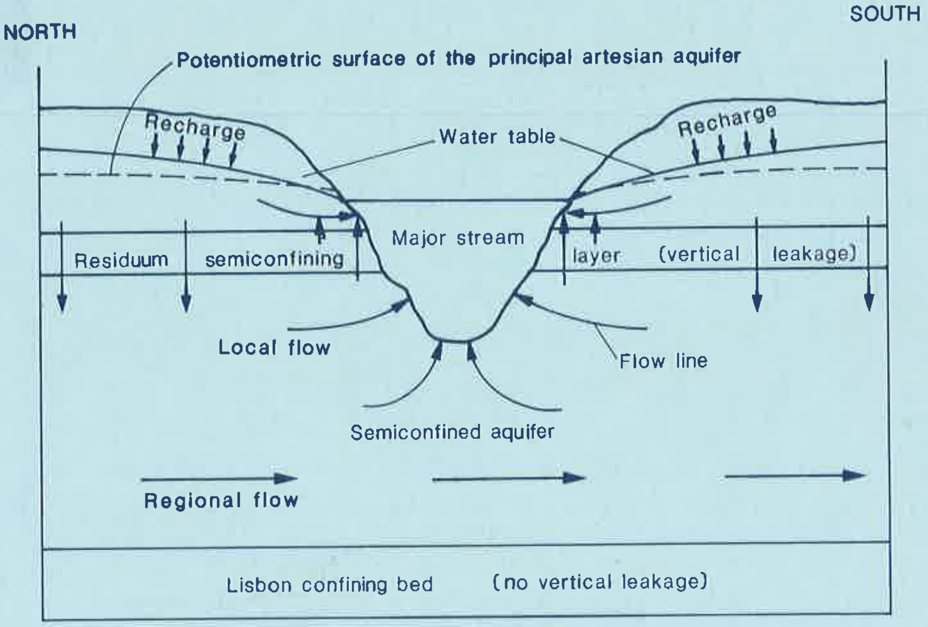
HYDROLOGY AND MODEL EVALUATION OF THE PRINCIPAL ARTESIAN AQUIFER, DOUGHERTY PLAIN, SOUTHWEST GEORGIA

by

Larry R. Hayes, Morris L. Maslia, and Wanda C. Meeks



Department of Natural Resources
Environmental Protection Division
Georgia Geologic Survey

Prepared in cooperation with the
U.S. Geological Survey

BULLETIN 97

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DEPARTMENT OF NATURAL RESOURCES
Joe D. Tanner, Commissioner
ENVIRONMENTAL PROTECTION DIVISION
J. Leonard Ledbetter, Director
GEORGIA GEOLOGIC SURVEY
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CONVERSION FACTORS

For those readers who may prefer to use metric units or the International System of Units (SI) rather than inch-pound units, conversion factors for the terms used in this report are listed below:

Multiply inch-pound unit	By	To obtain metric (SI) unit
	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 kilometers (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
	3.785×10^{-3}	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)
	6.309×10^{-5}	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/a)
cubic foot per second (ft^3/s) [(ft^3/s)/mi^2]	2.832×10^{-2}	cubic meter per second (m^3/s) [(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)

CONVERSION FACTORS

Multiply inch-pound unit	By	To obtain metric (SI) unit
	Leakance	
gallon 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]

EXPLANATION OF UNITS

Ground-water term		Original form		Reduced form
Transmissivity, T	=	(m^3/d)/m	=	m^2/d
	=	(ft^3/d)/ft	=	ft^2/d
	=	(gal/d)/ft	=	--
Hydraulic conductivity, K	=	(m^2/d)/m	=	m/d
	=	(ft^2/d)/ft	=	ft/d
	=	(gal/d)/ft	=	--

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

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ABSTRACT

Use of ground water for irrigation in the Dougherty Plain area of southwest Georgia increased from about 47 billion gallons in 1977 to about 76 billion gallons in 1980, and to 107 billion gallons in 1981. Most ground-water withdrawals are from a limestone aquifer, which is referred to locally as the Ocala aquifer but is more widely known in Georgia as the principal artesian aquifer. The aquifer in the Dougherty Plain area is overlain by about 25 to 125 feet of sandy clay residuum derived from chemical weathering of the Ocala Limestone.

Transmissivities of the principal artesian aquifer range from 2,000 to 1,300,000 feet squared per day. Storage coefficients range from 2×10^{-4} to 3×10^{-2}. Measured yields of wells in the principal artesian aquifer range from about 40 to 1,600 gallons per minute and commonly exceed 1,000 gallons per minute where transmissivity exceeds 50,000 feet squared per day.

Annual rainfall in the Dougherty Plain area averages about 53 inches. The annual mean, spring high, and late-summer low runoffs are, respectively, 5,200, 9,200, and 2,700 cubic feet per second. Average annual and summer mean base flows are, respectively, 4,000 and 2,300 cubic feet per second.

Under average hydrologic conditions, mean annual water levels in the principal artesian aquifer remain constant (recharge equals discharge). Annual mean recharge to the aquifer in the Dougherty Plain area is about 2,200 million gallons per day. About 90 percent of annual mean recharge is discharged to streams.

Water from the principal artesian aquifer is generally suitable for public-supply, industrial, and irrigation purposes. Pesticides were detected in water from 11 residuum wells and four principal artesian aquifer wells. None of the water samples from the principal artesian aquifer contained pesticide concentrations exceeding the recommended limits for public drinking supplies.

A two-dimensional finite difference model was used to simulate flow in the principal artesian aquifer. Simulation of a 3-year drought with pumpage of 113 billion gallons per year resulted in a mean water-level decline of 26 feet. Increasing pumpage to 408 billion gallons per year resulted in a mean decline of 33 feet. During the drought simulations, ground-water discharge to major streams was severely reduced and smaller streams ceased flowing. A 10-year simulation using average recharge and pumpage of 287 billion gallons per year resulted in a mean water-level decline of 4 feet and a 30-percent reduction in discharge to streams.

During drought conditions, present pumpage demands combined with reduced recharge could result in water-levels declining below the top of the aquifer and cause dry wells, well collapses, or possibly sinkhole development. Increased pumpage could increase the extent and magnitude of these problems.

INTRODUCTION

The principal artesian aquifer, which underlies parts of Alabama, South Carolina, Georgia, and all of Florida, is one of the most productive aquifers in the country. Large withdrawals of water from this aquifer for supplemental irrigation in the Dougherty Plain area of southwest Georgia (fig. 1); the potential withdrawal from the aquifer in other

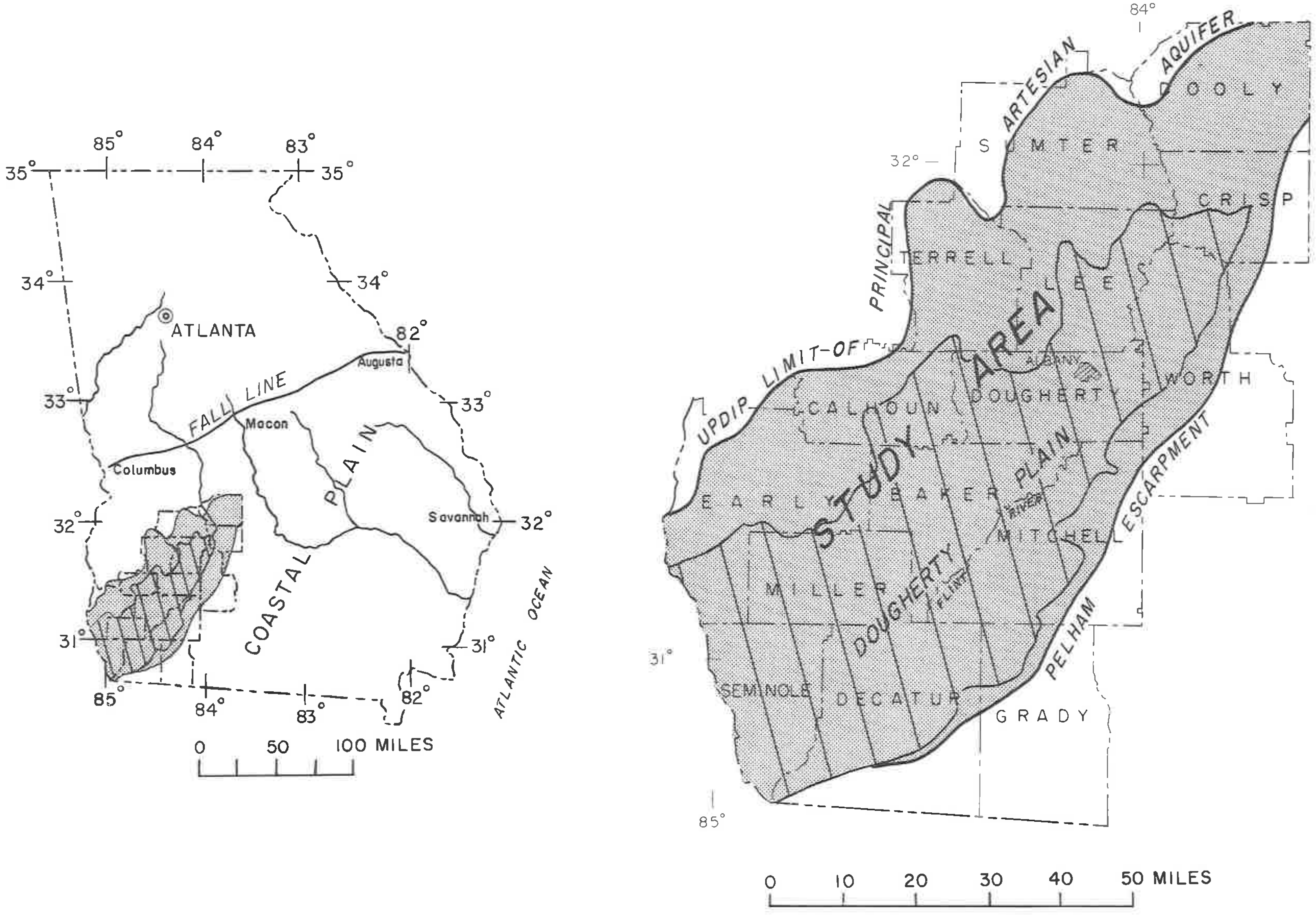

Figure 1.—Area of investigation.

areas of the Coastal Plain for irrigation; and declining water levels in the aquifer throughout the Coastal Plain are of concern to State and local officials. The Environmental Protection Division of the Georgia Department of Natural Resources, which has the responsibility of administering the Ground-Water Use Act (No. 1478, as amended through 1973), is especially concerned.

A mild climate, an abundant supply of good-quality ground water, a flat to gently rolling terrain, and the introduction of center-pivot irrigation systems have spurred a remarkable increase in agricultural irrigation in southwest Georgia. Ground-water use for irrigation in the Dougherty Plain between 1977 and 1980 increased from about 47 to 76 billion gallons per year (H. E. Gill, U.S. Geological Survey, written commun., 1981), with most of the water being pumped from the principal artesian aquifer.

Information regarding the hydrologic character of the principal artesian aquifer in the Dougherty Plain area is limited. Consequently, it was not known if the aquifer would be capable of supplying the increasing, long-term water needs of municipalities, industry, and agriculture, especially during hydrologic droughts such as occurred in 1954 and in 1980-81.

Previous Investigations

The general geology and ground-water resources of the Coastal Plain of Georgia have been previously discussed in McCallie (1898), Stephenson and Veatch (1915), Cooke (1943), and Herrick (1961). Geohydrologic reports primarily concerned with the Dougherty Plain include those by Wait (1963), Sever (1965a and 1965b), Pollard and others (1978), and Hicks and others (1981).

Purpose and Scope

The primary objectives of this investigation, which was carried out in cooperation with the Georgia Geologic Survey, were to (1) define the geohydrology and hydraulic characteristics of the principal artesian aquifer system within the Dougherty Plain, largely through an extensive test-well drilling program; (2) develop a hydrologic budget in which total streamflow, base streamflow, and ground-water recharge or discharge are defined and quantified; and (3) develop a digital hydrologic model that can be used to simulate water-level changes in the principal artesian aquifer resulting from real or hypothetical pumpage increases.

Secondary objectives of the investigation were to (1) verify, expand, and add new hydrologic data to the existing data base; (2) evaluate present water-level and water-quality networks and to modify and expand these networks where necessary; and (3) analyze ground-water samples for pesticides, herbicides, and major inorganic dissolved constituents.

The Dougherty Plain investigation concentrated on delineating the hydrogeology of middle Eocene and younger rocks in a 15-county area of southwest Georgia (fig. 1). Twelve of these counties lie wholly or partially in the Dougherty Plain, which is the main area of interest. The total investigation covers an area of about 4,400 mi^2 and lies within the High Irrigation Water-Use Zone, as defined by the Georgia Geologic Survey (W. H. McLemore, Georgia Geologic Survey, written commun., 1979).

Data Collection and Methods

Well and Surface-Water Station Numbering Systems

Data from 403 privately owned wells were entered into the computerized GWSI (Ground Water Site Inventory) system of the U.S. Geological Survey. A listing of these wells, with well construction and other pertinent information, and a location map are presented in a basic-data report prepared as part of the Dougherty Plain investigation (Mitchell, 1981, table 1 and plate 1).

The numbering system used to identify wells in this report follows that of Mitchell (1981) and consists of a 3-digit number that identifies the county in which a well is located, followed by a hyphen and a 2-digit number that is the serial number of the well in that county. For example, well 007-05 is in Baker County and has a serial number of 5. The table below lists the counties and their reference numbers:

Baker	007	Lee	177
Calhoun	037	Miller	201
Crisp	081	Mitchell	205
Decatur	087	Seminole	253
Dooly	093	Sumter	261
Dougherty	095	Terrell	273
Early	099	Worth	321
Grady	131		

The 3-digit county number has been omitted in figures and tables that include county names.

Since October 1, 1950, the order of listing surface-water stations in U.S. Geological Survey reports is in a downstream direction along the main stream. All stations on a tributary entering upstream from a main-stream station are listed before that station. A station on a tributary that enters between two main-stream stations is listed between them. A similar order is followed in listing stations on first rank, second rank, and lower ranks of tributaries.

As an added means of identification, each surface-water hydrologic station and partial-record station has been assigned a station number. In assigning station numbers, no distinction is made between partial-record stations and other stations; therefore, the station number for a partial-record station indicates downstream-order position in a list made up of both types of stations. Gaps are left in the series of numbers to allow for new stations that may be established; hence, the numbers are not consecutive. The complete 8-digit number for each station such as 02349500 includes the 2-digit part number "02" plus the 6-digit downstream order number "349500". In this report, the 3-digit sequence "023", which is common to all stations in the study area, has been omitted. Also for the reader's convenience, stations shown in all figures and referred to in the text are identified by a 1- or 2-digit map identification number. This number is keyed to the appropriate station number in the tables.

Test-Well Drilling

A test drilling program was necessary to obtain geophysical logs, lithologic samples, water samples, and hydraulic data where no wells existed or where existing data were inadequate. Thirty-five wells were drilled under private contract and 15 wells were drilled by the Georgia Geologic Survey. Twelve wells were drilled in 1979 and the remaining 38 wells were drilled in 1980. (See fig. 2 and table 1.)

Spontaneous-potential, electric-resistivity, gamma-gamma, neutron, caliper, and gamma logs were run in the 50 Dougherty Plain investigation test wells and in 18 privately owned wells. Drill cuttings from the test wells were collected, examined, and described lithologically (Mitchell, 1981, tables 3-46). These geophysical and lithologic logs and data from previous investigations were used as an aid in delineating and correlating stratigraphic and geohydrologic units. Watson (1981) presents this information diagrammatically in maps showing altitudes of the tops and thicknesses of the principal artesian aquifer and associated confining beds and a generalized geohydrologic section in a geohydrologic atlas prepared as part of the Dougherty Plain investigation.

Sources and Use of Hydrologic Data

The main sources of temperature, precipitation, and other climatological data are monthly bulletins and other reports published by the National Weather Service, National Oceanographic and Atmospheric Administration. Data concerning

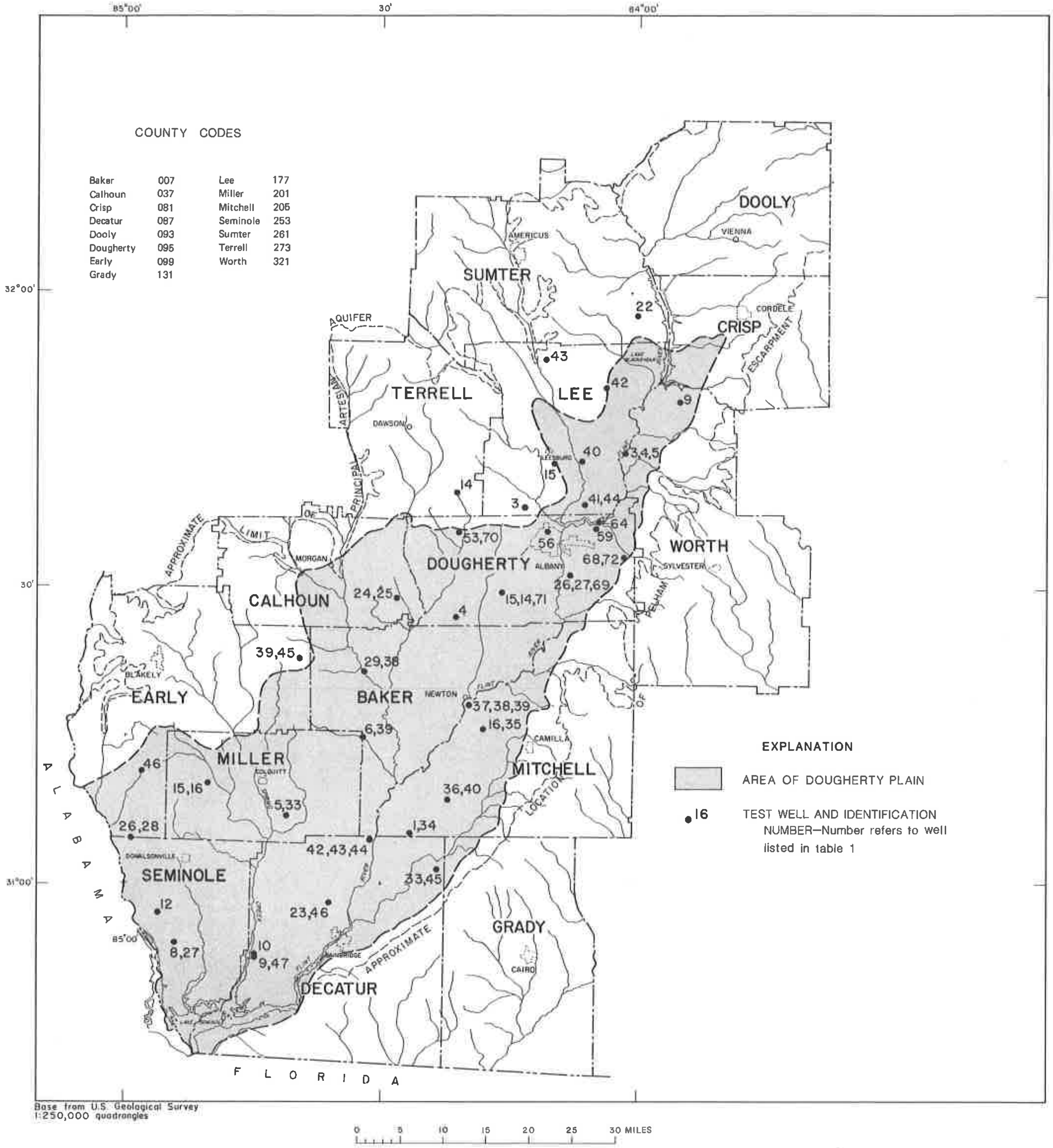

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Figure 2.— Locations of test wells.

