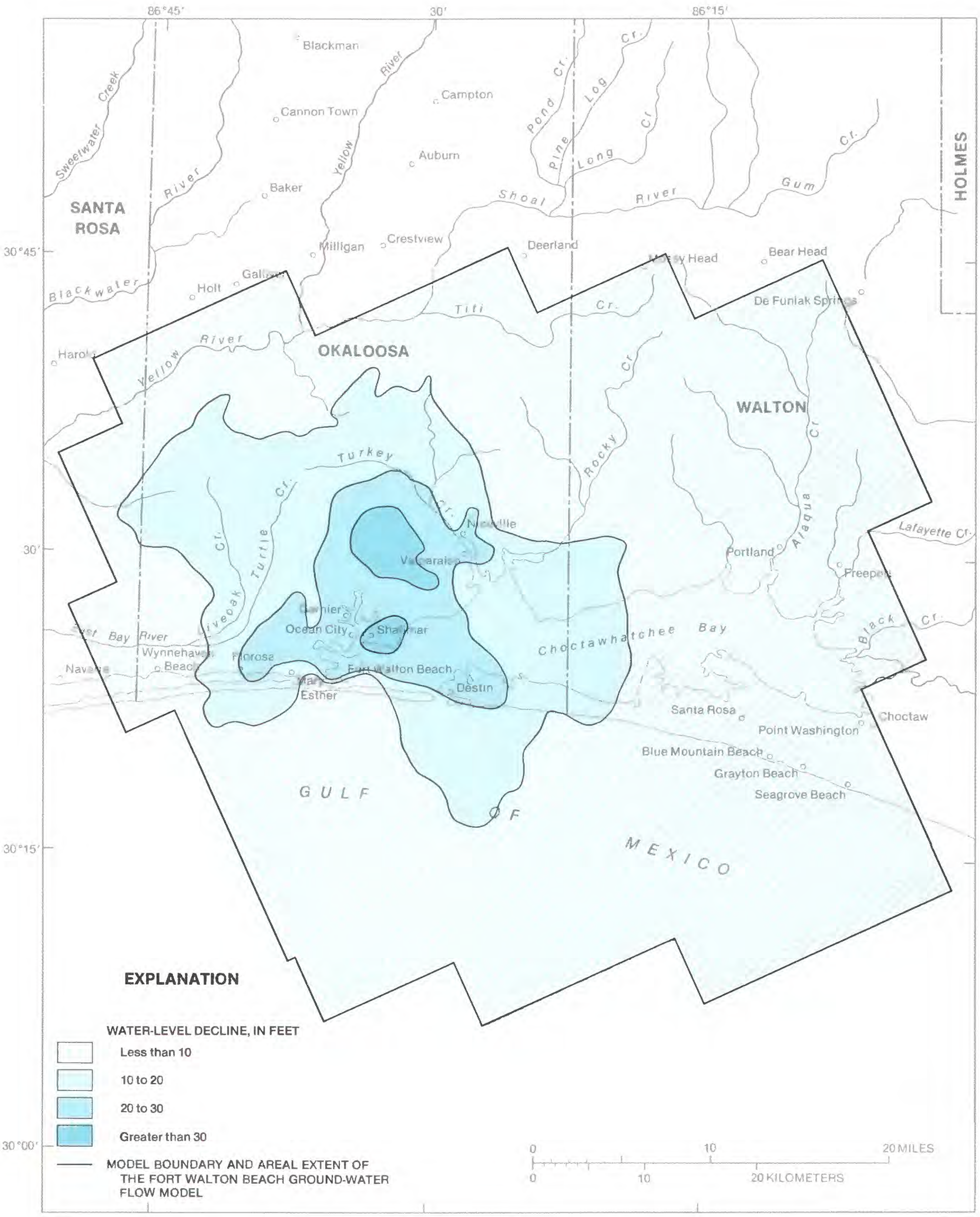


FIGURE 29.—Simulated water-level declines from 1978 to 2000 for pumpage of 20.5 million gallons per day after relocation of four Santa Rosa Island wells, Upper Floridan aquifer, southern Okaloosa and Walton Counties, Florida.