Table 1.--Summary of test-well data

[Geohydrologic unit: PCPA, principal artesian aquifer; RSDM, residuum; TLLT, Tallahatta aquifer. Lithology (number in parenthesis is clay percentage): LMST, limestone; CS, sandy clay; SC, clayey sand; SD, clean sand; SP, poorly sorted sand; SS, sand containing silt and clay]

						Geohydrologic unit characteristics	
Well No.	Well name	Geohydro-logic unit	Altitude of land surface (ft above NGVD)	Well depth (ft)	Casing depth (ft)	Thick-ness (ft)	Lithology
			Baker County				
06	Jo-Su-Li TW 1	PCPA	160	180	76	160	LMST
29	T. Rentz TW 1	PCPA	158	112	70	75	LMST
38	T. Rentz RW	RSDM	155	16	6	21	SS(15)
39	Jo-Su-Li RW	RSDM	160	20	10	29	CS(57)
			Calhoun County				
24	B. Jordan TW 1	RSDM	192	32	22	37	SC(30)
25	B. Jordan TW 2	PCPA	195	145	--	60	LMST
			Decatur County				
09	A. Newton, South TW	PCPA	115	145	60	250	LMST
10	A. Newton, North TW	PCPA	120	185	76	250	LMST
33	J. Hall TW 1	PCPA	142	160	88	325	LMST
42	1/DP 4	TLLT	145	455	382	--	SD
43	DP 5	PCPA	145	90	54	264	LMST
44	DP 6	RSDM	145	40	30	54	SC(30)
45	J. Hall TW 2	RSDM	135	35	25	40	SC(35)
46	G. Bolton TW 2	RSDM	128	27	17	32	SC(32)
47	A. Newton	RSDM	112	39	29	53	SP(9)
			Dougherty County				
14	Nilo, South TW	PCPA	203	150	60	150	LMST
15	Nilo, North TW	PCPA	201	150	63	165	LMST
69	School Bus Road TW 1	RSDM	195	29	19	35	CS(54)
70	Game and Fish TW 1	RSDM	215	15	6	19	SC(37)
71	Nilo TW 3	RSDM	202	40	30	50	SS(11)
72	USMC Supply TW 1	RSDM	227	45	35	107	SS(17)
			Early County				
39	I. Newberry TW 1	PCPA	230	125	61	70	LMST
45	I. Newberry TW 2	RSDM	230	30	20	40	CS(50)
46	V. Evans TW 1	RSDM	178	40	30	46	SC(40)
			Lee County				
15	M. Moorman TW 1	PCPA	240	190	64	140	LMST
40	Piedmont Plant Farm TW 1	RSDM	245	40	30	47	SC(37)
41	S. Stocks TW 1	RSDM	238	40	30	50	SP(6)
42	B. King TW 1	RSDM	306	19	9	24	SC(49)
43	H. Usry TW 1	RSDM	300	28	18	34	CS(68)
44	S. Stocks TW 2	PCPA	238	--	--	135	LMST
			Miller County				
15	DP 2	PCPA	180	75	64	120	LMST
16	DP 3	RSDM	180	40	30	55	CS(65)
33	J. Fleet TW 2	RSDM	152	36	26	41	SC(31)
			Mitchell County				
16	C. Holton TW 1	PCPA	150	190	50	250	LMST
34	H. Meinders TW 2	RSDM	145	40	30	59	SS(22)
35	C. Holton TW 2	RSDM	160	50	40	60	SD
36	H. Davis TW 1	RSDM	147	35	25	40	SC(25)
37	DP 10	TLLT	165	417	397	--	SD
38	DP 11	PCPA	165	225	62	252	LMST
39	DP 12	RSDM	165	37	21	40	SC
			Seminole County				
08	Roddenberry TW 1	PCPA	115	150	63	225	LMST
26	2/D. Harvey TW 1	PCPA	152	125	58	75	LMST
27	Roddenberry TW 2	RSDM	115	33	23	39	CS(55)
28	2/D. Harvey TW 2	RSDM	151	39	30	54	SC(48)
			Sumter County				
22	E. Stephens TW 1	RSDM	290	27	17	34	SC(37)
			Terrell County				
14	A. Vann TW 1	RSDM	263	20	10	20	CS(73)
			Worth County				
03	DP 7	TLLT	230	330	315	--	SD
04	DP 8	PCPA	230	120	63	162	LMST
05	DP 9	RSDM	230	28	10	40	SS(20)
09	C. Odom TW 1	RSDM	275	34	24	43	CS(55)

1/ DP indicates that the well is one of three test wells at the same site: DP 4, 7, and 10 are Tallahatta wells; DP 2, 5, 8, and 11 are principal artesian aquifer wells; and DP 3, 6, 9, and 12 are residuum wells.

2/ Well is actually just across county line in Early County; however, to avoid changes in the numbering system devised by Mitchell (1981), the well is listed in Seminole County.

streamflow and stage measurements in and adjacent to the study area are available from the files and publications on surface-water supply by the U.S. Geological Survey. Additional streamflow measurements were made in major streams in the Dougherty Plain during August 1980 and January 1981. Ground-water contributions to streamflow were estimated by using hydrograph separation techniques and baseflow recession and flow-duration curves. Water levels were measured twice a year in about 200 wells that are open only to the principal artesian aquifer (fig. 3).

Periodic water-level measurements also were made in wells open to the confining beds immediately overlying and underlying the principal artesian aquifer. Water from selected wells open to either the principal artesian aquifer or the overlying residuum was analyzed for organic and inorganic constituents.

Additional hydraulic data were obtained from aquifer tests, core samples, cuttings from test wells, and geophysical logs. Water-level drawdown and recovery measurements were made in pumping and observation well(s) and used to compute transmissivity and storage coefficients of the principal artesian aquifer. Results of digital ground-water flow modeling were used to aid in defining the aquifer flow system and to simulate results of hypothetical pumping situations.

Acknowledgments

Appreciation is extended to the following for allowing test drilling on their properties and for their continued cooperation throughout the study: Alvin Newton, I. M. Newberry, Jr., M. Moorman, Douglas Harvey, J. Hall, T. Rentz, Randall Newberry, Gerome Wells, Clyde Bradley of the Roddenberry Co., Clayton Holton of the Reba Corp., Robert Webber of AG-CON, Inc., and L. Johnson and Ralph Thompson of Jo-Su-Li Farms. The courtesies and help extended by T. Brogden, F. Thompson, and Kendall Bradley, and by John Flatt of Layne-Atlantic Co., are sincerely appreciated.

GEOGRAPHY

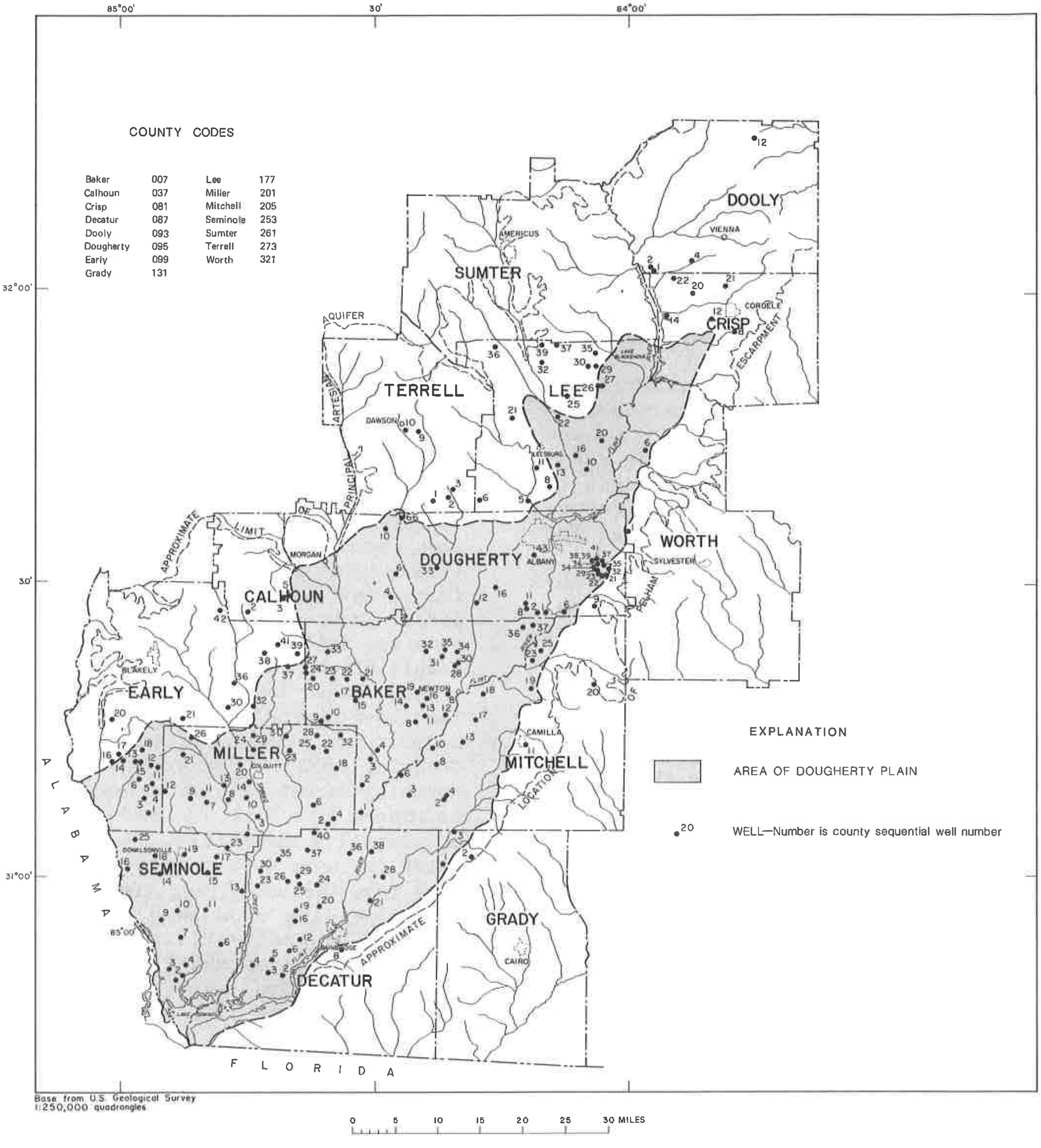
The Dougherty Plain, which receives its name from Dougherty County, is a nearly level area consisting of a series of level units. The plain is bounded on the west by the Chattahoochee River, on the east by the Pelham Escarpment, and lies roughly southward of the updip limit of the principal artesian aquifer (fig. 1). The plain slopes southeastward or southward from about 300 ft above sea level along the northern border to about 150 ft above sea level along the foot of the Pelham Escarpment and to about 50 ft above sea level below the confluence of the Flint and Chattahoochee Rivers. The average land-surface elevation is about 160 ft above sea level.

The Dougherty Plain is characterized by karst topography having numerous shallow, nearly circular, depressions (filled-in sinkholes) ranging in size from a few tens of square feet to many acres. Most of the older sink-hole bottoms are filled with silt and clay. As a result of the inability of water to move through these low permeability sediments, the older sinkholes form ponds that may hold water year round (Hendricks and Goodwin, 1952). The younger sinkholes normally do not hold water because their bottoms are not filled with low-permeability materials. Consequently, water can move easily from them or into them from the underlying limestone aquifer, depending upon head differential.

The Dougherty Plain is drained by the Chattahoochee and Flint Rivers and their tributaries. The drainage system will be discussed in more detail later in the report.

GEOLOGY

The area of investigation is underlain by a succession of sand, clay, and carbonate rocks to a depth of more than 5,000 ft (table 2). This report, however, is concerned with only the uppermost geologic units consisting of the residuum, the Ocala Limestone, and the



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EXPLANATION

▨ AREA OF DOUGHERTY PLAIN

•20 WELL—Number is county sequential well number

Figure 3.—Locations of water-level observation wells open to the principal artesian aquifer.

Table 2.—Generalized stratigraphy, water-bearing properties, and water-quality characteristics of formations underlying the Albany area

[From Hicks and others, 1981]

Era	System	Series	Gulf Coast Stage	Group and formation		Thickness (feet)	Lithology	Water-bearing properties	Water-quality characteristics
CENOZOIC	Quaternary	Pleistocene			Dune sand	0-35	Fine to coarse, well sorted, angular to subangular quartz sand	Not water bearing	
					Terrace deposits	0-20	Poorly sorted gravel, sand, and clay	Not water bearing	
	Tertiary	Oligocene	Vicksburgian		Flint River Formation		Light-gray, cherty limestone	Properties unknown	Quality unknown
		Eocene	Jacksonian		Ocala Limestone	150-200	White to light-pink, fossiliferous limestone	Ocala aquifer is a very productive water-bearing unit throughout the Dougherty Plain. Reported well yields of more than 2,000 gal/min. Yields decrease north and west of Albany	Water is generally a hard calcium bicarbonate type that meets all State drinking water standards (1977)
			Claibornian	Claiborne Group	Lisbon Formation	235-340	Slightly glauconitic, fine, calcareous sand, clay, and interbedded limestones	Limited water-bearing potential—used only in multiaquifer wells where other aquifers are tapped	Water is a hard calcium bicarbonate type that meets all State drinking water standards (1977) and is suitable for most uses
					Tallahatta Formation		Fine to medium sand, clayey sand, and interbedded limestone layers that are very fossiliferous at the top of the formation	Tallahatta aquifer is a major aquifer in the Albany area; used for municipal, agricultural, and industrial supplies. Reported well yields of as much as 1,400 gal/min	
			Sabinian	Wilcox Group	Hatchetigbee Formation		Very fine, green-stained quartz sand, locally calcareous and glauconitic	Aquifer is tapped by many multiaquifer wells; however, water-bearing properties unknown	
		Upper Paleocene			Tuscahoma Sand and Nanafalia Formation, undifferentiated	110-120	Fine to medium, micaceous, clay-rich sand. Glauconite is abundant throughout. Lower part is nonfossiliferous, clay-rich sand (occasionally greater than 50 percent clay)	Used in some multiaquifer wells; water-bearing properties unknown	Quality unknown
		Lower Paleocene	Midwayan	Midway Group	Clayton Formation (upper unit)	40-120	Fine to medium, calcareous quartz sand and interbedded thin limestones	Used in some multiaquifer wells; water-bearing properties unknown	The Clayton aquifer produces water that is suitable for municipal, agricultural, and industrial supply. It is generally a soft sodium bicarbonate type that meets all State drinking water standards (1977)
					Clayton Formation (limestone unit)	70-125	Massive, light-gray, recrystallized limestone. Very fossiliferous at the top of the unit	Clayton aquifer is a major aquifer in the Albany area. East of Albany the aquifer is a poor producer; however, to the west and northwest, well yields as great as 2,000 gal/min have been reported	
					Clayton Formation (lower unit)	15-40	Fine to medium, arkosic sand, locally glauconitic and silty	Water-bearing properties unknown	
MESOZOIC	Cretaceous	Gulfian	Navarroan		Providence Sand	>2,500	Upper part of unit is a dense, gray, clayey sand. Middle part is generally a coquina. Lower part is sand containing varying amounts of silt	Providence aquifer is used in the Albany area for municipal and industrial supply. Yields range from less than 25 to about 500 gal/min	Water from this aquifer is a soft sodium bicarbonate type that is suitable for most uses and meets State drinking water standards (1977)
					Ripley Formation		Fine to medium, calcareous sand and fossiliferous claystone	Not water bearing	
			Tayloran		Cusseta Sand		Fine, micaceous, calcareous sand containing varying amounts of silt and clay	Not used as an aquifer in the Albany area; however, in other areas of Georgia yields as great as 500 gal/min have been reported	Water is a soft sodium bicarbonate type that has concentrations of chloride and dissolved solids that exceed State drinking water standards (1977)
					Blufftown Formation				
			Austinian		Eutaw Formation		Alternating layers of sand, sandy clay, and clay	Not used in the Albany area	Water quality is about the same as that in the Cusseta and does not significantly change through the Tuscaloosa. Below the Tuscaloosa, the concentration of sodium chloride is reported to increase significantly
			Eaglefordian Woodbinian		Tuscaloosa Formation				
		Comanchean	Washitan, Fredericksburgian, and Trinitian		Undifferentiated				

Lisbon Formation. The reader is referred to Hicks and others (1981) and Wait (1963) for a discussion of the lower units.

Residuum

The surficial geology of the Dougherty Plain consists of a residual layer of sand and clay derived from chemical weathering of the Ocala Limestone. The ratio of sand to clay in this 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 (fig. 4).

Ocala Limestone

The Ocala Limestone is light colored and fossiliferous. The upper surface dips generally southeastward and occurs from about 300 ft above sea level in the northern part of the study area to about sea level in the southern part, but is highly irregular because of differential weathering (fig. 5).

The Ocala ranges in thickness from a few feet at the updip limit to about 350 ft in the southeastern part of the Dougherty Plain (fig. 6). The limestone is exposed along sections of major streams such as the Chattahoochee and Flint Rivers and Spring Creek, where erosion has removed the residuum. The Ocala is reduced in thickness at these exposures and near the updip limit may be entirely removed by a deeply incised stream.

The irregular surface of the top of the Ocala Limestone reflects solution that probably occurred during advances and retreats of Pleistocene seas. Numerous circular depressions in the topography of the study area seem to be the result of settling of sediment-filled sinkholes.

Sinkholes formed by recent collapse and erosion are also common. Collapse sinks, which are normally steep sided and a few feet to tens of feet deep, can develop without warning and be fully developed in a short time. Erosion sinks occur where large volumes of residuum migrate downward into solution openings in the limestone and are carried away by moving water, creating a large cavity in the overlying residuum (Newton, 1976). When the cavity becomes so large that the strength of the overlying material is insufficient to maintain a cavity roof, collapse takes place, forming a sink. Most erosion sinks are shallow and have gently sloping sides.

Lisbon Formation

The Ocala Limestone is underlain by the Lisbon Formation, which consists of hard, well-cemented, sandy, clayey limestone of middle Eocene age. The Lisbon dips generally southwestward at about 12 ft per mile. The top surface occurs at altitudes ranging from nearly 300 ft above sea level in the northwestern part of the report area to about 350 ft below sea level in the southeastern part (fig. 7). Because of its distinctly lower water-yielding capability compared to the Ocala Limestone, the top of the Lisbon is considered to be the base of the principal artesian aquifer in the Dougherty Plain area.

THE HYDROLOGIC SYSTEM

Rainfall

Annual rainfall in the Dougherty Plain area averages about 53 inches and ranges from about 46 to 56 inches (fig. 8). Average monthly rainfall varies from 2 inches in October to 5 inches in March and 6 inches in July. Rainfall during the periods January through March and

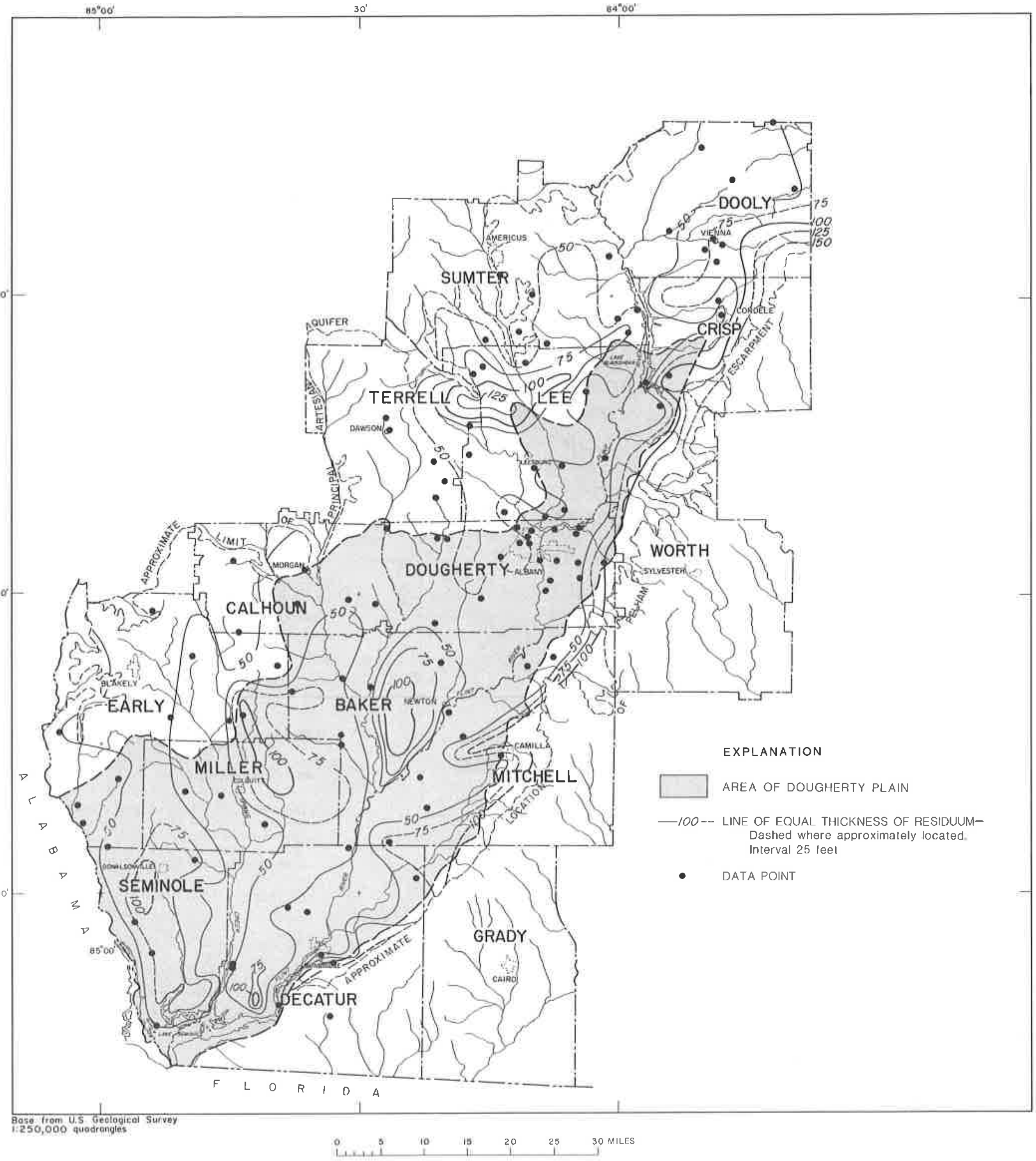
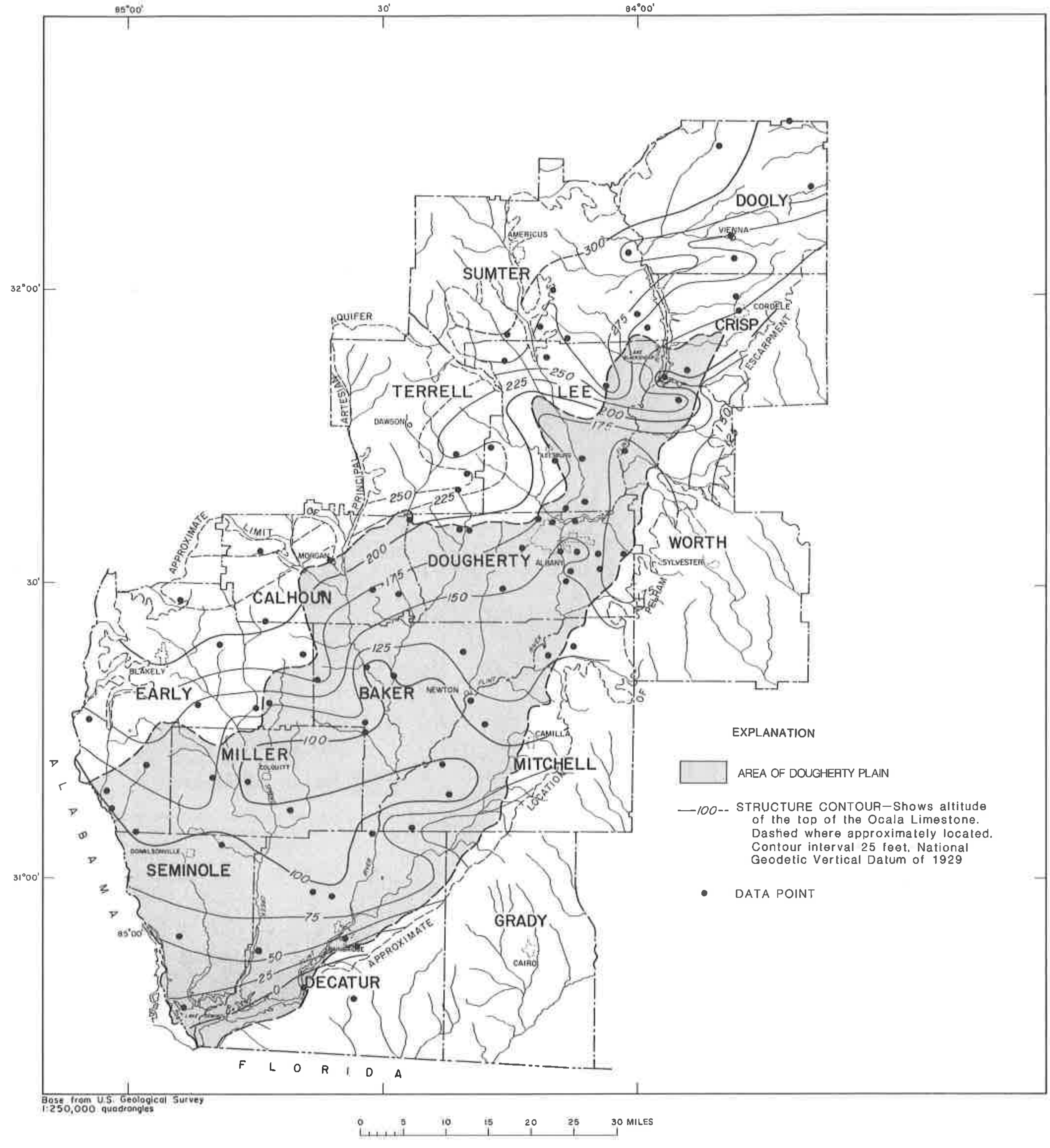
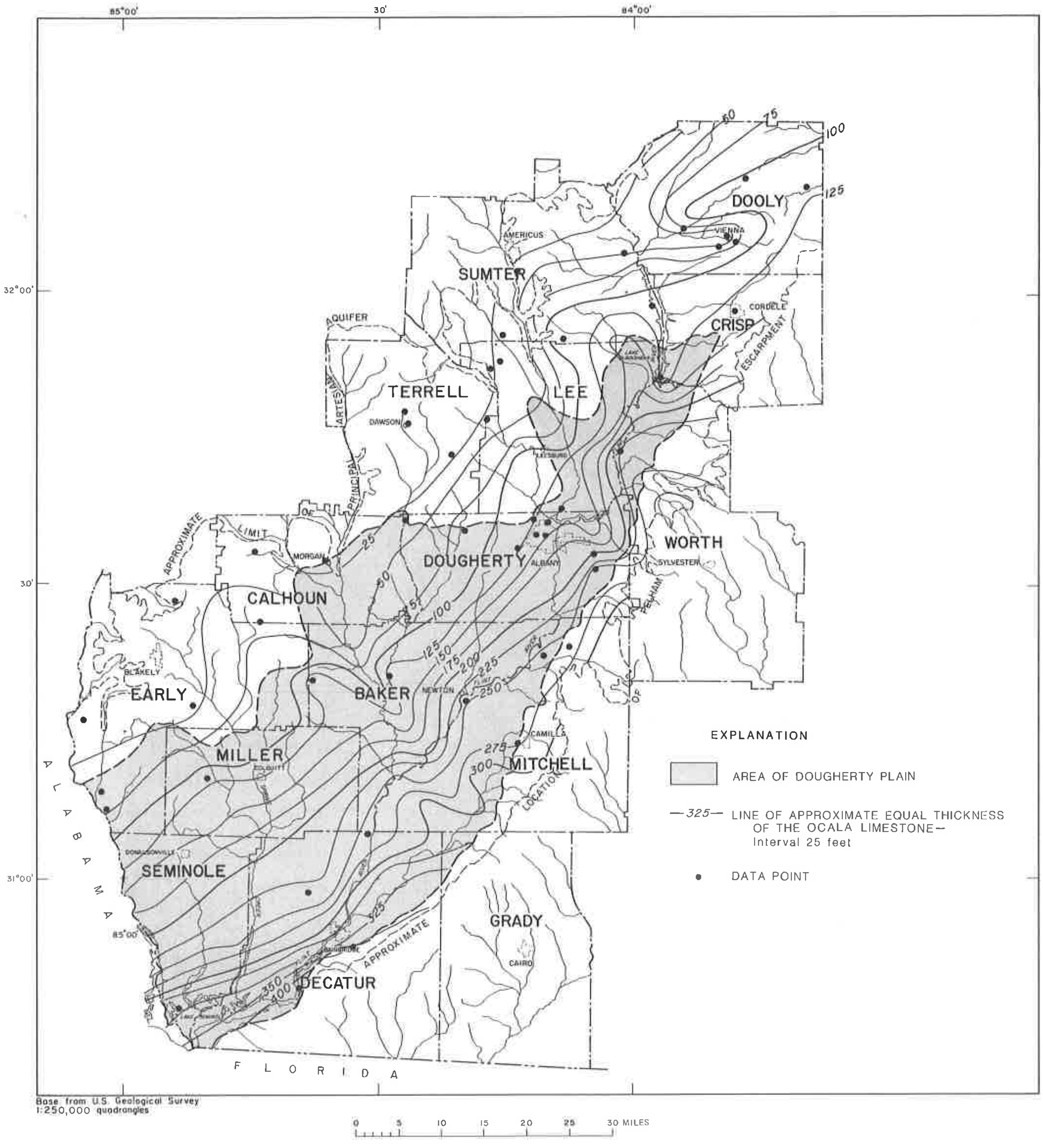


Figure 4.—Approximate thickness of the residuum. From Watson (1981).



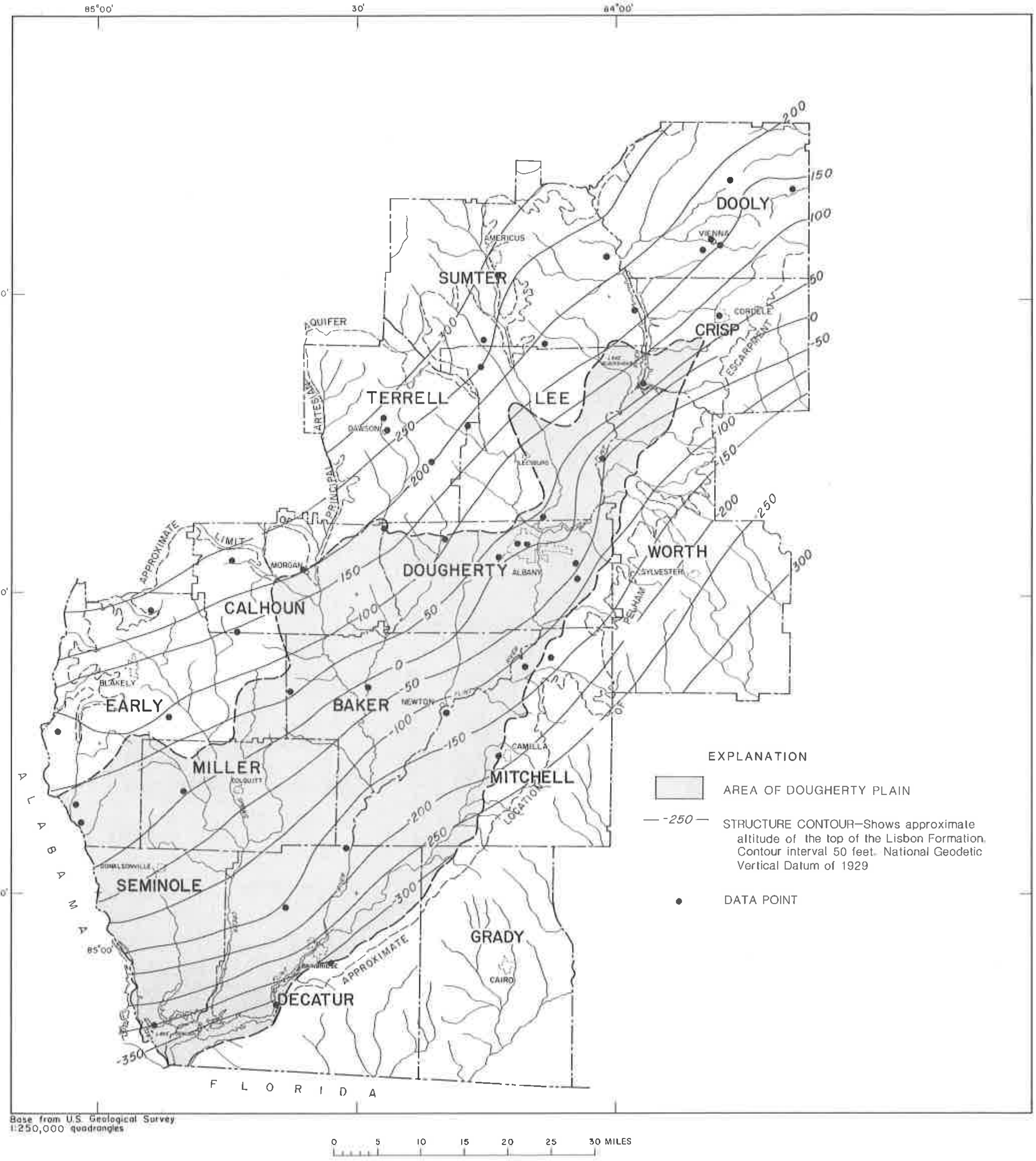
Base from U.S. Geological Survey 1:250,000 quadrangles

Figure 5.—Altitude of top of the Ocala Limestone. From Watson (1981).



Base from U.S. Geological Survey
1:250,000 quadrangles

Figure 6.—Approximate thickness of the Ocala Limestone. From Watson (1981).



Base from U.S. Geological Survey 1:250,000 quadrangles

Figure 7.—Generalized altitude of the top of the Lisbon Formation. From Watson (1981).

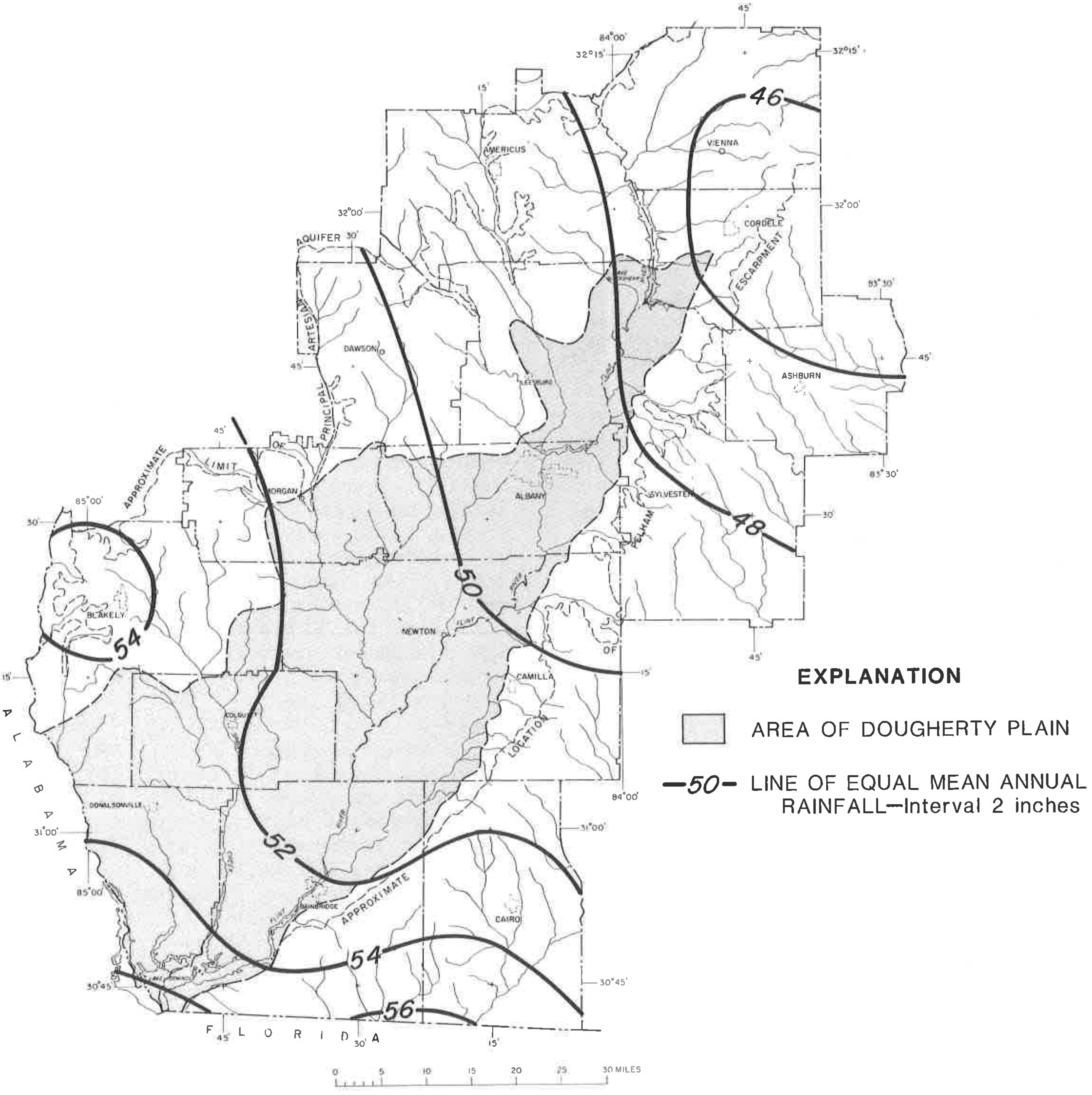


Figure 8.—Average annual rainfall in the Dougherty Plain area, 1941—70. From Carter and Stiles (1982)

June through August is about equal in magnitude (15 inches), but differs greatly in duration and distribution. 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.

Rainfall varies considerably from year to year and from month to month. For example, annual rainfall at Albany varied from 35 inches in 1968 to 73 inches in 1964 (fig. 9). Monthly rainfall varied from 0.4 inch in October 1979 to 10 inches in February 1979 and from 0.8 inch in November 1980 to 12 inches in March 1980. Rainfall data collected at eight other stations in the Dougherty Plain indicate that spatial variation of rainfall is considerable and may vary from half to twice as much as that recorded at Albany for the same month.

As shown in figure 10, during September through May there is usually a direct correlation among precipitation, streamflow, and water levels in the principal artesian aquifer. Streamflow peaks occur soon after rainfall peaks as a result of direct runoff and precipitation falling directly into the stream channel. Ground-water peaks shown in figure 10 generally occur about 1 month after major precipitation peaks. This lag occurs because the precipitation moves slowly downward through the low-permeability residuum and takes some time to show up as recharge to the principal artesian aquifer. Ground-water recharge resulting from rainfall will be discussed in more detail later in the report.

Rainfall seems to have little effect on streamflow and water levels from June through September (figs. 9 and 10). This is because evaporation-transpiration is extremely high during these months in the Dougherty Plain area, and almost all rainfall is lost to the evaporation-transpiration process. Consequently, rainfall is ineffective in recharging the ground-water system during summer months, and ground-water discharge is the primary source of streamflow.

Surface Water

Drainage Description

Streams draining the Dougherty Plain are of two types: (1) through-flowing streams that originate outside the area, including the Chattahoochee and Flint Rivers, and (2) streams that originate within the area, such as Spring, Kinchafoonee, Muckalee, and Turkey Creeks. (See fig. 11 for stream locations.)

The Flint River, which receives its name from large boulders of flint and silicified limestone, drains an area of about 6,000 mi^2 within the Coastal Plain. Major tributaries to the Flint River in the Dougherty Plain include Cooleewahee, Ichawaynochaway, and Spring Creeks, all of which originate in the Dougherty Plain. Muckafoonee Creek, which enters the Flint River upstream from Albany, is formed by Muckalee and Kinchafoonee Creeks, which rise near the western edge of the Dougherty Plain. Cooleewahee Creek flows southward from its origin west of Albany through a shallow, swampy valley to the Flint River at Newton. Ichawaynochaway Creek and its tributary, Chickasawhatchee Creek, drain shallow, swampy valleys and flow southward from their origin in Terrell County to the Flint River south of Newton. Spring Creek rises north of Colquitt and flows southward into Lake Seminole, about 3 miles northeast of the junction of the Flint and Chattahoochee Rivers. No large streams enter the Flint from the east. The Pelham Escarpment to the east of the Flint River forms both a surface-water and a ground-water divide. Numerous small streams on the west side of the divide flow westward to the Flint River.

The Chattahoochee River is longer and larger than the Flint River but drains only about 1,800 mi^2 within the Coastal Plain, or less than one-third of the area drained by the Flint. The Chattahoochee, like the Flint, is deeply incised within its flood plain and cuts into the underlying limestone aquifer.

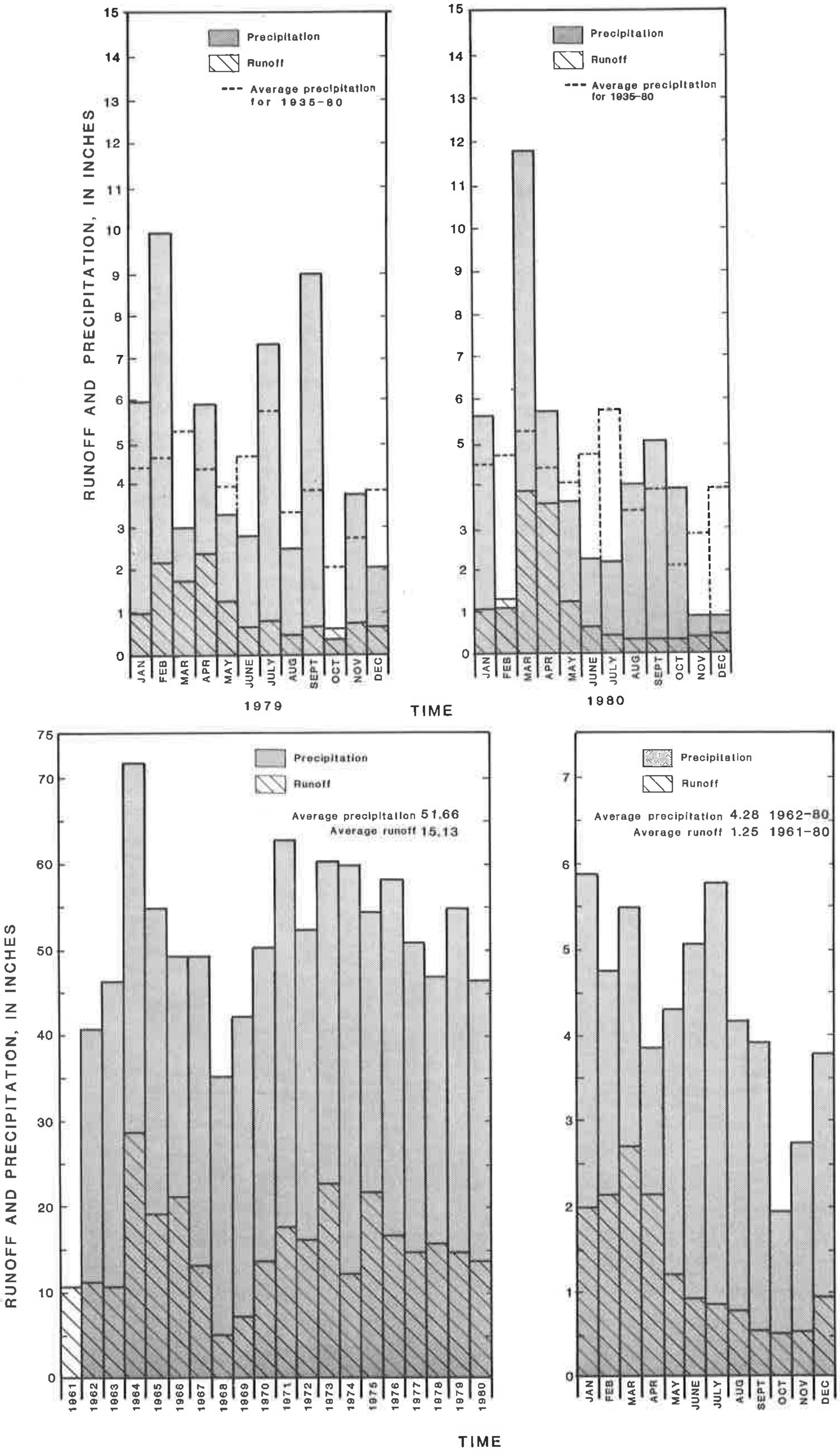


Figure 9.—Monthly and annual precipitation at Albany and monthly and annual runoff of Flint River between Montezuma 3 and Albany 24.