1978 to the year 2000 around Fort Walton Beach and Mary Esther. Simulated head declines with the wells relocated range from 10 to 20 ft around Fort Walton Beach and Mary Esther, instead of from 40 to 60 ft. Also, the area of 30-foot head decline near Valparaiso is much smaller than in the first simulation. Therefore, the FWBM-simulated results indicate that moving the well field, presently located on Santa Rosa Island where the transmissivity of the Upper Floridan aquifer is extremely low, to an area more inland where the transmissivity is higher could be an effective alternative to reduce the deep pumping cones currently existing in the coastal area near Fort Walton Beach.

SUMMARY AND CONCLUSIONS

The hydrogeology of the Floridan aquifer system in southwest Georgia, northwest Florida, and southernmost Alabama, an area of about 20,000 mi^2, was investigated. The objectives of the study were to (1) define the hydrogeologic framework, (2) describe the ground-water-flow regimen prior to development and after withdrawals began, and (3) develop a series of digital models capable of evaluating the flow system and the recharge-discharge relation, and of evaluating various pumping scenarios and their impact on the Floridan aquifer system.

Two areas are significantly affected by pumping. In the Dougherty Plain of southwest Georgia, seasonal withdrawals for irrigation have increased from about 47 billion gallons in 1977 to about 76 billion gallons in 1980, and to about 107 billion gallons in 1981—a drought year. However, these seasonal withdrawals have not resulted in significant water-level declines in the Upper Floridan aquifer over the long term.

In contrast, moderate withdrawals for public supply in southern Okaloosa and Walton Counties, Fla., have resulted in long-term water-level declines in the Upper Floridan aquifer. Total pumpage amounted to about 15.5 Mgal/d (5.7 billion gallons per year) in 1978. At the center of the cone of depression near Fort Walton Beach, Fla., water levels have declined more than 140 ft since predevelopment time (prior to 1940).

Annual precipitation in the study area averages 51 in in southwest Georgia and 63 in in northwest Florida. Because the Floridan aquifer system is not deeply buried in southwest Georgia, during September through May there generally is a direct correlation between precipitation, streamflow, and water levels in the aquifer. In the northwest Florida part of the study area, the Floridan aquifer system is generally deeply buried, and responses of ground-water levels to precipitation are changes in artesian pressure rather than additions of water to the unsaturated and saturated zones.

In southwest Georgia and the Florida Panhandle, streams receive most of their flow from ground-water discharge. Analysis of eight watersheds within southwest Georgia gave an annual mean base flow of 4,000 ft^3/s, a late-summer (September–November) mean base flow of 2,300 ft^3/s, and an early-spring (February–April) mean base flow of 7,400 ft^3/s.

Ground water in the study area is present in two main aquifers: a surficial sand-and-gravel aquifer—important only in westernmost Florida—and the Floridan aquifer system. The sand-and-gravel aquifer consists of fine to coarse sand, fine gravel, and lenses of sandy clay. It is separated from the underlying Floridan aquifer system by the Pensacola confining unit, but there is some hydraulic connection through the confining unit. The sand-and-gravel aquifer extends from land surface to the Pensacola confining unit and ranges in thickness from a few tens of feet in its easternmost area to more than 400 ft in western Escambia County. Water from the sand-and-gravel aquifer generally has a pH of 4.5 to 6.5 and a dissolved-solids concentration of less than 50 mg/L. Water from the sand-and-gravel aquifer normally is of excellent quality and is suitable for public supply and industrial, domestic, and irrigation use. Near the coast, though, some water may have high concentrations of chloride and other dissolved constituents as a result of surface saline-water contamination.

In southwest Georgia, the Floridan aquifer system consists primarily of the light-colored, fossiliferous Ocala Limestone of late Eocene age. The upper surface of the Upper Floridan aquifer generally dips southwestward and occurs from about 300 ft above sea level in Dooly County to about sea level in Decatur County. However, the surface is highly irregular because of differential weathering. The Upper Floridan aquifer ranges in thickness from a few feet at the updip limit to approximately 700 ft in Decatur County. In southwest Georgia the Upper Floridan aquifer is confined by a leaky confining unit (residuum) that allows significant vertical movement of water into and out of the aquifer.

In northwest Florida, the top of the Floridan aquifer system ranges from about 200 ft above sea level near the updip limit to about 2,000 ft below sea level in Escambia County. In parts of Escambia, Santa Rosa, and southern Okaloosa Counties, and in a small part of coastal Walton County, Fla., the Floridan aquifer system is distinguishable as two separate hydrologic units owing to the presence of the Bucatunna confining unit. In these areas, the Lower Floridan aquifer is composed of white to gray, soft to hard limestone. Some sections, particularly in Walton County, are highly fossiliferous and consist principally of foraminifera and shell fragments. In southern Okaloosa County, the Bucatunna Formation confines the Lower Floridan aquifer. Cores of the Bucatunna Formation from a well in Santa Rosa County had laboratory-measured vertical hydraulic conductivities ranging from 1.9×10^{-6} to 2.6×10^{-7} ft/d.

Transmissivity values derived from aquifer-test and specific-capacity data for the Upper Floridan aquifer range from 200 to 330,000 ft^2/d. Model-calibrated transmissivity values, which are assumed to be effective areally, range from 250 to 600,000 ft^2/d. The lowest transmissivity value occurred in the southeast part of the study area between coastal Florida and the assumed position of the freshwater-saltwater interface. High transmissivity values are in areas adjacent to major streams such as the Apalachicola, Chipola, Chattahoochee, and Flint Rivers and Spring Creek. The highest transmissivity value occurs in a belt extending from Decatur County, Ga., to Washington County, Fla. In southwest Georgia, transmissivity may vary abruptly by more than 200 percent within a square mile, but in northwest Florida, transmissivity does not vary abruptly.

In southwest Georgia, where the Upper Floridan aquifer is semiconfined, storage coefficients range from 3×10^{-2} to 2×10^{-4} but are generally in the 1×10^{-3} to 1×10^{-4} range. Storage coefficients in southern Okaloosa and Walton Counties, Fla., where the aquifer is thickly confined, range from about 6×10^{-4} to 2×10^{-5}.

Within the study area, the Upper Floridan aquifer flow system is bounded on the east by a ground-water divide, on the south and west by the presumed saltwater-freshwater interface (which cannot be located precisely owing to insufficient data), and on the north by the updip limit of the aquifer. In southwest Georgia, water moves downward through the overlying residuum, with the lower, less permeable half of the residuum acting as a leaky confining layer. The aquifer discharges water to streams that are hydraulically connected to the aquifer, thus giving rise to many local flow systems. In southern Okaloosa and Walton Counties, the Upper Floridan aquifer is thickly confined by the Pensacola confining unit and is recharged by water in the overlying sand-and-gravel aquifer seeping downward through the Pensacola confining unit. Because there are no significant surface-water bodies directly connected hydraulically to the Upper Floridan aquifer, except for Choctawhatchee Bay, the major natural method for Upper Floridan aquifer discharge in southern Okaloosa and Walton Counties is diffuse leakage upward through the Pensacola confining unit into the overlying sand-and-gravel aquifer or into overlying streams, the bay, or the ocean. Diffuse upward leakage occurs when the heads in the Upper Floridan aquifer are higher than the heads in the overlying sand-and-gravel aquifer or higher than the stages in the overlying water bodies.

Prior to development, recharge to the Upper Floridan aquifer occurred in most inland areas. Aquifer discharge occurred along and seaward of coastal areas and along flood plains of major streams. Model simulation indicates that about 94 percent of the mean annual aquifer discharge of 1,175 billion gallons (157 billion ft^3) occurred in thinly confined or semiconfined areas, generally east of Washington County, Fla. The general direction of ground-water flow during predevelopment time was from outcrop areas to coastal areas.

Comparison of the estimated predevelopment and May 1980 potentiometric surfaces indicates very little difference in head during this period, with the exception of a cone of depression near the Fort Walton Beach area. Pumping in the Fort Walton Beach area increased from about 1.5 Mgal/d in 1940 to about 11.8 Mgal/d in 1968. By 1978, average water use had increased to 15.5 Mgal/d. The moderate pumpage (15.5 Mgal/d) in an area having low transmissivity (250 to 15,000 ft^2/d) and limited recharge results in present-day (1980) water-level declines of more than 140 ft since predevelopment time. Owing to pumping in the Fort Walton Beach area, the direction of ground-water flow is now (1980) from the northeast, north, and northwest toward the centers of pumping near Valparaiso, Niceville, and Fort Walton Beach.