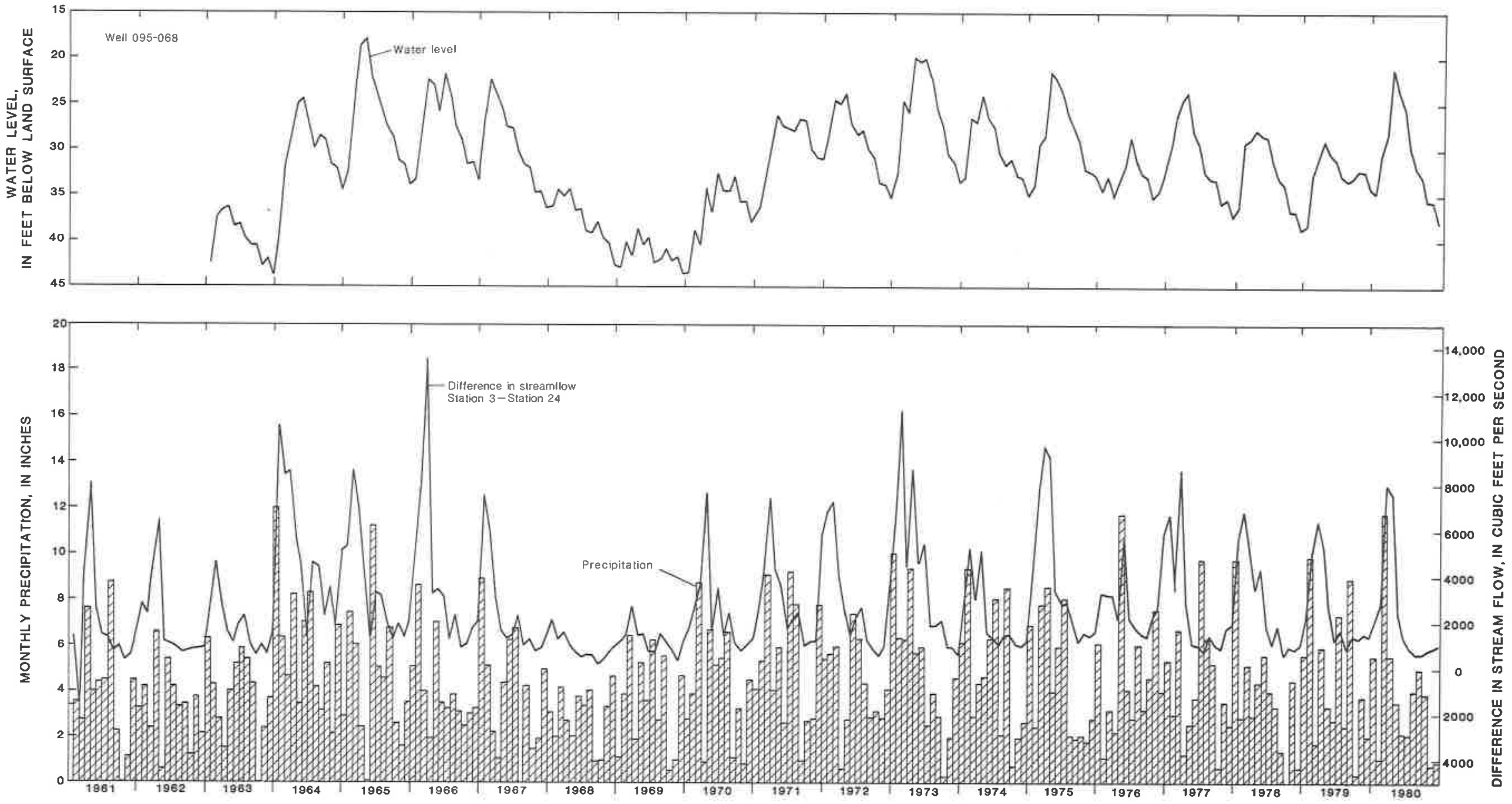


Figure 10.—Difference in monthly streamflow, precipitation, and principal artesian aquifer water levels near Albany.

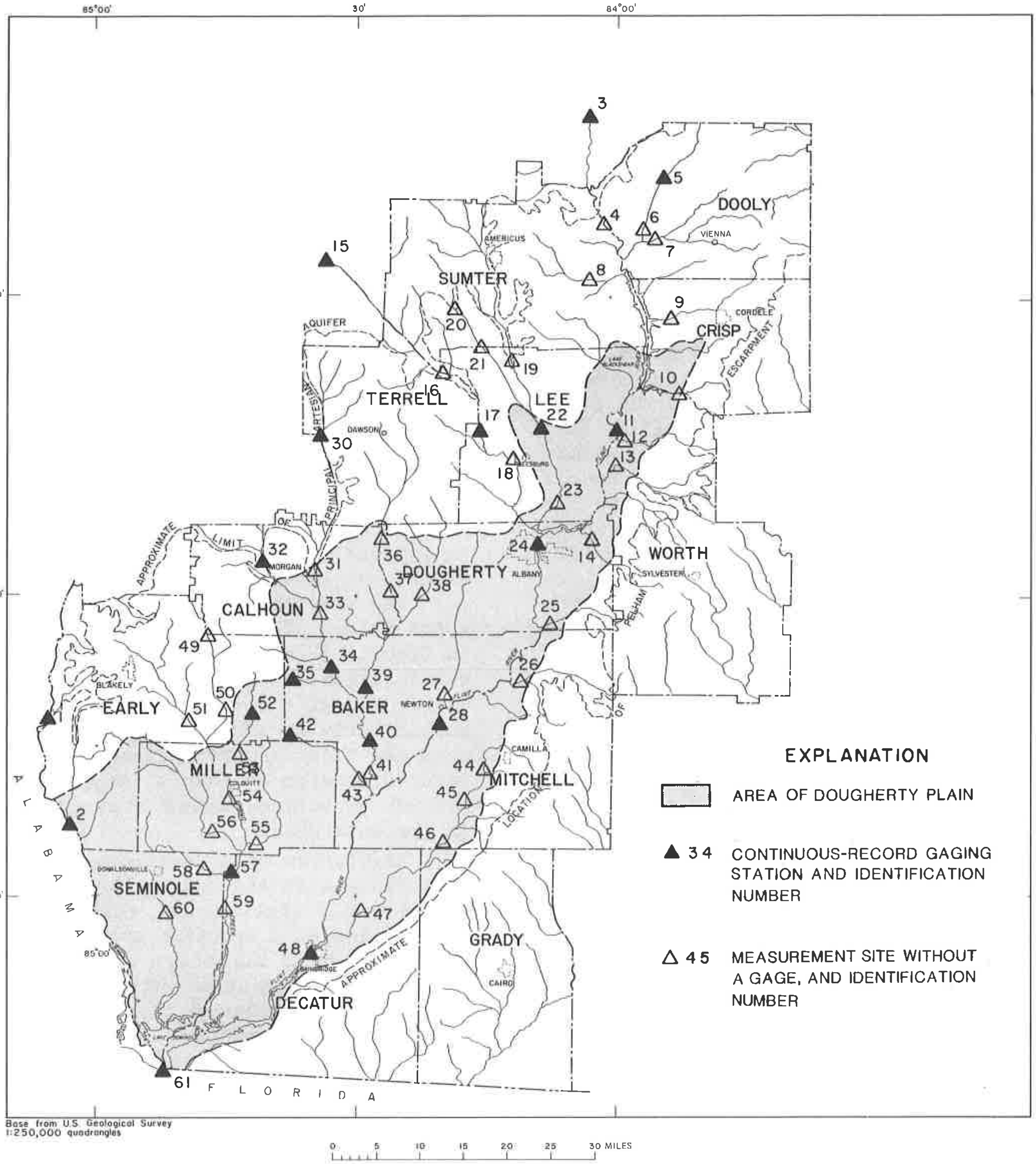


Figure 11.—Locations of streamflow gaging stations.

Swamps occur only along the lower reach of the Chattahoochee, primarily in Seminole and southern Early Counties. No large tributaries to the Chattahoochee River occur in the Dougherty Plain.

Streamflow

An important characteristic of streamflow is its variability with time and location. In order to measure and record streamflow on a systematic basis, continuous-record gaging stations have been operated in southwestern Georgia since the early 1900's. (See table 3 for a listing and figure 11 for locations of continuous-record stations referred to in this report.) Additional streamflow data used in this investigation include measurements of discharge at partial-record measurement stations made during August 4-7, 1980, and January 5-7, 1981 (table 4). Because streams in the Dougherty Plain area are utilized appreciably for both irrigation and power generation, collection and analysis of streamflow records are necessary to evaluate streamflow characteristics that may be used by planners, designers, and farmers in deciding how to best utilize the stream resources.

Flow duration

The flow-duration curve is a cumulative frequency curve that shows the percentage of time during which specified discharges were equaled or exceeded in a given period (Searcy, 1959). A flow-duration curve simply provides a means of representing in one curve streamflow characteristics throughout the range of discharge. It is important, however, to note that the flow-duration curve does not show the chronological sequence of flows and therefore is not a reliable method for predicting the dependability of flow. It is also not generally applicable to flood studies. If the curve is based on a sufficiently long period of stream-discharge data, the curve may be used to predict the distribution of future flows for water-power, water-supply, and pollution-load studies. The flow-duration curve also may be used for studying and comparing watershed characteristics.

Flow-duration curves were developed for stations in the Dougherty Plain area having more than 7 years of daily record by using standard computer programs developed by the U.S. Geological Survey (figs. 12 and 13). Selected streamflow station data and computer-generated coordinates used in plotting the curves are listed in table 5.

Except in watersheds where soils are highly permeable, the distribution of high flows is governed mainly by the climate, watershed physiography, and plant cover. Low-flow distribution is controlled mainly by basin geology. Consequently, the high end of the 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.

The moderately steep slopes of the upper halves of the flow-duration curves in figures 12 and 13 indicate that direct runoff significantly contributes to the higher flows; the relatively flat slopes, particularly at the lower end, 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.

Regulation of streamflows resulting from changes in storage in reservoirs or lakes has a significant effect on the flow regime at a specific stream site and is reflected in the stage and character of the flow-duration curve. Normally high flows are reduced in magnitude and low flows are augmented. Flow-duration curves for the Apalachicola River at Chattahoochee, Fla. (station 61), before and after regulation illustrate a moderate change in duration resulting from regulation by the Jim Woodruff Dam (fig. 12).

The low discharge parts of the flow-duration curves at stations 5, 35, and 40 (fig. 13) show distinctly steeper slopes than do the other curves shown in figures 12 and 13. During extended periods of

Table 3.--Continuous-record streamflow gaging stations

Station No.	Station name	Drainage area (mi^2)	Period of record used	Average annual runoff (in.)	Median discharge (ft^3/s)	Average discharge			Max. discharge (ft^3/s)	Min. discharge (ft^3/s)
						ft^3/s	[(ft^3/s)/mi^2]	Mgal/d		
43500	Chattahoochee River at Columbia, Ala.	8,050	1928-60	17.80	7,300	10,540	1.31	6,812	203,000	1,210
44000	Chattahoochee River at Alaga, Ala.	8,340	1939-70	18.87	8,500	11,590	1.40	7,490	112,000	1,230
49500	Flint River at Montezuma	2,900	1930-80	16.92	2,500	3,613	1.24	2,335	68,900	585
49500	do.	2,900	1980	17.46	2,280	3,719	1.28	2,403	28,700	845
49900	Turkey Creek at Byromville	45	1958-80	14.97	19	50	1.10	32	3,940	.1
49900	do.	45	1980	11.77	--	39	.86	25	679	2.5
50500	Flint River at Oakfield 1/	3,860	1929-58	15.46	3,100	4,397	1.14	2,842	60,500	152
50600	Kinchafoonee Creek at Preston	197	1951-77	14.82	150	215	1.09	139	8,200	18
52500	Flint River at Albany 1/	5,310	1901-80	16.21	4,300	6,338	1.19	4,096	77,000	372
52500	do.	5,310	1980	16.03	3,800	6,251	1.18	4,040	39,100	1,220
53000	Flint River at Newton 1/	5,740	1938-80	16.77	5,000	7,090	1.24	4,582	66,600	790
53000	do.	5,740	1980	15.60	--	6,579	1.15	4,252	34,500	1,610
53400	Pachitla Creek near Edison	188	1959-69	17.70	170	245	1.3	158	9,060	35
53500	Ichawaynochaway Creek at Milford	620	1939-80	17.57	560	802	1.29	518	11,900	116
53500	do.	620	1980	16.13	--	734	1.18	474	7,240	122
54000	Alligator Creek near Milford	14	1942-50	11.63	6.9	12	.86	7.8	84	0
54500	Chickasawhatchee Creek at Elmodel	320	1940-50	16.08	180	379	1.18	245	3,630	5
55000	Ichawaynochaway Creek near Newton	1,020	1938-47	15.80	880	1,187	1.16	767	10,300	205
55500	Big Cypress Creek near Milford	--	1942-49	--	.6	3.3	--	2.1	105	0
56000	Flint River at Bainbridge 1/	7,570	1908-71	15.68	6,400	8,730	1.15	5,648	83,200	1,340
56000	do.	7,570	1958-71	16.31	6,500	9,093	1.20	5,877	67,500	1,340
56500	Long Branch near Damascus	18	1945-49	17.35	27	23	1.27	15	787	0
57000	Spring Creek near Iron City	485	1938-70	13.36	230	477	.98	308	12,600	9
57000	do.	485	1958-70	14.28	230	510	1.05	330	8,260	11
58000	Apalachicola River at Chattahoochee, Fla.	17,200	1929-80	17.86	17,000	22,570	1.31	14,586	291,000	5,010
58000	do. 2/	17,200	1958-80	19.31	17,000	24,400	1.42	15,769	165,000	6,730
58000	do.	17,200	1980	20.12	20,000	25,420	1.48	16,428	103,000	8,790

1/ Discharge affected by powerplant operation, but normal operation of powerplant does not materially affect average monthly figures of runoff.

2/ After construction and filling of Jim Woodruff Dam (1954-57).

Table 4.—Base-flow discharge measurements

			Measurements			
Station No.	Station name	Drainage area (mi^2)	Date	Discharge (ft^3/s)	Date	Discharge (ft^3/s)
49800	Flint River near Methvins	3,200	8-4-80	1,070	1-5-81	1,600
49910	Turkey Creek near Drayton	76.0	8-6-80	10	1-5-81	21.1
49980	Pennahatchee Creek near Drayton	102	8-6-80	1.5	1-5-81	5.24
50070	Lime Creek near DeSoto	35.9	8-5-80	21	--	--
50220	Gum Creek at Coney	73.0	8-5-80	14	1-5-81	9.29
50360	Swift Creek near Warwick	40.0	8-5-80	15	1-5-81	11.0
50509	Jones Creek near Oakfield	50.5	8-5-80	7.1	1-5-81	4.39
50524	Abrams Creek near Oakfield	80.2	8-4-80	12	1-5-81	10.7
50543	Piney Woods Creek above Albany	60.4	8-4-80	0	1-6-81	0
50860	Kinchafoonee Creek near Smithville	485	8-5-80	66	1-6-81	210
51000	Kinchafoonee Creek near Leesburg	586	8-5-80	105	1-6-81	230
51700	Muckalee Creek near Smithville	265	8-5-80	39	1-5-81	163
51780	Muckaloochee Creek near Americus	27.1	8-7-80	8.9	1-6-81	16.8
51800	Muckaloochee Creek at Smithville	47	8-5-80	16	1-5-81	30.4
51920	Muckalee Creek below Leesburg	416	8-5-80	77	1-6-81	222
52760	Dry Creek near Putney	68.1	8-4-80	0	1-6-81	0
52920	Raccoon Creek near Baconton	92.9	8-4-80	0	1-6-81	0
52980	Cooleewahee Creek at Newton	151	8-5-80	7.8	1-6-81	1.84
53100	Ichawaynochaway Creek near Dawson	118	8-4-80	28	1-5-81	66.5
53265	Ichawaynochaway Creek near Morgan	301	8-5-80	70	1-5-81	158
53460	**Ichawaynochaway Creek near Leary**	570	8-5-80	130	1-6-81	280

Table 4.—Base-flow discharge measurements—Continued

			Measurements			
Station No.	Station name	Drainage area (mi^2)	Date	Discharge (ft^3/s)	Date	Discharge (ft^3/s)
54350	Chickasawhatchee Creek near Albany	118	8-4-80	.62	1-19-81	28
54410	Chickasawhatchee Creek near Leary	157	8-5-80	1.3	1-7-81	37.1
54440	Kiokee Creek near Pretoria	67.0	8-5-80	0	1-7-81	0
55000	Ichawaynochaway Creek near Newton	1,020	8-5-80	260	1-6-81	374
55350	Ichawaynochaway Creek below Newton	1,040	8-5-80	268	1-5-81	380
55600	Big Cypress Creek near Newton	—	8-5-80	0	1-5-81	0
55785	Big Slough near Camilla	105	8-4-80	1.1	1-5-81	4.6
55830	Big Slough below Camilla	157	8-4-80	0	1-5-81	.28
55880	Big Slough near Pelham	214	8-4-80	0	1-5-81	0
55950	Big Slough near Bainbridge	315	8-4-80	0	1-5-81	0
56100	Spring Creek near Arlington	49	8-5-80	3.0	1-6-81	2.40
56220	Spring Creek at Damascus	99.8	8-4-80	11	1-5-81	4.95
56290	Dry Creek near Blakely	45.5	8-4-80	6.9	1-5-81	8.78
56600	Long Branch near Colquitt	—	8-4-80	0	1-5-81	0
56640	Spring Creek at Colquitt	281	8-4-80	42	1-5-81	36.6
56860	Big Drain Creek near Boykin	—	8-5-80	0	1-6-81	0
56970	Aycocks Creek below Colquitt	—	8-5-80	0	1-6-81	0
57025	Dry Creek near Iron City	—	8-5-80	0	1-6-81	0
57050	Spring Creek at Brinson	560	8-5-80	150	1-6-81	82.7
57310	Fishpond Drain near Donalsonville	—	8-5-80	0	1-6-81	0

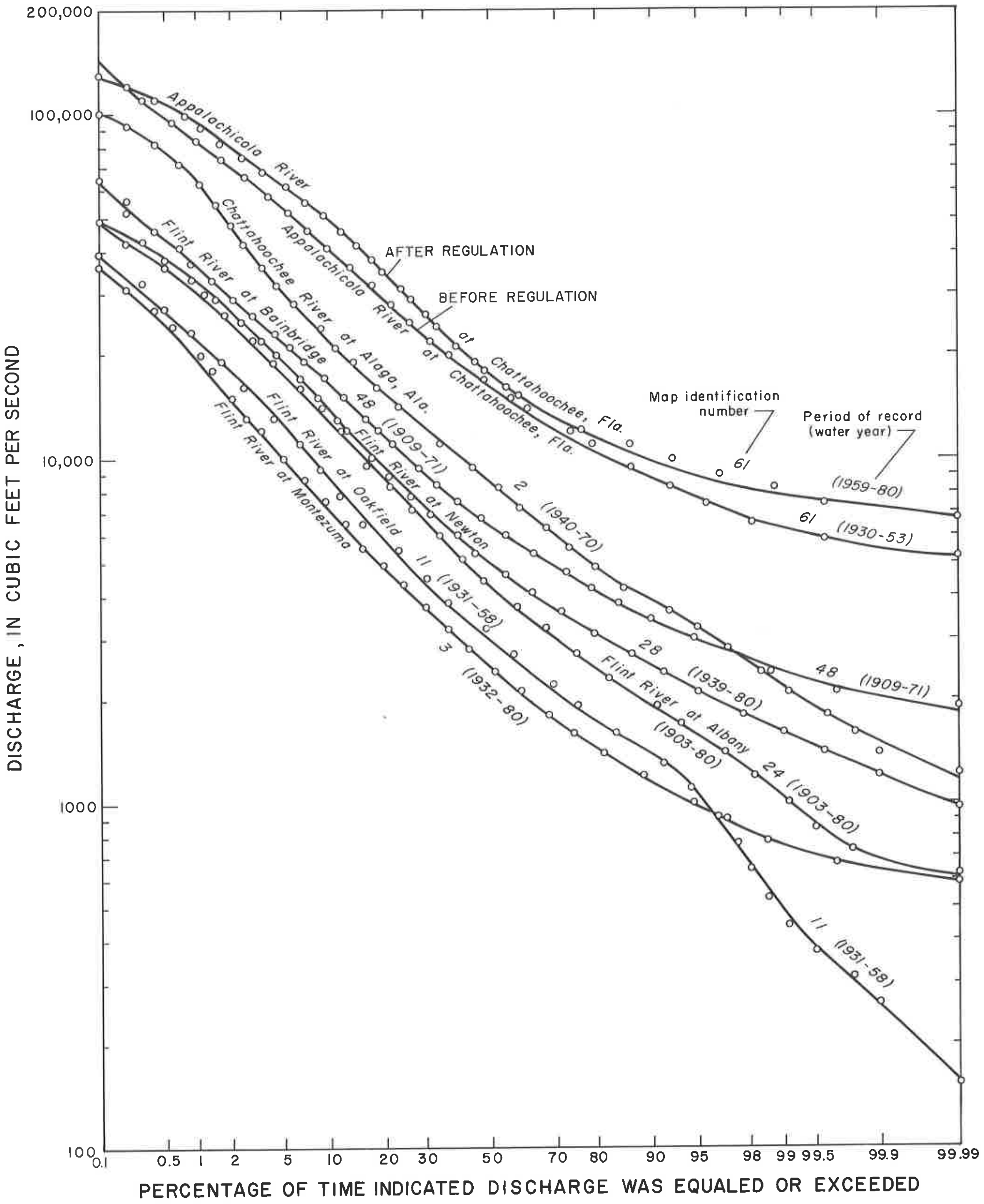


Figure 12.—Duration of daily flow at selected stations for eight major streams.