During predevelopment time, southern Okaloosa and Walton Counties were primarily areas of Upper Floridan aquifer discharge to the overlying sand-and-gravel aquifer, Choctawhatchee Bay, and the Gulf of Mexico. Currently (1980), however, because pumping has lowered heads in the Upper Floridan aquifer below those in the overlying sand-and-gravel aquifer and below sea level, substantial induced recharge to the Upper Floridan aquifer from the sand-and-gravel aquifer takes place. In southern Okaloosa and Walton Counties, the Bucatunna Formation, where present, separates the Floridan aquifer system into an upper and lower aquifer. Heads in the Lower Floridan aquifer are still higher than those in the Upper Floridan aquifer. However, flow from the Lower to the Upper Floridan aquifer through the Bucatunna Formation is considered minimal owing to the low vertical hydraulic conductivity of the Bucatunna Formation. Aquifer discharge takes place only in the southeastern and coastal areas of Walton County. According to model simulation (predevelopment time to March 1978), 8.6

billion gallons (1.1 billion ft^3) of water was removed from aquifer storage by pumping about 147 billion gallons (19.7 billion ft^3). Thus, storage accounted for less than 6 percent of total pumpage. Additionally, 85 percent of the water removed from aquifer storage occurred before 1970.

During average hydrologic conditions, pumpage accounts for about 5 to 10 percent of the aquifer's discharge in southwest Georgia. Use of ground water for irrigation in southwest Georgia has increased from 47 billion gallons in 1977 to 76 billion gallons in 1980, and to 107 billion gallons in 1981—a drought year. In addition, pumpage for municipal supplies and industries accounts for about 6 billion gallons of water annually. Long-term water-level records indicate that, except for cyclic seasonal fluctuations and hydrologic extremes, the potentiometric surface of the Upper Floridan aquifer in southwest Georgia has not changed since predevelopment time. This implies that over the long term, aquifer storage changes have been minimal and recharge approximately equaled discharge. Additionally, simulation indicates that about 90 percent of the annual discharge in southwest Georgia occurs as discharge to streams, lakes, and springs.

Pesticides were detected in water from 10 of 16 wells open to the residuum and 4 of 16 wells open to the Upper Floridan aquifer in southwest Georgia. None of the water samples from the Upper Floridan aquifer, though, contained total pesticide concentrations exceeding the limits for public drinking supply recommended by the U.S. Environmental Protection Agency (1976). Some wells in coastal Walton County, Fla., contain more than 500 mg/L of chloride.

Three two-dimensional finite-difference ground-water-flow models were calibrated to simulate flow in the Upper Floridan aquifer. The subregional model (SRM), having an areal extent of about 20,000 mi^2, was calibrated in a steady-state simulation against measured and estimated predevelopment water levels of the Upper Floridan aquifer. Small, more detailed flow models were constructed and calibrated to better define the hydrologic parameters in two major pumping areas. The finer grid finite-difference models consisting of 1-square-mile cell-block areas were used to simulate the flow system of the Upper Floridan aquifer in the Dougherty Plain area of southwest Georgia and the Fort Walton Beach area of southern Okaloosa and Walton Counties, Fla.

The Dougherty Plain model (DPM), having an area of 4,400 mi^2, was calibrated in a steady-state simulation against November 1979 measured water levels. Most simulated heads were within ±5 ft of measured or estimated water heads. The calibrated hydrologic parameters were further tested by using a transient simulation against the measured or estimated heads of the Upper Floridan aquifer from May to November 1980—the irrigation season in southwest Georgia. Simulated seasonal water-level declines of the potentiometric surface compared reasonably with recorded hydrographs for selected wells in southwest Georgia.

The Fort Walton Beach model (FWBM) was used to simulate the Fort Walton Beach area and areas in southern Okaloosa and Walton Counties, Fla. The model covered a land area of about 1,700 mi^2. Hydrologic parameters were calibrated using a transient simulation against the measured or estimated potentiometric surface from January 1941 to March 1978. Pumpage was increased by steps during simulation to the March 1978 level of 15.5 Mgal/d. Most simulated heads were within ±4 ft of measured or estimated heads of the Upper Floridan aquifer. A predevelopment (prior to 1941) potentiometric surface of the Upper Floridan aquifer in southern Okaloosa and Walton Counties was constructed by using the calibrated hydrologic parameters in a steady-state simulation (all pumping stresses were removed).

Transient simulations were conducted using the DPM to simulate changes in the potentiometric surface of the Upper Floridan aquifer and discharge to or recharge from overlying streams for three hypothetical hydrologic conditions. The first simulation was based on the assumptions that (1) there would be a drought lasting 3 consecutive years, and (2) the amount of irrigation pumpage would remain at 1981 levels (total annual pumpage of 113 billion gallons, consisting of 1981 irrigation pumpage of 107 billion gallons plus other-use pumpage of 6 billion gallons). The second simulation was made on the assumptions that (1) there would be a drought lasting 3 consecutive years, and (2) all available agricultural land would be irrigated (total annual pumpage of 408 billion gallons, consisting of 1981 irrigation pumpage of 107 billion gallons plus a projected increase in annual irrigation pumpage of 295 billion gallons plus other-use annual pumpage of 6 billion gallons). The third simulation was based on the assumptions that (1) a 10-year normal recharge condition would prevail and (2) annual pumpage would be 287 billion gallons (1980 pumpage of 82 billion gallons plus a projected increase in annual pumpage of 205 billion gallons).

Simulated head declines at the end of a 3-year drought with pumpage of 113 billion gallons annually averaged about 26 ft and were generally less than 50 ft. Declines varying from 50 to 60 ft occurred in about 15 percent of the modeled area. In some areas, heads declined from 1 to 10 ft below the top of the Upper Floridan aquifer. Aquifer discharge to streams was significantly reduced, and all streams originating within the Dougherty Plain area of southwest Georgia stopped flowing.

Simulated head declines at the end of a 3-year drought with annual pumpage of 408 billion gallons averaged about 33 ft and were generally less than 50 ft. Declines of 50 to 75 ft occurred in about 15 percent of the modeled area. Water levels declined from 1 to 10 ft below the top of the aquifer in about 30 percent of the modeled area and from 10 to 50 ft in some interstream tracts. Induced recharge to the aquifer from streams exceeded aquifer discharge to streams. About half of the pumpage came from aquifer storage and about half came from induced stream infiltration to the aquifer and leakage through the residuum.

The mean decline in the potentiometric surface at the end of the 10 years of average recharge conditions and annual pumpage of 287 billion gallons was 4 ft, with the general range of decline being 0 to 9 ft. Maximum declines of 9 to 15 ft occurred in less than 15 percent of the area. Over the 10-year simulation period, only 6 Mgal/d was removed from storage—about 1 percent of the total pumpage. Net discharge to streams, however, was reduced by 30 percent. Consequently, the major effect of increased pumping under average recharge conditions would be to reduce the base flow of streams in the southwest Georgia area during the irrigation season.

Transient simulations were conducted using the FWBM to evaluate the effects of increased pumping on water levels in the Upper Floridan aquifer in the Fort Walton Beach area from 1978 to 2000. Total pumpage used in the simulation was 20.5 Mgal/d. In the first simulation, all increased pumpage was allocated to existing well fields. In the second simulation, the coastal well field located on Santa Rosa Island, where transmissivity is low (less than 1,000 ft^2/d), was moved inland, west of Valparaiso where transmissivity is higher (5,000 ft^2/d).

In the first simulation, head declines ranging from 40 to 60 ft (below the March 1978 levels) occurred in the vicinity of Fort Walton Beach. Destin, Valparaiso, Niceville, and Mary Esther had averaged simulated head declines of 20 to 30 ft.

Relocating coastal wells from Santa Rosa Island inland to west of Valparaiso resulted in much smaller head declines in the year 2000. Simulated water-level declines ranged from 10 to 20 ft at Fort Walton Beach. Also, the area of the 30-foot head decline near Niceville and Valparaiso was much smaller than in the first simulation. Therefore, the simulation indicates that moving the coastal well field now on Santa Rosa Island to an area more inland could be an effective alternative in reducing the deep pumping cone currently centered in the coastal area at Fort Walton Beach.

SELECTED REFERENCES

Barnett, R.S., 1975, Basement structure of Florida and its tectonic implications: Gulf Coast Association of Geological Societies Transactions, v. 25, p. 122–142.