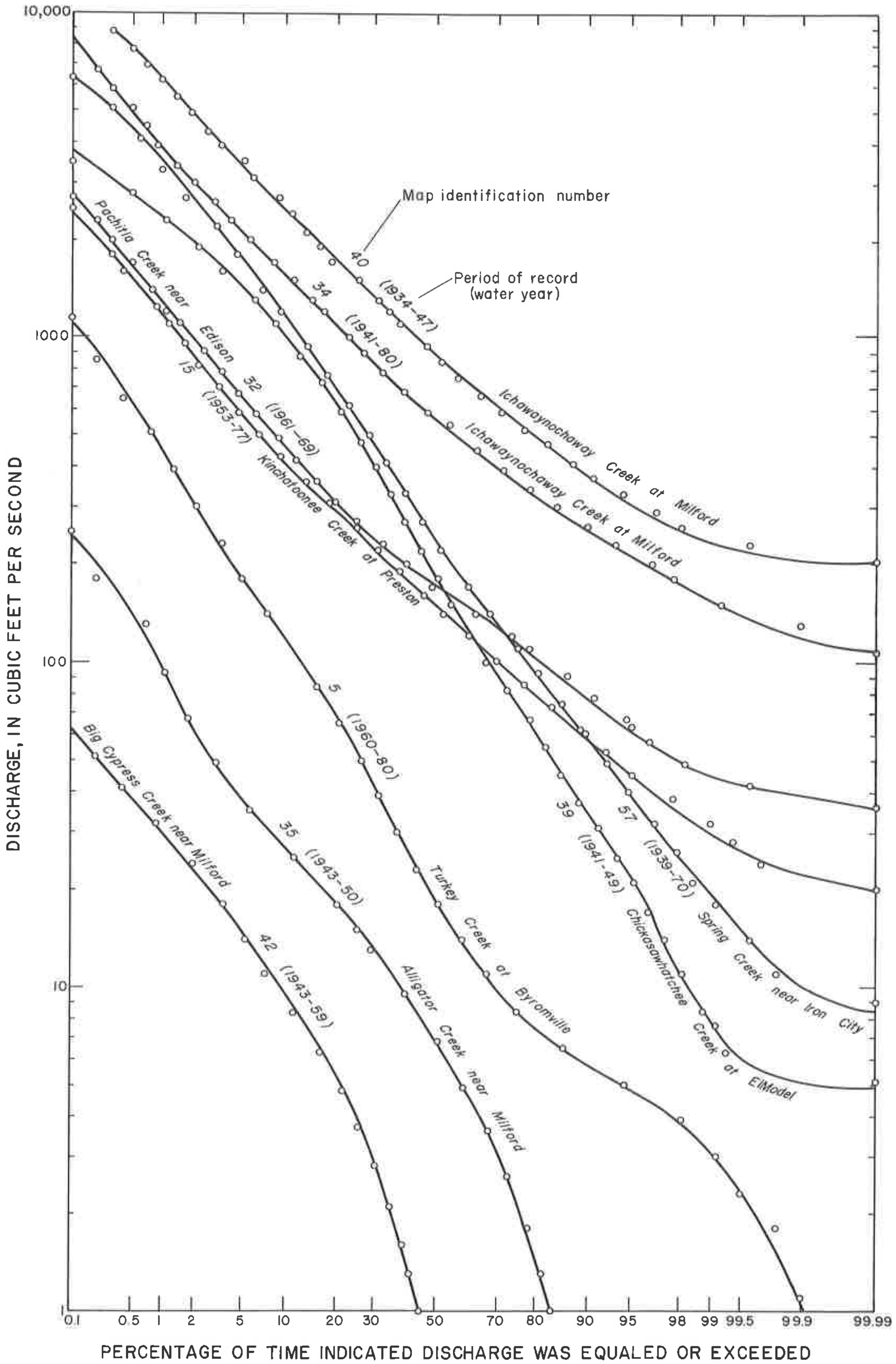


Figure 13.—Duration of daily flow at selected stations for nine minor streams.

Table 5.--Summary of flow-duration data

Station No.	Station name	Drainage area (mi^2)	Period of record	Percentage of time flow, in ft^3/s, was equaled or exceeded																	Variability index q50/q90
				0.1	0.5	1	2	5	10	20	30	50	70	80	90	95	98	99	99.5	99.9	
43500	Chattahoochee River at Columbia, Ala.	8,040	1930-60	90,000	70,000	57,000	44,000	28,000	20,000	13,000	11,000	7,200	5,000	4,200	3,200	2,500	2,000	1,700	1,500	1,200	2.25
44000	Chattahoochee River at Alaga, Ala.	8,340	1940-70	100,000	78,000	64,000	48,000	30,000	22,000	15,000	12,000	8,400	5,800	4,800	3,800	3,200	2,500	2,200	1,900	1,500	2.21
49500	Flint River at Montezuma	2,900	1932-80	36,000	25,000	20,000	15,000	10,000	7,400	5,000	3,800	2,500	1,700	1,400	1,200	1,000	840	780	720	640	2.08
49900	Turkey Creek at Byromville	45	1960-80	1,100	640	450	310	180	120	68	42	18	10	7.6	5.8	4.8	3.8	3.1	2.4	1.1	3.10
50500	Flint River at Oakfield	3,860	1931-58	39,000	27,000	23,000	18,000	13,000	8,800	5,800	4,400	3,000	2,100	1,700	1,400	1,000	660	480	380	250	2.14
50600	Kinchafoonee Creek at Preston	197	1953-77	2,400	1,500	1,200	880	580	410	290	220	150	100	80	58	46	35	30	27	22	2.59
52500	Flint River at Albany	5,310	1903-80	49,000	36,000	31,000	25,000	18,000	13,000	8,600	6,600	4,600	3,000	2,500	1,900	1,600	1,200	1,000	880	700	2.42
53000	Flint River at Newton	5,740	1939-80	49,000	39,000	33,000	27,000	19,000	14,000	9,200	7,000	4,900	3,700	3,100	2,500	2,100	1,800	1,600	1,500	1,200	1.96
53400	Pachitla Creek near Edison	188	1961-69	2,700	1,700	1,300	980	640	460	310	240	170	130	100	80	64	50	45	42	39	2.12
53500	Ichawaynochaway Creek at Milford	620	1941-80	8,400	4,900	3,800	3,000	2,100	1,600	1,100	820	560	400	330	260	220	180	150	140	120	2.15
54000	Alligator Creek near Milford	14	1943-50	240	140	98	62	38	27	18	13	6.8	3.1	1.5	--	--	--	--	--	--	--
54500	Chickasawhatchee Creek at Elmodel	320	1941-49	3,800	2,800	2,300	1,900	1,400	1,000	620	400	130	90	62	34	21	11	7.8	6.2	5.2	5.29
55000	Ichawaynochaway Creek near Newton	1,020	1939-47	--	7,800	6,200	4,800	3,300	2,500	1,700	1,300	880	600	490	370	310	260	240	230	210	2.38
55500	Big Cypress Creek near Milford	--	1943-49	62	39	32	23	15	10	5.4	3	--	--	--	--	--	--	--	--	--	--
56000	Flint River at Bainbridge	7,570	1909-71	64,000	44,000	36,000	30,000	22,000	16,000	12,000	9,000	6,400	4,800	4,200	3,400	5,000	2,600	2,400	2,200	2,000	1.88
57000	Spring Creek near Iron City	485	1939-70	6,400	4,300	3,500	2,600	1,700	1,100	700	470	230	130	94	60	40	25	19	15	10	3.83
58000	Apalachicola River near Chattahoochee, Fla.	17,200	1930-80	130,000	99,000	90,000	74,000	57,000	44,000	31,000	24,000	17,000	12,000	10,000	9,000	7,700	6,500	5,900	5,600	5,000	1.89
58000	do. 1/	17,200	1930-53	140,000	98,000	84,000	70,000	54,000	40,000	28,000	22,000	16,000	12,000	10,000	8,800	7,800	6,800	6,400	6,000	5,600	1.82
58000	do. 2/	17,200	1959-80	130,000	110,000	94,000	82,000	64,000	50,000	35,000	27,000	18,000	13,000	11,000	9,800	9,000	8,200	7,800	7,600	7,200	1.84

1/ Prior to construction and filling of Jim Woodruff Dam.

2/ After construction and filling of Jim Woodruff Dam.

little or no rainfall, these streams receive little base runoff from the underlying principal artesian aquifer, and usually cease flowing. The sharp downward steepening of the curve below the 98-percent duration of flow at Turkey Creek at Byromville (station 5) may be partly due to irrigation withdrawals from the stream upstream of the gage.

Normally the flow-duration curve for a particular station is based on all the observations of flow throughout the year for the available period of record; and, as indicated before, a curve computed in this manner fails to take into account time and seasonal effects. But, 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 all the January months for which records are available, are used to define a January curve.

Table 6 summarizes individual monthly flow-duration data for five stations and indicates seasonal variability in expected streamflows. If a graphical presentation is desired, the data can be plotted on log-probability paper which would give curves similar to those in figures 12 and 13. Because of the seasonal importance of low flows and to allow the low-water season to be considered as a unit, the climatic year (April 1 to March 31) was used as a basis for period of record for monthly flow-duration data and for low-flow frequency data.

Flow-duration values defined from all flows or from only individual months for similar periods of record vary considerably. For example, at station 24 (Flint River at Albany) for the same period of record, the 50-percent duration flow based on all March data is 10,000 ft^3/s, while the 50-percent duration flow based on all October data is 2,300 ft^3/s (table 6).

The seasonal nature of streamflow is of particular importance to those who use streamflow for supplemental irrigation. Those who use streamflow for irrigation are primarily concerned with the streamflow available from May through September. Data in table 6 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 predictive period. As will be discussed later, decline of ground-water levels associated with irrigation pumpage may result in some streams becoming influent, i.e., supplying water to the ground-water system whereas before ground water discharged to the streams, and to some extent "drying up." Where this occurs, streamflow will be less than discussed above.

Low-flow frequency

Information on low-flow recurrence is particularly important in the design of water-supply and waste-treatment facilities, because the lowest discharge commonly establishes the limit of supply without storage or the expected minimum dilution level for treatment operations during critical low-flow periods. For design purposes, the 7-day, 10-year low flow is the most commonly used value. It is based on annual minimum flows and indicates the lowest average flow during 7 consecutive days that is likely to be equaled or exceeded in severity on the average of 10 times in 100 years. This is not a common, nor is it an extremely rare flow.

The low-flow frequency data given in this report are for two types of stations: (1) daily-record stations having 10 consecutive years or more of daily record, and (2) low-flow partial-record stations. The data for the long-term daily-record stations were developed using the log-Pearson Type III method of analysis. At partial-record gaging stations, flow measurements made usually once a year during a time of base flow are related to concurrent flows at a nearby index continuous-record gaging station. The relation between these concurrent flows is used along with a frequency curve for the continuous-record

Table 6.--Flow duration for individual months at selected streamflow gaging stations

[Period of record, climatic years 1959-70]

	Percentage of time flow, in ft³/s, was equaled or exceeded					Percentage of time flow, in ft³/s, was equaled or exceeded					Percentage of time flow, in ft³/s, was equaled or exceeded				
Month	10	25	50	75	90	10	25	50	75	90	10	25	50	75	90
	Station 44000					Station 49900					Station 50500				
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 50600					Station 52500					Station 53000				
Jan.	510	350	250	170	110	19,000	11,000	6,700	4,400	3,100	19,000	11,000	7,400	4,700	3,700
Feb.	650	470	290	180	130	21,000	15,000	9,100	5,300	3,900	21,000	16,000	9,700	5,900	4,500
Mar.	650	430	300	200	140	23,000	15,000	10,000	6,700	5,000	24,000	16,000	11,000	7,600	5,700
Apr.	690	380	250	150	99	22,000	14,000	7,100	4,800	3,700	23,000	15,000	8,500	5,700	4,400
May	360	210	130	88	56	11,000	6,300	4,300	3,200	2,500	12,000	7,400	5,100	4,000	3,300
June	280	170	110	77	37	9,300	5,400	3,600	2,700	2,100	9,800	6,200	4,300	3,600	3,000
July	260	170	110	81	42	7,100	4,900	3,500	2,600	2,000	7,600	5,600	4,300	3,300	2,600
Aug.	260	160	93	67	36	6,900	4,900	3,000	2,200	1,500	7,600	5,700	3,800	2,800	2,200
Sept.	170	120	81	54	28	4,400	3,200	2,300	1,700	1,100	5,200	4,000	3,000	2,300	1,800
Oct.	240	120	80	60	36	6,300	3,400	2,300	1,600	940	6,600	3,900	2,900	2,200	1,600
Nov.	220	160	110	90	53	5,300	3,900	2,700	1,700	1,200	5,800	4,400	3,100	2,200	1,700
Dec.	350	230	160	120	98	8,700	6,000	3,900	2,800	2,100	8,700	6,200	4,200	3,200	2,700

Table 6.--Flow duration for individual months at selected streamflow gaging stations--Continued

[Period of record, climatic years 1959-70]

	Percentage of time flow, in ft^3/s, was equaled or exceeded					Percentage of time flow, in ft^3/s, was equaled or exceeded					Percentage of time flow, in ft^3/s, was equaled or exceeded				
Month	10	25	50	75	90	10	25	50	75	90	10	25	50	75	90
	Station 53500					Station 54500					Station 56000				
Jan.	2,000	1,200	750	570	450	1,300	810	400	250	110	21,000	13,000	8,900	6,100	4,800
Feb.	2,400	1,600	1,100	660	500	1,200	850	510	310	200	24,000	19,000	12,000	7,200	5,700
Mar.	2,300	1,600	1,100	790	630	1,900	1,200	680	460	230	26,000	21,000	14,000	10,000	7,400
Apr.	2,100	1,300	860	550	390	1,700	810	510	320	120	27,000	18,000	12,000	7,500	5,900
May	1,200	690	480	350	280	800	440	210	110	45	14,000	10,000	7,100	5,400	4,500
June	1,200	720	440	330	210	380	170	92	42	16	13,000	8,700	6,100	4,700	3,800
July	1,000	680	480	320	250	480	260	120	78	41	9,800	7,700	5,900	4,600	3,500
Aug.	860	570	420	320	240	520	290	170	75	24	9,800	7,200	5,400	4,000	3,200
Sept.	590	440	330	240	180	230	140	75	34	12	6,700	5,400	4,300	3,300	2,600
Oct.	840	490	330	250	200	230	120	63	33	6.3	8,900	5,700	4,200	3,300	2,700
Nov.	690	530	370	300	250	250	120	70	36	12	7,500	6,200	4,300	3,400	2,700
Dec.	1,100	720	520	400	350	1,300	400	120	76	41	11,000	7,900	5,800	4,500	3,800
	Station 57000					Station 58000									
Jan.	1,600	800	410	220	140	53,000	36,000	25,000	16,000	12,000					
Feb.	2,100	1,400	810	320	220	62,000	47,000	31,000	20,000	14,000					
Mar.	2,000	1,400	900	590	370	65,000	52,000	38,000	24,000	17,000					
Apr.	1,900	1,000	610	370	220	73,000	50,000	31,000	19,000	13,000					
May	680	430	260	180	130	38,000	26,000	17,000	13,000	11,000					
June	790	330	190	130	90	30,000	21,000	15,000	13,000	11,000					
July	610	370	180	100	65	25,000	19,000	14,000	12,000	10,000					
Aug.	450	290	200	110	73	22,000	17,000	13,000	11,000	9,800					
Sept.	330	160	110	68	46	19,000	14,000	12,000	9,800	8,600					
Oct.	470	230	120	68	36	22,000	13,000	11,000	8,800	7,500					
Nov.	390	170	110	68	39	21,000	16,000	11,000	9,200	7,400					
Dec.	430	250	170	97	75	34,000	22,000	14,000	12,000	10,000					

site to approximate flow-frequency data for the partial-record site. All low-flow data prior to 1977 used in this report are from Carter and Putnam (1978). Low-flow data extending beyond 1977 have been analyzed in accordance with their methods. (See table 7 for a listing of these data.) The areal distribution of 7-day, 10-year minimum annual flows is shown in figure 14.

Figure 14 and table 7 may be helpful to those interested in the use of streamflow for irrigation during periods of less than normal rainfall. Since the minimum flows often coincide with peak irrigation demands, the low-flow data give an indication of sustained streamflow available at that critical time. Expected low flows for gaged streams can be estimated from table 7, while expected low flows for ungaged streams can be estimated from figure 14 by using the data pertinent to that specific stream or watershed. Note, however, that their suggested use requires one to make an assessment of the severity of the hydrologic drought condition in order to choose the appropriate set of low-flow data.

Smaller streams in the Dougherty Plain generally have very low flows during dry seasons, with most having 7-day, 10-year flows of zero. Only the large streams are incised deeply enough to remain below the potentiometric surface of the principal artesian aquifer and receive ground-water discharge during extended dry periods. Contribution to 7-day, 10-year flow derived from drainage within the Dougherty Plain study area is about 1,600 ft^3/s.

Average Runoff

Runoff in the Dougherty Plain area varies from year to year and from month to month (fig. 9). Average runoff for selected basins was estimated by using runoff data from eight stations operated during a common period when average climatic conditions are believed to have been similar to long-term average climatic conditions. The common period selected was water years 1959 through 1970. Average annual rainfall for seven precipitation stations in the area of study during this period was 52.8 inches; long-term average annual precipitation (generally 1935 to 1979) for the same stations was 53.1 inches. Average runoff for the base period, 1959-70, is considered to be representative of expected basin runoff for periods of average hydrologic and climatic conditions.

The annual mean, early-spring high (Feb.-Apr.), and late-summer low (Sept.-Nov.) runoffs for the eight watersheds in the Dougherty Plain were determined for water years 1959-70. The runoff for each watershed (fig. 15) is that runoff measured at the most upstream part of the watershed subtracted from that runoff measured at the most downstream part. Runoff is much less during the summer months, primarily because of extremely high evapotranspiration losses and secondarily because of less rainfall than in the spring months.

Runoff for that part of each watershed within the Dougherty Plain was estimated. The sum (rounded) of these runoffs gives an annual mean runoff of 5,200 ft^3/s; a spring high of 9,200 ft^3/s; and a late-summer low of 2,700 ft^3/s. These quantities are the approximate total annual, spring high, and late-summer low-water yields of the Dougherty Plain area under average climatic and hydrologic conditions.

Base flow

The base flow of streams in the Dougherty Plain consists mostly of ground water discharged from aquifers hydraulically connected to the streams. Therefore, base flow can provide an estimate of the perennial ground-water yield of watersheds in the Dougherty Plain.

The base flow of a stream can be estimated by separating the overland flow from total discharge on a streamflow hydrograph by using techniques described by Riggs (1963). The base flows of nine streams in the Dougherty Plain were estimated by hydrograph separation techniques

Table 7.—Low-flow characteristics at selected streamflow gaging stations

Station No.	Station name	Drainage area (mi^2)	Period of record, climatic year	Recurrence interval (years)	Annual low flow, in ft^3/s, for indicated consecutive days							
					1	7	14	30	60	90	120	183
43500	Chattahoochee River at Columbia, Ala.	8,040	1930-60	2	2,540	2,860	2,990	3,330	3,780	4,300	4,660	5,480
				5	1,890	2,070	2,160	2,360	2,660	3,060	3,390	4,070
				10	1,600	1,730	1,800	1,940	2,170	2,510	2,840	3,460
				20	1,390	1,480	1,540	1,640	1,820	2,110	2,440	3,020
				30	1,200	1,300	1,360	1,370	1,500	1,800	2,100	2,600
				50	1,180	1,230	1,280	1,340	1,480	1,720	2,050	2,590
44000	Chattahoochee River at Alaga, Ala. 1/	8,340	1940-70	2	2,420	3,500	3,800	4,230	4,780	5,130	5,600	6,640
				5	1,760	2,300	2,660	3,070	3,460	3,800	4,230	5,290
				10	1,450	1,820	2,190	2,570	2,900	3,260	3,650	3,730
				20	1,200	1,470	1,860	2,500	2,500	2,890	3,230	4,340
49500	Flint River at Montezuma	2,900	1932-80	2	950	990	1,050	1,160	1,330	1,470	1,620	1,870
				5	750	800	830	910	1,030	1,140	1,280	1,500
				10	670	720	750	800	910	1,000	1,130	1,330
				20	603	650	680	730	810	890	1,020	1,210
				30	600	630	620	660	740	800	920	1,100
				50	540	590	620	650	720	90	910	1,090
49900	Turkey Creek at Byromville	45	1960-80	2	5.2	5.4	5.4	6.0	7.0	7.9	8.6	15
				5	3.3	4.1	4.3	5.0	6.2	6.3	7.4	8.2
				10	2.0	2.8	3.5	4.2	5.1	5.2	6.2	7.0
				20	.86	1.6	2.4	3.2	3.6	4.2	4.8	5.0
				30	.52	.88	1.9	2.0	2.8	3.5	4.0	4.2
50500	Flint River at Oakfield 1/	3,860	1931-58	2	430	1,300	1,400	1,500	1,700	1,800	2,000	2,400
				5	260	910	1,050	1,100	1,200	1,400	1,600	1,700
				10	200	760	920	960	1,000	1,200	1,400	1,500
				20	170	660	840	870	910	1,000	1,200	1,300
				30	150	610	800	830	850	950	1,100	1,250
50600	Kichafoonee Creek at Preston	197	1953-77	2	48	52	57	65	77	89	98	120
				5	32	35	39	45	54	64	71	84
				10	25	28	31	37	45	53	59	70
				20	21	23	26	31	39	46	51	60
				30	19	21	24	20	38	41	47	56
50900	Kinchafoonee Creek near Dawson	527	Partial record 2/	2	—	170	—	190	210	250	—	--
				5	—	110	—	130	160	170	—	--
				10	—	90	—	110	130	140	—	--
				20	—	84	—	97	110	120	—	--
				30	—	77	—	90	100	110	—	--
51700	Muckalee Creek near Smithville	265	Partial record 3/	2	—	73	—	88	110	120	—	--
				5	—	46	—	60	72	86	—	--
				10	—	38	—	50	58	74	—	--
				20	—	32	—	45	48	68	—	--
				30	—	29	—	42	44	67	—	--
51900	Muckalee Creek near Leesburg	405	Partial record 4/	2	—	160	—	170	200	250	—	—
				5	—	110	—	130	160	165	—	--
				10	—	89	—	110	130	135	—	--
				20	—	80	—	95	110	120	—	--
				30	—	76	—	89	97	110	—	--
52500	Flint River at Albany 1/	5,310	1903-80	2	1,080	1,670	1,820	2,000	2,310	2,580	2,850	3,460
				5	720	1,260	1,400	1,550	1,790	2,000	2,210	2,560
				10	590	1,090	1,220	1,370	1,580	1,770	1,960	2,270
				20	500	960	1,090	1,240	1,430	1,610	1,780	2,070
				30	450	920	1,000	1,200	1,400	1,500	1,700	1,950
				50	410	840	960	1,110	1,280	1,460	1,600	1,870
53000	Flint River at Newton 1/	5,740	1939-80	2	1,650	2,160	2,310	2,440	2,690	2,910	3,160	3,660
				5	1,330	1,780	1,910	2,020	2,250	2,440	2,670	3,130
				10	1,180	1,600	1,740	1,850	2,080	2,270	2,480	2,930
				20	1,070	1,470	1,610	1,730	1,960	2,150	2,350	2,790
				30	1,000	1,360	1,500	1,700	1,860	2,100	2,300	2,700
				50	950	1,340	1,480	1,620	1,850	2,055	2,230	2,650
53200	Nochaway Creek near Shellman	52	Partial record 5/	2	—	26	29	—	33	35	—	--
				5	—	19	22	--	26	29	—	--
				10	—	16	20	--	22	26	—	--
				20	—	15	19	—	20	25	—	--
				30	—	14	18	—	19	24	—	--