Barr, D.E., Hayes, L.R., and Kwader, Thomas, 1985, Hydrology of the southern parts of southern Okaloosa and Walton Counties, northwest Florida, with special emphasis on the upper limestone of the Floridan aquifer: U.S. Geological Survey Water-Resources Investigations Report 84–4305, 66 p.

Barr, D.E., Maristany, A.R., and Kwader, Thomas, 1981, Water resources availability for development in southern Okaloosa and Walton Counties, northwest Florida: Northwest Florida Water Management District Water Resources Asssessment 81–1, 41 p.

Barraclough, J.T., and Marsh, O.T., 1962, Aquifers and quality of ground water along the Gulf Coast of western Florida: Florida Geological Survey Report of Investigations 29, 28 p.

Bear, Jacob, 1972, Dynamics of fluids in porous media: New York, American Elsevier, 764 p.

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

Bush, P.W., and Johnston, R.H., in press, 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: U.S. Geological Survey Professional Paper 1403–C.

Chowns, T.M., and Williams, C.T., 1983, Pre-Cretaceous rocks beneath the Georgia Coastal Plain—Regional implications, *in* Gohn, G.S., ed., Studies related to the Charleston, South Carolina, earthquake of 1886–Tectonics and seismicity: U.S. Geological Survey Professional Paper 1313–L, p. L1–L42.

Cooke, C.W., 1943, Geology of the Coastal Plain of Georgia: U.S. Geological Survey Bulletin 941, 121 p.

De Weist, R.J.M., 1967, Geohydrology: New York, Wiley, 366 p.

Hayes, L.R., and Barr, D.E., 1983, Hydrology of the sand-and-gravel aquifer, southern Okaloosa and Walton Counties, northwest Florida: U.S. Geological Survey Water-Resources Investigations Report 82–4110, 43 p.

Hayes, L.R., Maslia, M.L., and Meeks, W.C., 1983, Hydrology and model evaluation of the principal artesian aquifer, Dougherty Plain, southwest Georgia: Georgia Geologic Survey Bulletin 97, 93 p.

Herrick, S.M., 1961, Well logs of the Coastal Plain of Georgia: Georgia Geological Survey Bulletin 70, 462 p.

Hicks, D.W., Krause, R.E., and Clarke, J.S., 1981, Geohydrology of the Albany area, Georgia: Georgia Geologic Survey Information Circular 57, 31 p.

Johnston, R.H., 1976, Relation of ground water to surface water in four small basins of the Delaware Coastal Plain: Delaware Geological Survey Report of Investigations 25, 56 p.

——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., and Bush, P.W., in press, Summary of the hydrology of the Floridan aquifer system in Florida and in parts of Georgia, South Carolina, and Alabama: U.S. Geological Survey Professional Paper 1403–A.

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.

Lohman, S.W., 1979, Ground-water hydraulics: U.S. Geological Survey Professional Paper 708, 70 p.

Marsh, O.T., 1966, Geology of Escambia and Santa Rosa Counties, western Florida panhandle: Florida Geological Survey Bulletin 46, 140 p.

McCallie, S.W., 1898, A preliminary report on the artesian-well system of Georgia: Georgia Geological Survey Bulletin 7, 214 p.

Miller, J.A., 1982a, Thickness of the Tertiary limestone aquifer system, Southeastern United States: U.S. Geological Survey Open-File Report 81-1124, 1 sheet.

———1982b, Geology and configuration of the base of the Tertiary limestone aquifer system, Southeastern United States: U.S. Geological Survey Open-File Report 81-1176, 1 sheet.

———1982c, Configuration of the base of the upper permeable zone of the Tertiary limestone aquifer system, Southeastern United States: U.S. Geological Survey Water-Resources Investigations Open-File Report 81-1177, 1 sheet.

———1982d, Geology and configuration of the top of the Tertiary limestone aquifer system, Southeastern United States: U.S. Geological Survey Open-File Report 81-1178, 1 sheet.

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

———1986, Hydrogeologic framework of the Floridan aquifer system in Florida and parts of Georgia, Alabama, and South Carolina: U.S. Geological Survey Professional Paper 1403-B, 91 p.

Mitchell, G.D., 1981, Hydrogeologic data of the Dougherty Plain and adjacent areas, southwest Georgia: Georgia Geologic Survey Information Circular 58, 124 p.

National Academy of Sciences, 1977, Drinking water and health: Washington, D.C., 796 p.

Neathery, T.L., and Thomas, W.A., 1975, Pre-Mesozoic basement rocks of the Alabama Coastal Plain: Gulf Coast Association of Geological Societies Transactions, v. 25, p. 86-99.

Newton, J.G., 1976, Early detection and correction of sinkhole problems in Alabama, with a preliminary evaluation of remote sensing applications: Montgomery, State of Alabama Highway Department, Bureau of Materials and Tests, HPR Report 76, 83 p.

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

Pascale, C.A., 1974, Water resources of Walton County, Florida: Florida Department of Natural Resources, Bureau of Geology Report of Investigation 76, 65 p.

Pierce, R.R., Barber, N.L., and Stiles, H.R., 1983, Georgia irrigation: A decade of growth: U.S. Geological Survey Water-Resources Investigations Report 83-4177, 40 p.

Pinder, G.F., and Bredehoeft, J.D., 1968, Application of a digital computer for aquifer evaluation: Water Resources Research, v. 4, no. 5, p. 1069-1093.

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.

Pollard, L.D., Grantham, R.G., and Blanchard, H.E., Jr., 1978, A preliminary appraisal of the impact of agriculture on ground-water availability and quality in southwest Georgia: U.S. Geological Survey Water-Resources Investigations 79-7, 22 p.

Radtke, D.B., McConnell, J.B., and Carey, W.P., 1980, A preliminary appraisal of the effects of agriculture on stream quality in southwest Georgia: U.S. Geological Survey Water-Resources Investigations 80-771, 40 p.

Riggs, H.C., 1963, The base flow recession curve as an indicator of ground water: International Association of Scientific Hydrology, Surface Water Symposium, Berkeley, 1963, Pub. 63, p. 352-363.

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

Searcy, J.K., 1959, Flow-duration curves: U.S. Geological Survey Water-Supply Paper 1542-A, 33 p.

Sever, C.W., 1965a, Ground-water resources and geology of Seminole, Decatur, and Grady Counties, Georgia: U.S. Geological Survey Water-Supply Paper 1809-Q, 30 p.

———1965b, Ground-water resources of Bainbridge, Georgia: Georgia Geological Survey Information Circular 32, 10 p.

Sprinkle, C.L., 1982a, 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 Open-File Report 81-1103, 1 sheet.

———1982b, 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 Open-File Report 82-94, 1 sheet.

———1982c, 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 Open File Report 82-1101, 1 sheet.

Stephenson, L.W., and Veatch, J.O., 1915, Underground waters of the Costal Plain of Georgia, *and a discussion of* The quality of the waters, by R.B. Dole: U.S. Geological Survey Water-Supply Paper 341, 539 p.

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.

Trapp, Henry, Jr., 1978, Preliminary hydrologic budget of the sand-and-gravel aquifer under unstressed conditions, with a section on water-quality monitoring, Pensacola, Florida: U.S. Geological Survey Water-Resources Investigations 77-96, 62 p.

Trescott, P.C., Pinder, G.F., and Larson, S.P., 1976, Finite-difference model for aquifer simulation in two dimensions with results of numerical experiments: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 7, Chapter C1, 116 p.

U.S. Environmental Protection Agency, 1975, National interim primary drinking water regulations: Federal Register, v. 4, pt. IV, no. 248, December 24, 1975, p. 59566-59588.

———1976, National interim primary drinking water regulations: EPA-570/9-76-003, 159 p.

———1979, Water quality criteria: Federal Register, v. 44, no. 52, p. 15926-15981.

Wagner, J.R., Lewis, C.E., Hayes, L.R., and Barr, D.E., 1980, Hydrologic data for Okaloosa, Walton, and southeastern Santa Rosa Counties, Florida: U.S. Geological Survey Open-File Report 80-741, 228 p.

Wait, R.L., 1963, Geology and ground-water resources of Dougherty County, Georgia: U.S. Geological Survey Water-Supply Paper 1539-P, 102 p.

Warren, M.A., 1944, Artesian water in southeastern Georgia, with special reference to the coastal area: Georgia Geological Survey Bulletin 49, 140 p.

Watson, T.W., 1981, Geohydrology of the Dougherty Plain and adjacent areas, southwest Georgia: Georgia Geologic Survey Hydrologic Atlas 5, 4 sheets.