Table 7.--Low-flow characteristics at selected streamflow gaging stations--Continued

Station No.	Station name	Drainage area (mi^2)	Period of record, climatic year	Recurrence interval (years)	Annual low flow, in ft^3/s, for indicated consecutive days							
					1	7	14	30	60	90	120	183
53400	Pachitla Creek near Edison	188	1961-69	2	75	82	88	94	---	---	---	---
				5	53	58	61	66	---	---	---	---
				10	43	47	49	55	---	---	---	---
53500	Ichawaynochaway Creek at Milford	620	1941-80	2	220	240	560	290	330	370	390	450
				5	170	180	190	210	250	270	290	340
				10	140	150	165	180	210	230	250	290
				20	130	140	150	160	180	200	220	260
				30	120	120	140	150	160	180	200	230
				50	110	118	130	140	155	170	190	220
54500	Chickasawhatchee Creek at Montezuma	320	1940-49	2	14	16	17	22	25	39	45	61
				5	5.6	6.6	7.8	11	15	16	20	30
				10	3.7	4.6	4.6	7.2	10	11	14	21
55000	Ichawaynochaway Creek near Newton	1,020	1939-47	2	320	330	350	370	430	500	550	640
				5	240	250	270	290	340	380	400	460
				10	210	230	240	260	300	320	340	390
56000	Flint River at Bainbridge 1/	7,570	1909-71	2	2,840	3,270	3,420	3,600	3,930	4,220	4,490	4,970
				5	2,250	2,620	2,740	2,850	3,110	3,320	3,540	3,900
				10	2,010	2,340	2,450	2,550	2,780	2,970	3,150	3,460
				20	1,840	2,140	2,240	2,340	2,550	2,720	2,880	3,150
				30	1,800	2,100	2,200	2,200	2,450	2,500	2,700	2,900
				50	1,680	1,950	2,040	2,130	2,320	2,490	2,600	2,850
57000	Spring Creek near Iron City	485	1938-71	2	52	58	62	67	80	100	120	150
				5	27	29	30	34	41	46	56	82
				10	17	18	19	21	25	30	35	52
				20	11	12	13	14	16	20	23	33
				30	8.4	9.0	10	11	12	15	18	26
				50	6.0	6.5	7.5	8.0	8.8	11	13	19
58000	Apalachicola River at Chattahoochee, Fla. 1/, 6/	17,200	1930-53	2	7,940	8,420	8,630	9,030	9,860	10,700	11,400	12,700
				5	6,570	6,860	6,970	7,200	7,800	8,350	9,030	10,100
				10	5,960	6,160	6,230	6,400	6,900	7,330	8,050	8,990
				20	5,500	5,620	5,680	5,800	6,240	6,580	7,340	8,200
				30	5,200	5,400	5,600	5,700	5,850	5,900	6,400	7,700
58000	do. 1/, 7/	17,200	1959-80	2	9,470	9,800	10,000	10,400	10,800	11,400	12,200	13,600
				5	8,030	8,380	8,540	8,860	9,190	9,640	10,300	11,600
				10	7,320	7,735	7,900	8,200	8,600	9,040	9,540	11,000
				20	6,760	7,250	7,430	7,730	8,230	8,670	9,070	10,500
				30	6,000	6,600	6,800	7,000	7,400	8,000	8,400	10,000

1/ Affected by regulation.
2/ Based on correlation of 14 independent base-flow measurements with concurrent base flows at gaging station 53500.
3/ Based on correlation of 10 independent base-flow measurements with concurrent base flows at gaging station 50600.
4/ Based on correlation of 12 independent base-flow measurements with concurrent base flows at gaging station 53500.
5/ Based on correlation of 10 independent base-flow measurements with concurrent base flows at gaging station 50600.
6/ Prior to construction and filling of Jim Woodruff Dam.
7/ After construction and filling of Jim Woodruff Dam.

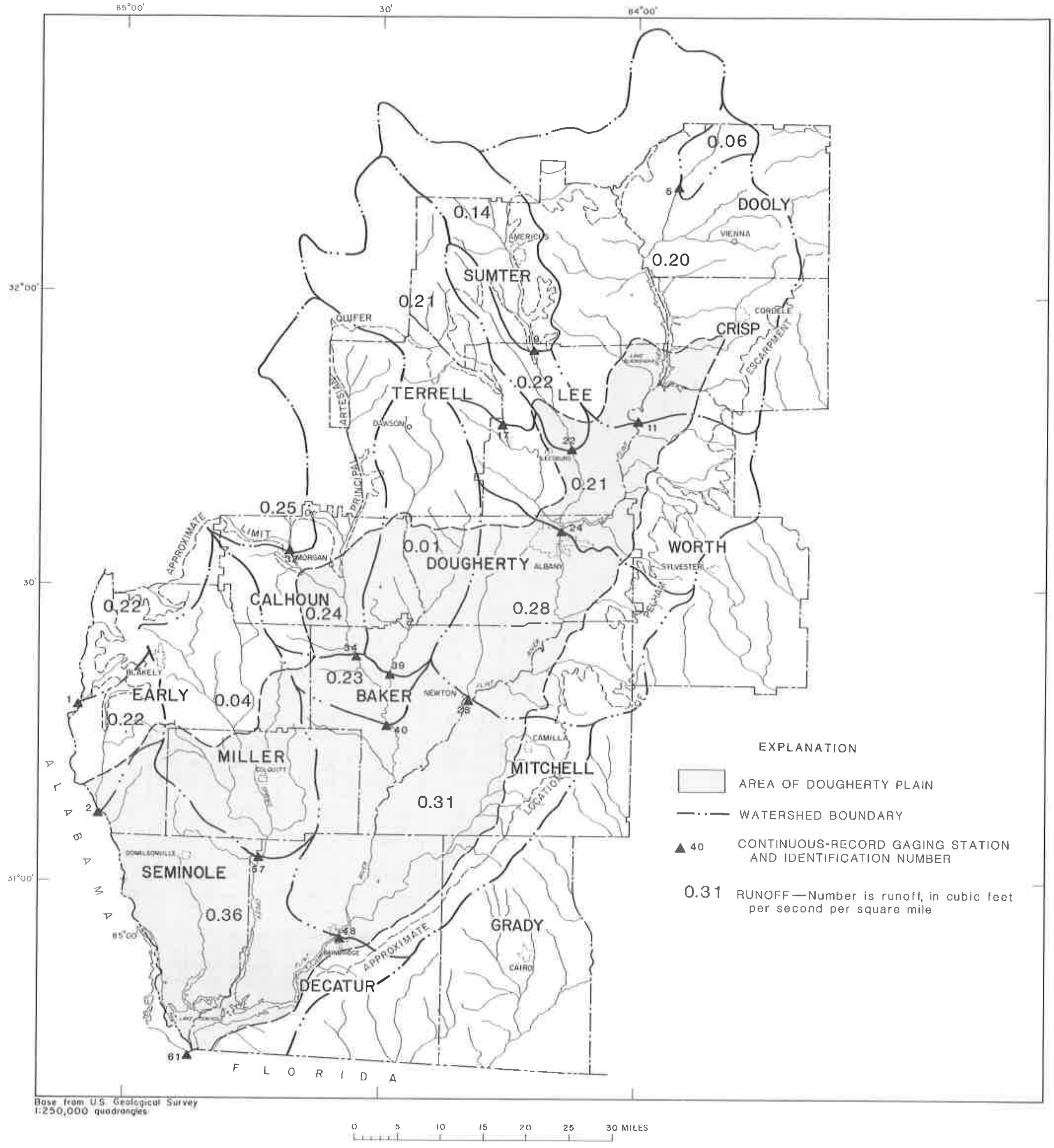
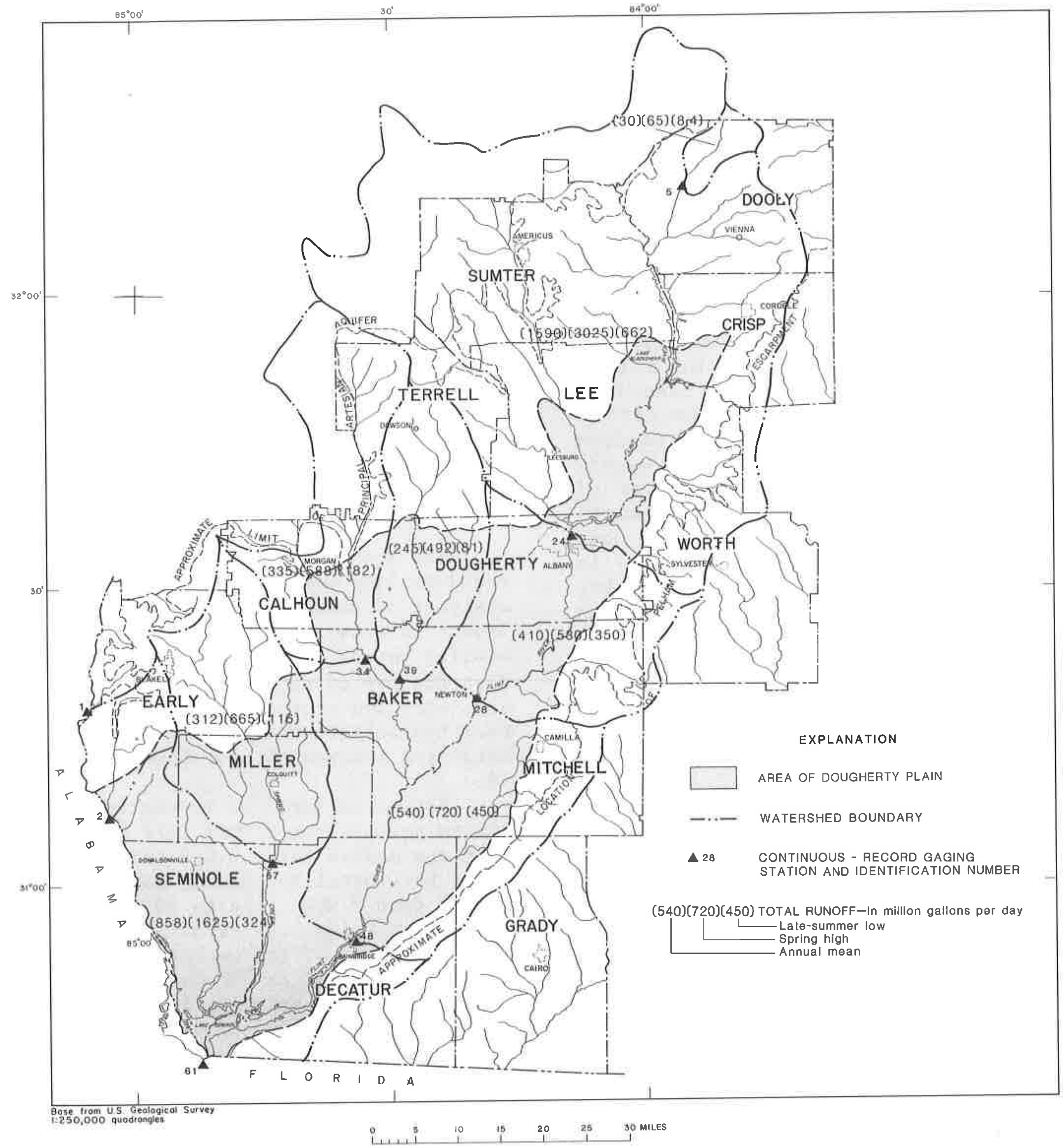


Figure 14.—Distribution of 7-day, 10-year minimum annual flows.



Base from U.S. Geological Survey 1:250,000 quadrangles

Figure 15.—Distribution and range of annual mean and seasonal runoff.

and compared with discharges at the 50-percent flow duration or median flow value. (See table 8.) Figure 16 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 particular year determined from hydrograph separation techniques. The lower curve shows monthly median flow for a month of record plotted against monthly base runoff for that particular month determined from 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 determined from hydrograph separation techniques and base flow determined 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 estimating monthly base flow from monthly median flow.

The relation between base flow and median flow illustrated in figure 16 provides a means of estimating base flow in the Dougherty Plain without using time-consuming hydrograph separation methods. Median flow at gaging stations can easily be calculated by standard U.S. Geological Survey programs, using daily-flow values.

Using the above 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. 17).

Weighting the above data on the basis of watershed area within the Dougherty Plain area gives an annual mean base flow of 4,000 ft^3/s; a late-summer (Sept.-Nov.) mean base flow of 2,300 ft^3/s; and an early-spring (Feb.-Apr.) mean base flow of 7,400 ft^3/s. 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 spearation techniques or median flow (T. W. Hale, U.S. Geological Survey, oral commun., 1981).

Ground Water

The primary geohydrologic units of interest in this investigation are, in decending vertical order, (1) the residuum; (2) the Ocala Limestone, called the principal artesian aquifer; and (3) the Lisbon Formation, which hydraulically separates the principal artesian aquifer from underlying sediments. Figure 18 shows the stratigraphic position and thickness of these units, selected geophysical logs, and a summary of water-bearing and lithologic characteristics determined from test well 205-37 in Mitchell County east of Newton.

Residuum

Hydraulic properties

The hydraulic conductivity of the residuum has been estimated from sieve analyses of drill cuttings collected at 5-foot intervals, geophysical logs, and aquifer tests. (See table 9.) The areal distribution of estimated hydraulic conductivity and transmissivity (estimated from hydraulic conductivity and average saturated thickness) are shown in figure 19.

Estimated vertical hydraulic conductivity varies from 0.0001 ft/d to 9 ft/d, with the median being 0.003 ft/d. Estimated horizontal hydraulic conductivity varies from 0.0004 ft/d to 30 ft/d, with the median being 0.02 ft/d.

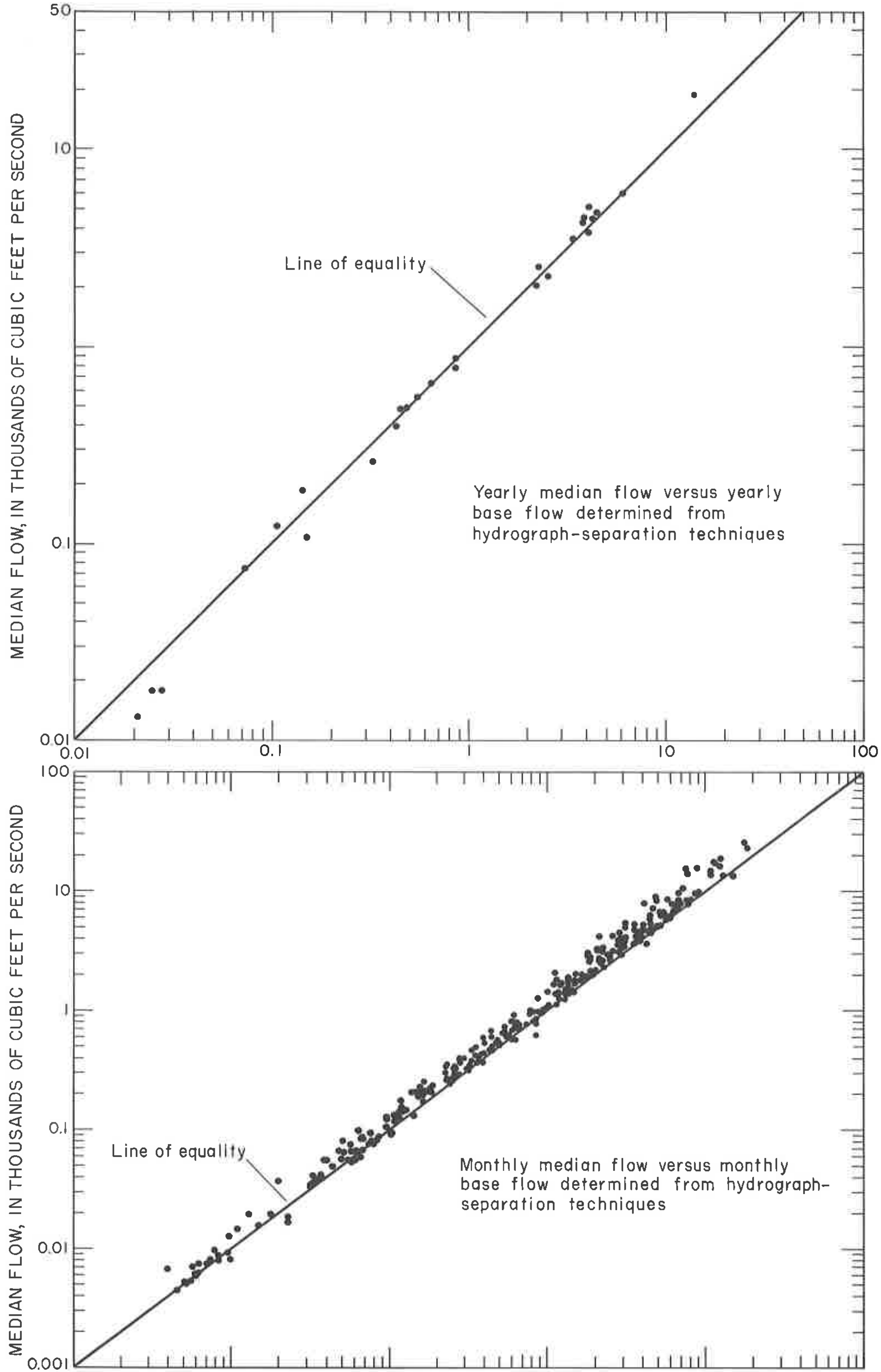
Estimates of transmissivity values range from 0.002 ft^2/d to 1,000 ft^2/d, with the median being 0.3 ft^2/d (table 9). An average value of saturated thickness based on observed seasonal water-level changes at each well was used to calculate transmissivity. Consequently, the estimated transmissivity values represent average conditions only.

The predominant lithologic factor determining transmissivity, however, is the presence or absence of permeable sand lenses within the saturated residuum thickness. Test drilling indicates that such sand lenses occur more commonly in the upper half of the residuum than in the lower half. Consequently, transmis-

Table 8.--Base flow estimated from hydrograph separation and median flow

[A, hydrograph separation technique of Riggs (1963); B, median flow]

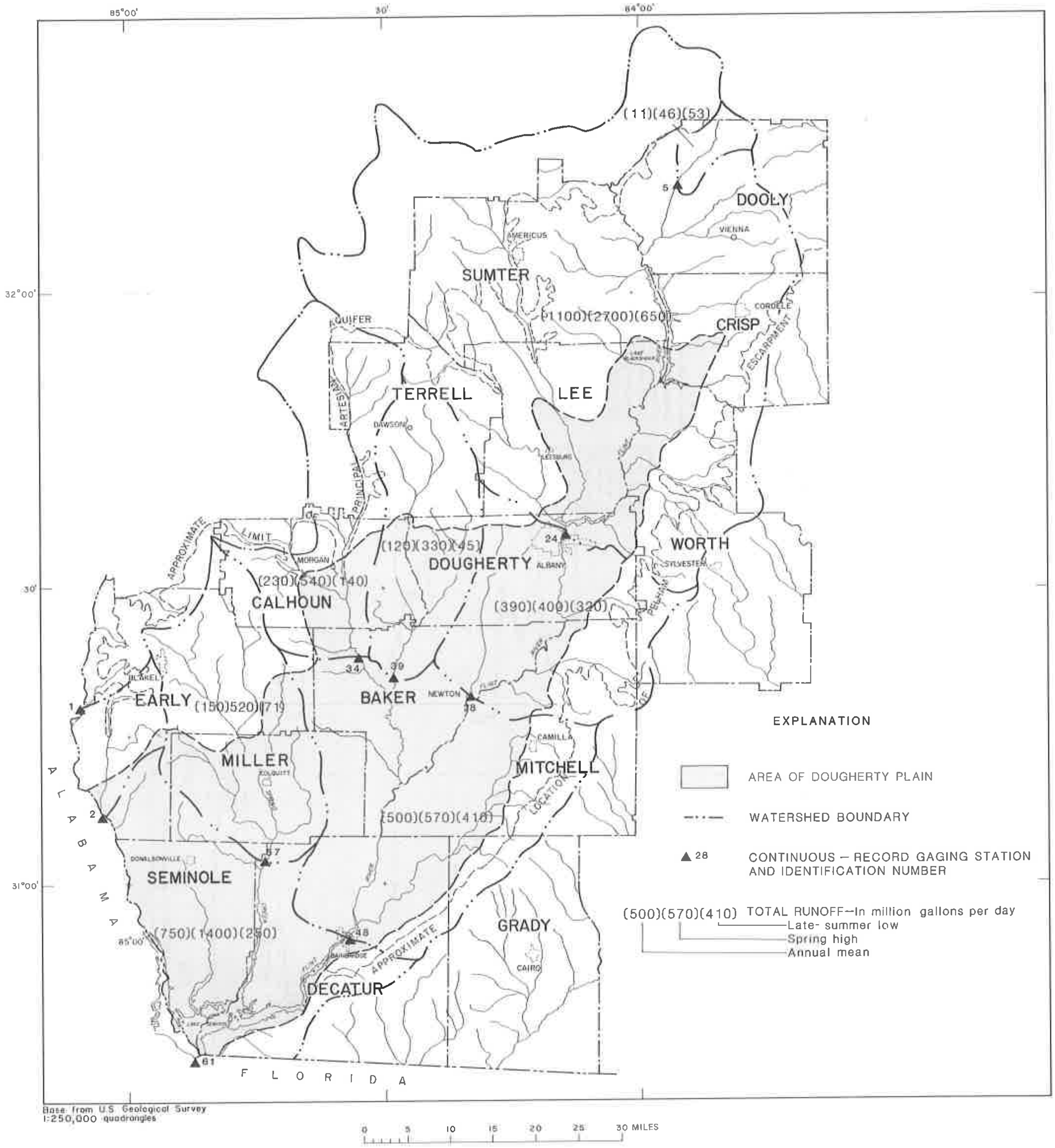
Station No.	Water year	Method	Estimated monthly mean base runoff, in ft^3/s												Est. annual base runoff (ft^3/s)	Annual mean run-off (ft^3/s)
			Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.		
49500	1978	A	1,200	2,030	2,180	3,570	4,260	3,670	2,960	2,820	1,360	1,030	1,490	919	2,290	
		B	1,280	2,250	2,540	4,810	3,700	4,340	3,010	3,980	1,940	1,140	1,830	982	2,530	3,608
	1979	A	839	945	1,620	2,860	3,041	5,025	4,850	2,630	1,440	1,320	966	1,160	2,220	
		B	818	986	1,810	3,160	4,270	5,050	9,180	3,260	1,520	1,540	1,040	1,860	2,070	3,428
	1980	A	1,380	1,610	1,950	2,290	3,100	6,790	6,330	2,100	1,860	1,300	985	955	2,550	
		B	1,410	1,840	2,020	2,360	3,870	9,820	7,040	3,240	2,160	1,270	1,070	1,040	2,280	3,719
49900	1978	A	6.2	7.0	13	66	84	66	33	33	10	7.4	7.9	6.0	28	
		B	6.3	7.6	20	60	84	85	36	42	8.3	8.3	10	6.3	17	50.9
	1979	A	5.6	6.0	8.4	23	39	58	40	38	9.6	9.8	5.2	5.7	21	
		B	5.5	6.0	9.0	17	57	67	57	40	9.5	13	5.2	7.2	13	42.8
	1970	A	8.4	11	18	23	32	96	77	15	6.3	4.6	4.0	5.1	25	
		B	8.1	15	20	19	35	131	83	16	7.6	4.6	6.9	5.4	17	38.7
50600	1956	A	37	68	80	80	156	156	122	50	36	52	32	20	74	
		B	42	69	83	77	225	233	150	58	40	66	34	38	74	121
	1957	A	69	74	122	129	116	153	188	167	116	57	44	48	107	
		B	86	77	145	150	130	194	242	260	145	77	50	68	125	177
	1958	A	104	139	187	168	165	268	259	108	68	119	107	62	146	
		B	96	210	210	217	202	290	300	120	89	180	135	66	187	219
52500	1978	A	1,890	2,140	2,860	7,700	7,810	6,270	4,470	4,670	3,090	1,830	2,760	1,330	3,900	
		B	2,230	4,240	4,560	8,010	7,910	7,920	5,960	7,350	3,470	1,990	3,610	1,460	4,550	6,483
	1979	A	1,370	1,240	2,130	3,130	5,780	8,600	7,470	4,390	1,890	2,270	1,520	1,880	3,470	
		B	1,750	1,750	2,800	5,500	8,740	9,720	15,800	5,120	2,710	3,450	2,070	2,880	3,510	5,844
	1980	A	2,510	2,210	2,250	3,140	5,600	11,600	10,900	4,050	2,600	1,760	1,360	1,300	4,110	
		B	2,740	3,270	3,150	4,220	6,460	17,400	14,000	5,370	3,210	1,970	1,660	1,430	3,800	6,251
53000	1978	A	1,850	2,590	3,130	6,530	6,790	8,100	5,200	4,100	3,890	2,500	2,970	1,760	4,120	
		B	2,630	4,320	5,060	7,300	8,550	8,740	6,760	7,990	4,440	2,890	4,150	1,970	5,110	6,693
	1979	A	1,670	1,650	2,420	3,570	4,910	9,140	7,690	5,340	2,780	3,120	2,130	2,080	3,880	
		B	2,040	2,060	3,020	5,380	8,570	10,000	14,300	6,650	3,690	4,230	2,680	3,350	4,230	6,077
	1980	A	2,980	2,800	3,030	3,710	5,480	11,300	10,800	4,470	3,000	2,260	1,890	1,710	4,450	
		B	3,380	3,620	3,790	4,640	6,830	17,900	14,900	6,390	4,280	2,680	2,180	1,880	4,360	6,579
53500	1978	A	372	479	631	861	1,150	1,470	825	650	446	326	385	254	654	
		B	398	544	751	784	1,150	1,480	836	823	472	360	441	261	653	964
	1979	A	245	280	400	632	786	900	621	450	261	356	232	260	452	
		B	248	298	450	788	964	998	938	615	348	504	269	333	485	666
	1980	A	320	334	433	507	554	1,130	1,190	540	281	234	146	184	488	
		B	321	390	475	530	618	2,130	1,420	677	390	362	212	224	485	734
55000	1940	A	635	500	610	876	1,820	1,220	1,380	660	603	1,190	610	397	875	
		B	585	515	585	1,300	2,970	1,650	1,650	700	700	1,470	820	375	865	1,211
	1941	A	310	525	607	913	834	1,010	860	370	257	453	284	233	555	
		B	334	655	695	1,000	1,000	1,470	865	410	277	518	372	277	552	690
	1942	A	354	325	680	1,500	1,500	1,830	1,140	581	543	748	789	405	866	
		B	428	353	728	1,720	1,460	3,080	1,420	636	747	785	1,020	544	785	1,230
56000	1908	A	6,100	4,500	12,500	18,400	17,600	13,000	12,400	15,000	7,000	6,570	5,280	6,030	10,400	
		B	6,300	4,970	19,100	23,400	26,100	13,700	16,500	13,700	8,030	7,790	6,400	6,100	10,900	14,055
	1909	A	4,700	5,000	5,200	5,700	7,240	8,890	9,062	7,784	5,300	5,590	5,230	3,870	6,130	
		B	4,890	5,290	5,290	5,900	10,800	16,000	10,100	8,670	6,300	5,810	6,400	3,900	6,000	8,128
	1910	A	3,600	3,500	4,000	4,500	5,560	7,000	4,790	4,460	4,000	5,380	4,270	3,640	4,560	
		B	3,790	3,660	4,240	4,520	6,400	7,910	5,050	5,400	4,800	6,730	4,810	4,300	4,800	5,655
57000	1940	A	229	165	120	334	1,110	646	489	180	161	300	143	58	328	
		B	346	177	159	475	1,680	810	574	213	213	414	135	55	264	480
	1941	A	34	51	86	228	253	395	362	97	61	102	96	55	152	
		B	38	82	89	309	286	607	376	125	57	92	108	57	108	191
	1942	A	76	62	64	598	855	1,360	674	266	448	281	300	157	428	
		B	96	68	100	835	635	1,880	775	334	695	408	408	204	394	603



Yearly median flow versus yearly base flow determined from hydrograph-separation techniques

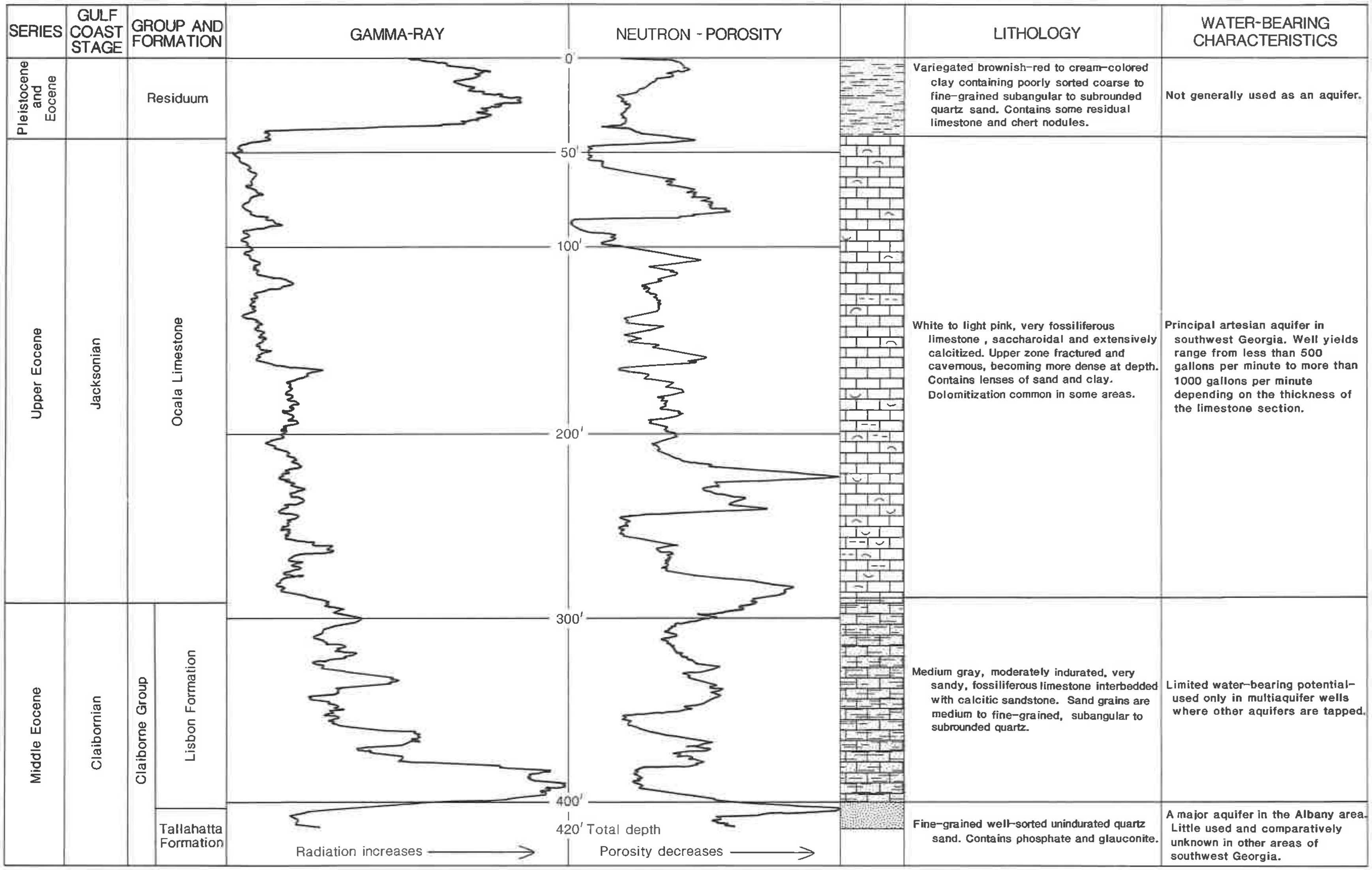
Monthly median flow versus monthly base flow determined from hydrograph-separation techniques

Figure 16.—Relation between base flow estimated from hydrograph separation and median flow.



Base from U.S. Geological Survey
1:250,000 quadrangles

Figure 17.—Distribution and range of annual mean and seasonal base flows.



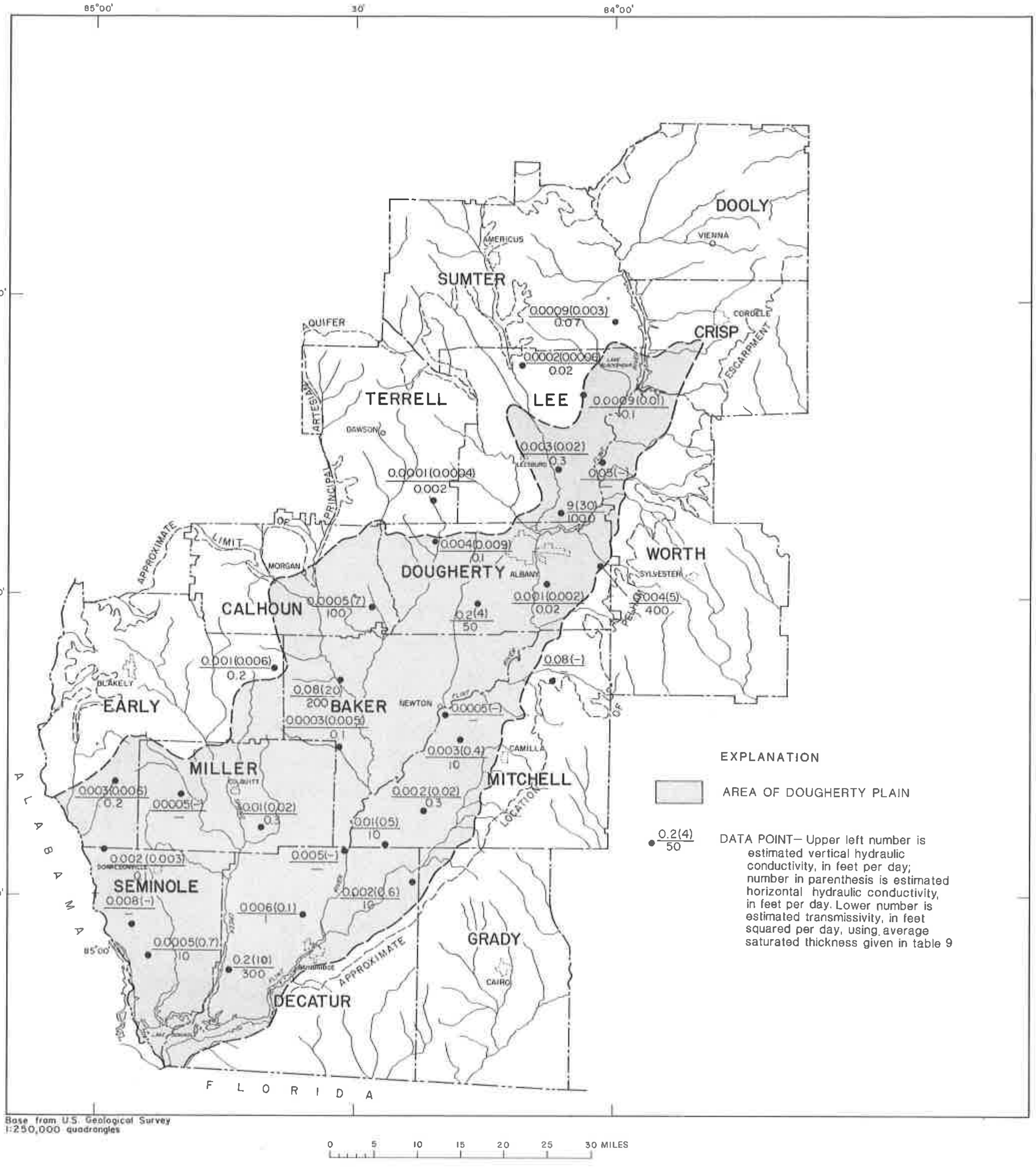
SERIES	GULF COAST STAGE	GROUP AND FORMATION	LITHOLOGY	WATER-BEARING CHARACTERISTICS
Pleistocene and Eocene		Residuum	Variegated brownish-red to cream-colored clay containing poorly sorted coarse to fine-grained subangular to subrounded quartz sand. Contains some residual limestone and chert nodules.	Not generally used as an aquifer.
Upper Eocene	Jacksonian	Ocala Limestone	White to light pink, very fossiliferous limestone , saccharoidal and extensively calcitized. Upper zone fractured and cavernous, becoming more dense at depth. Contains lenses of sand and clay. Dolomitization common in some areas.	Principal artesian aquifer in southwest Georgia. Well yields range from less than 500 gallons per minute to more than 1000 gallons per minute depending on the thickness of the limestone section.
Middle Eocene	Claibornian	Claiborne Group: Lisbon Formation	Medium gray, moderately indurated, very sandy, fossiliferous limestone interbedded with calcitic sandstone. Sand grains are medium to fine-grained, subangular to subrounded quartz.	Limited water-bearing potential–used only in multiaquifer wells where other aquifers are tapped.
		Claiborne Group: Tallahatta Formation	Fine-grained well-sorted unindurated quartz sand. Contains phosphate and glauconite.	A major aquifer in the Albany area. Little used and comparatively unknown in other areas of southwest Georgia.

Figure 18.—Stratigraphic section, geophysical logs, and water-bearing characteristic of geohydrologic units near Newton, test well 205-37.

Table 9.--Hydraulic and water-level data for residuum test wells

[Water levels measured January 1980-September 1981]

Well No.	Well name	Estimated average hydraulic conductivity (ft/d)		Ratio of average horizontal to vertical hydraulic conductivity	Estimated transmissivity (ft^2/d)	Residuum water levels, in ft below land surface			Residuum thickness (ft)	Saturated thickness (ft)		
		Vertical	Horizontal			Max.	Min.	Average		Max.	Min.	Average
007-38	T. Rentz RW	0.08	20	300	200	Dry	Dry	Dry	21	--	--	--
007-39	Jo-Su-Li RW	.0003	.005	20	.1	Dry	Dry	Dry	29	--	--	--
037-24	B. Jordan TW1	.0005	7	10,000	100	23.4	20.8	21.6	37	16.2	13.6	15.4
087-44	DP 6	.005	--	--	--	--	--	--	54	--	--	--
087-45	J. Hall TW2	.002	.6	300	10	Dry	Dry	Dry	40	--	--	--
087-46	G. Bolton TW2	.006	.1	20	1	24.9	19.5	22.7	32	12.5	7.1	9.3
087-47	A. Newton	.2	10	50	300	Dry	Dry	Dry	53	--	--	--
095-69	School Bus Road TW1	.001	.002	2	.02	29.5	17.5	26.7	35	17.5	5.5	8.3
095-70	Game and Fish TW1	.004	.009	2	.1	12.0	10.1	11.4	19	8.9	7.0	7.6
095-71	Nilo TW3	.2	4	20	50	38.4	35.5	36.4	50	14.5	11.6	13.6
095-72	USMC Supply TW1	.004	5	1,000	400	28.0	23.3	25.2	107	83.7	79.0	81.8
099-45	I. Newberry TW2	.001	.006	6	.2	21.8	7.6	14.3	40	32.4	18.2	25.7
099-46	V. Evans TW1	.003	.006	2	.2	9.0	6.2	7.7	46	39.8	37.0	38.3
177-40	Piedmont Plant Farm TW1	.003	.02	7	.3	34.5	31.4	32.9	47	15.6	12.5	14.1
177-41	S. Stocks TW1	9	30	3	1,000	13.4	11.7	13.0	50	38.3	36.6	37.0
177-42	B. King TW1	.0009	.01	10	.1	16.6	8.3	11.4	24	15.7	7.4	12.6
177-43	H. Usry TW1	.0002	.0006	3	.02	11.5	2.3	5.0	34	31.7	22.5	29.0
201-16	DP 3	.0005	--	--	--	22.8	1.2	12.0	55	--	--	--
201-33	J. Fleet TW2	.01	.02	2	.3	32.2	22.3	26.4	41	13.7	8.8	14.6
205-34	H. Meinders TW2	.01	.5	50	10	Dry	Dry	Dry	59	--	--	--
205-35	C. Holton TW2	.003	.4	100	10	32.8	28.8	30.8	60	21.2	27.2	29.2
205-36	H. Davis TW1	.002	.02	10	.3	32.6	23.0	27.1	40	17.0	7.4	12.9
205-39	DP 12	.0005	--	--	--	--	--	--	40	--	--	--
253-27	Roddenberry TW2	.0005	.7	1,000	10	27.4	19.5	22.8	39	19.5	11.6	16.2
253-28	D. Harvey TW2	.002	.003	2	.1	28.1	18.4	22.3	54	35.6	25.9	31.7
261-22	E. Stephens TW1	.0009	.003	3	.07	20.1	6.6	11.6	34	27.4	13.9	22.4
273-14	A. Vann TW1	.0001	.0004	4	.002	16.8	11.3	15.0	20	8.7	3.2	5.0
321-05	DP 9	.05	--	--	--	--	--	--	40	--	--	--
321-09	C. Odom TW1	.0007	.0006	9	.2	8.2	6.4	7.2	43	36.6	34.8	35.8



Base from U.S. Geological Survey
1:250,000 quadrangles

Figure 19—Distribution of estimated vertical and horizontal hydraulic conductivity and transmissivity of the residuum.

sivities may increase greatly during periods of high water levels as the permeable sand lenses in the upper half of the residuum become saturated.

Figure 20 illustrates a generalization of the areal range of leakance coefficients of the residuum. Preliminary leakance values were calculated by dividing estimated residuum vertical hydraulic conductivity (k') by residuum confining bed thickness (b'), which is considered to be equivalent to the bottom half of the residuum. The point values presented in figure 20 are considered to be accurate within an order of magnitude. But, because of the paucity and variability of leakance data, the regionalization is highly generalized. Regionalization of the data has, in part, been estimated using digital modeling techniques that will be discussed later in this report.

Small quantities of water are obtained from some residuum wells throughout the study area. As expected, yields are highly variable, ranging from generally less than 1 gal/min to, in a few places, as much as 50 gal/min. During drought conditions or toward the end of periods of low rainfall, residuum wells may go dry as the water table falls below the bottom of the well.

Water levels

Continuous water-level recorders were installed on four of the 29 residuum test wells drilled for the Dougherty Plain investigation, and water levels were measured 2 or 3 times monthly in the remaining 25 wells. The data available indicate that water levels respond in a subdued manner to rainfall and are highest during March-April and decline to their lowest values during November-January (fig. 21). Late spring and summer rains seem to have little effect on residuum water levels, probably because most of this rainfall either replaces soil moisture in the unsaturated zone or is lost to evapotranspiration before the water can percolate down through the sandy clay to the saturated zone.

Water levels in 21 wells ranged from about 1 to 38 ft below land surface from January 1980 to September 1981 (table 9). Water-level fluctuations in individual wells ranged from about 2 to 14 ft, with an average fluctuation for all wells of 6 ft.

A generalized map of the altitude of the water table in the residuum for estimated average yearly levels is shown in figure 22. Where the residuum is relatively thick and impermeable, the water table is believed to be a subdued replica of the topography; where the residuum is relatively thin and permeable, the water table is believed to be a subdued but higher replica of the potentiometric surface of the principal artesian aquifer. Relatively steep water-table gradients are believed to adjoin the major stream courses, and relatively low water-table gradients occur in the interstream areas.

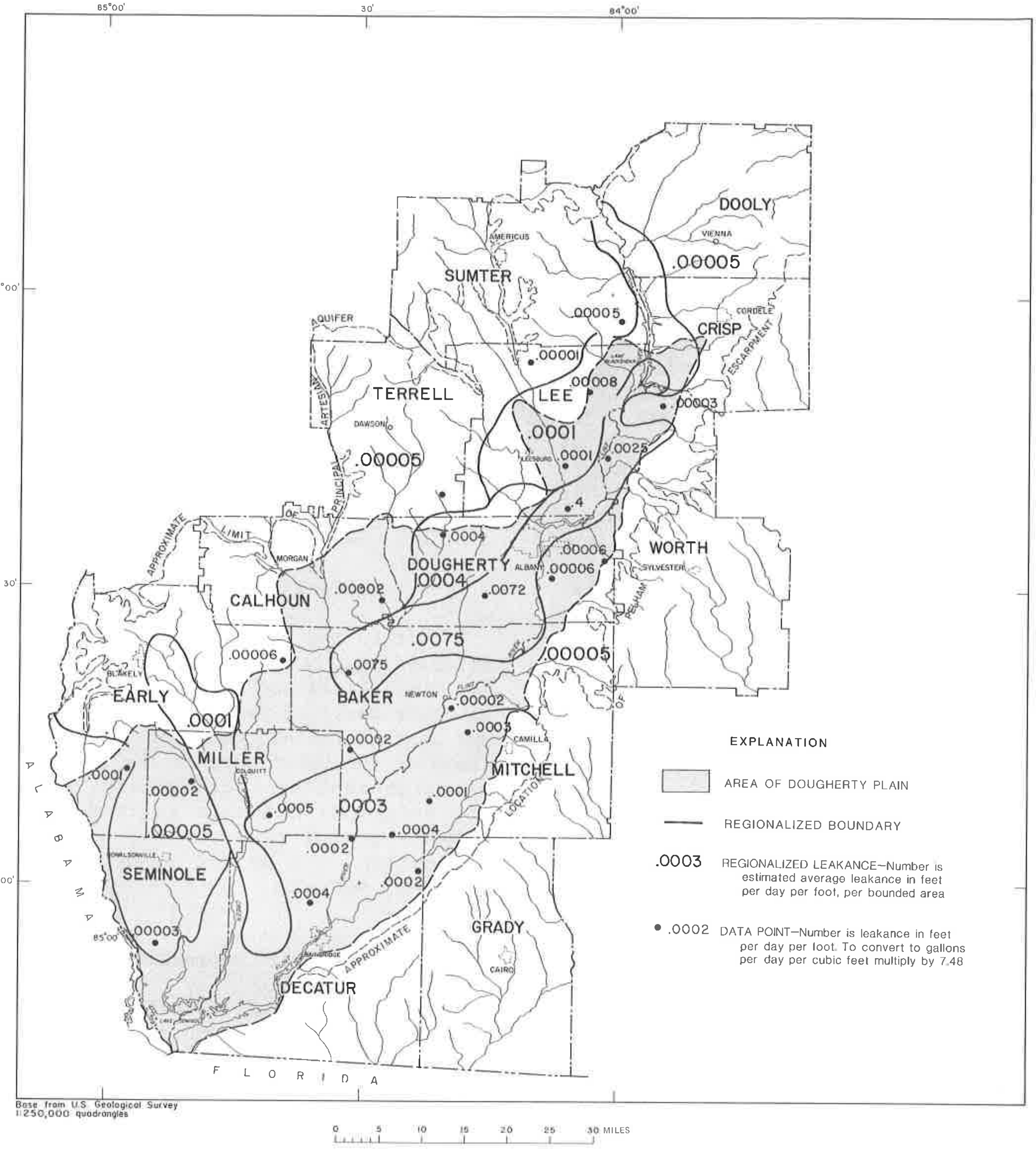
Principal Artesian Aquifer

Within the study area, the principal artesian aquifer consists primarily of the Ocala Limestone of late Eocene age. In other parts of Georgia and in Florida and South Carolina, rocks of younger age comprise the upper part of the principal artesian aquifer (Stringfield, 1966). The principal artesian aquifer is the primary source of water for domestic, irrigation, and public supply use in southwest Georgia.

Hydraulic properties

The capacity of the principal artesian aquifer to store and transmit large quantities of water is due largely to the fractured nature of the Ocala Limestone. Water moving through small fractures or cracks in the limestone has slowly enlarged these fractures, through solution, forming an interconnected labyrinth of subterranean channels, giving the rock a high permeability.

Figure 23 shows the distribution of transmissivity in the principal artesian aquifer. The control points are trans-



Base from U.S. Geological Survey 1:250,000 quadrangles

Figure 20.—Distribution of estimated leakance based on test-well data and digital modeling analyses.

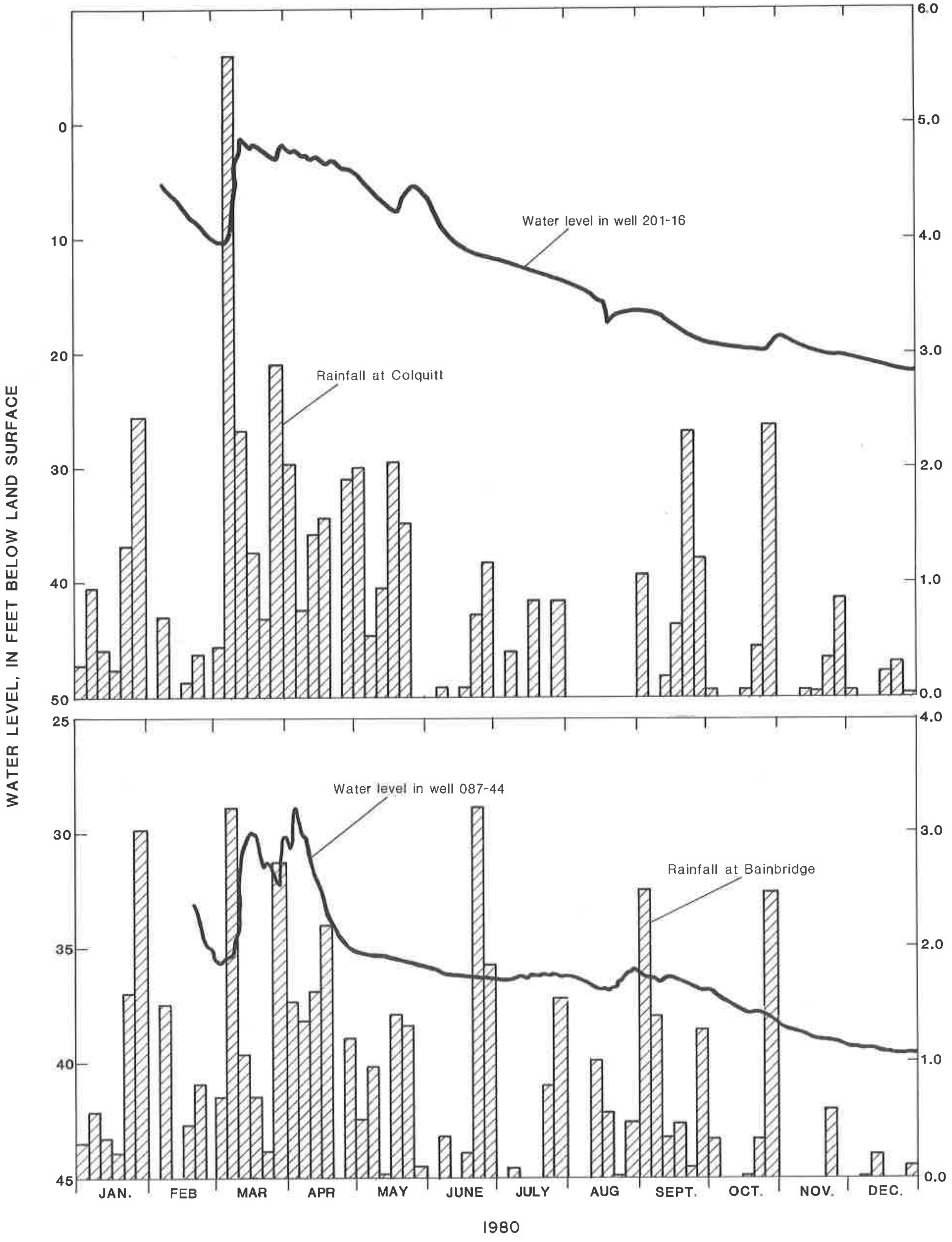


Figure 21.—Water levels in residuum wells 087-44 and 201-16 and rainfall at Bainbridge and Colquitt for 1980.

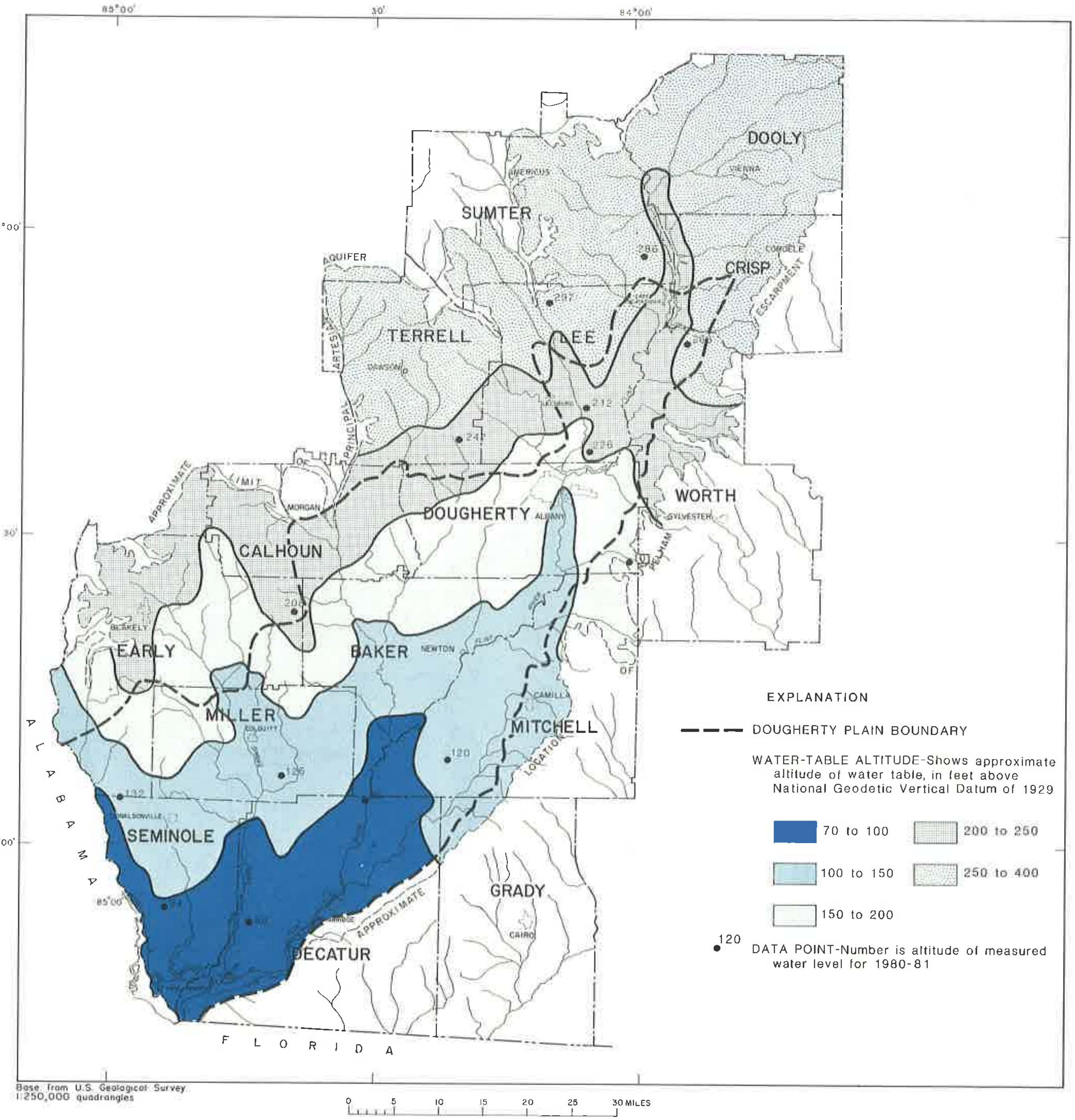


Figure 22.—Generalized altitude of water table in the residuum for mean yearly hydrologic conditions.

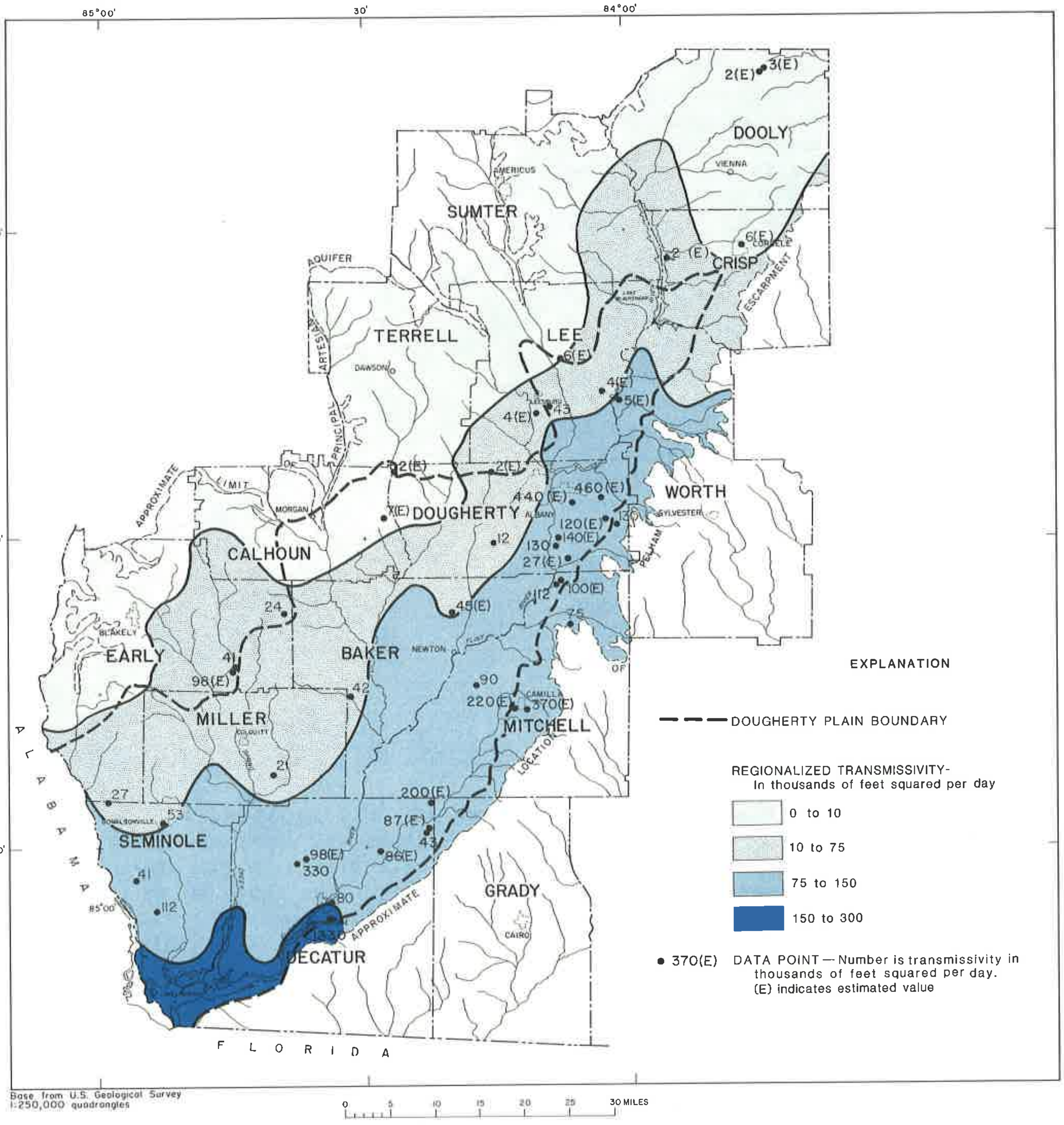


Figure 23.—Distribution of point and regional values of transmissivity in the principal artesian aquifer.

missivity data obtained from aquifer tests or estimated from specific-capacity tests. (See tables 10 and 11.)

The transmissivity data have been extrapolated to cover the entire study region. The regionalization is based on aquifer thickness, data average and trends, regional hydraulic gradients, and digital modeling results. The variability of the data is large; thus the point value, while locally accurate, may not be representative of regional transmissivity.

Large interconnected solution channels may account for only a small part of the cross-sectional flow area, but they carry a major part of the flow. Consequently, where wells do not penetrate these solution channels, aquifer tests may not indicate point values as high as the "effective" regional transmissivity. Conversely, a well that penetrates exceptionally large solution channels may not be stressed enough during aquifer testing to yield results representative of regional aquifer characteristics and may indicate a point value that is greater than the regional transmissivity.

Computed point values of transmissivity of the principal artesian aquifer range from 2,000 to 1,300,000 ft^2/d, whereas effective regional values range from 3,000 to 300,000 ft^2/d (fig. 23). Transmissivity is lowest in the northern part of the report area, where the aquifer is relatively thin, and increases to the south where the aquifer is thicker. Transmissivity is high near the Chattahoochee and Flint Rivers and Spring Creek, because water moving between the surface-water system and the ground-water system adjacent to these major recharge-discharge areas has accelerated the development of solution channels.

Figure 24 shows the areal distribution of storage coefficients computed from aquifer test data. Storage coefficients range from 2×10^{-4} to 3×10^{-2}, but generally range from 10^{-3} to 10^{-4}. The storage values indicate that the principal artesian aquifer generally can be considered confined to semiconfined.

Well yields are largely dependent on hydraulic conductivity, length of well open to the aquifer, well efficiency, well diameter, and pump capacity. Measured well yields in the Dougherty Plain area range from about 40 to 1,600 gal/min (table 11). Many wells in the area do not penetrate the full thickness of the aquifer and, consequently, yield less than the maximum possible rate. Yields of 1,000 to 2,000 gal/min, however, are common in areas where transmissivity exceeds 50,000 ft^2/d, and yields of more than 2,000 gal/min may be expected where transmissivity exceeds 75,000 ft^2/d.

A commonly used measure of well yield is specific capacity. Specific capacity is defined as the yield per unit of drawdown. Because specific capacity will generally decrease with time as the drawdown increases, the time of pumping prior to the time the drawdown is meas-

Table 10.--Transmissivities and storage coefficients for the principal artesian aquifer

Well No.	Casing depth (ft)	Length of open hole (ft)	Aquifer thickness (ft)	Method of analysis	Transmissivity (ft^2/d)	Storage coefficient
007-06	79	101	160	Theis	42,000	0.02
087-16 [1]	144	325	325	do.	80,000	.003
087-33	88	72	325	Hantush-Jacob	43,000	.001
087-48 [2], [3]	120	350	350	Theis	1,300,000	.002
087-49 [1]	168	408	235	do.	330,000	.001
095-15	63	87	165	Delayed yield	12,000	.004
095-39 [4]	60	240	260	Hantush-Jacob	130,000	.0004
095-73 [5]	--	--	205	Theis	130,000	.03
099-26 [4]	50	105	80	Hantush-Jacob	41,000	.003
099-39	61	64	70	Theis	24,000	.0004
177-15	64	126	140	Hantush-Jacob	43,000	.01
201-05	130	95	165	Theis	21,000	.001
205-16	50	140	250	Hantush-Jacob	90,000	.003
205-22	77	131	260	do.	75,000	.001
205-30 [4]	110	140	235	do.	112,000	.0003
253-08	63	87	225	Theis	112,000	.001
253-12	118	107	180	do.	41,000	.0002
253-26	58	67	75	Delayed yield	27,000	.003

[1] From Sever, 1965a.

[2] From Sever, 1965b.

[3] Open-hole section extends below base of principal artesian aquifer and penetrates the Lisbon Formation.

[4] From P. E. Lamoreaux and Associates, written commun., 1980.

[5] From R. L. Wait, U.S. Geological Survey, written commun., 1957.

Table 11.--Specific-capacity data and estimated transmissivities for the principal artesian aquifer

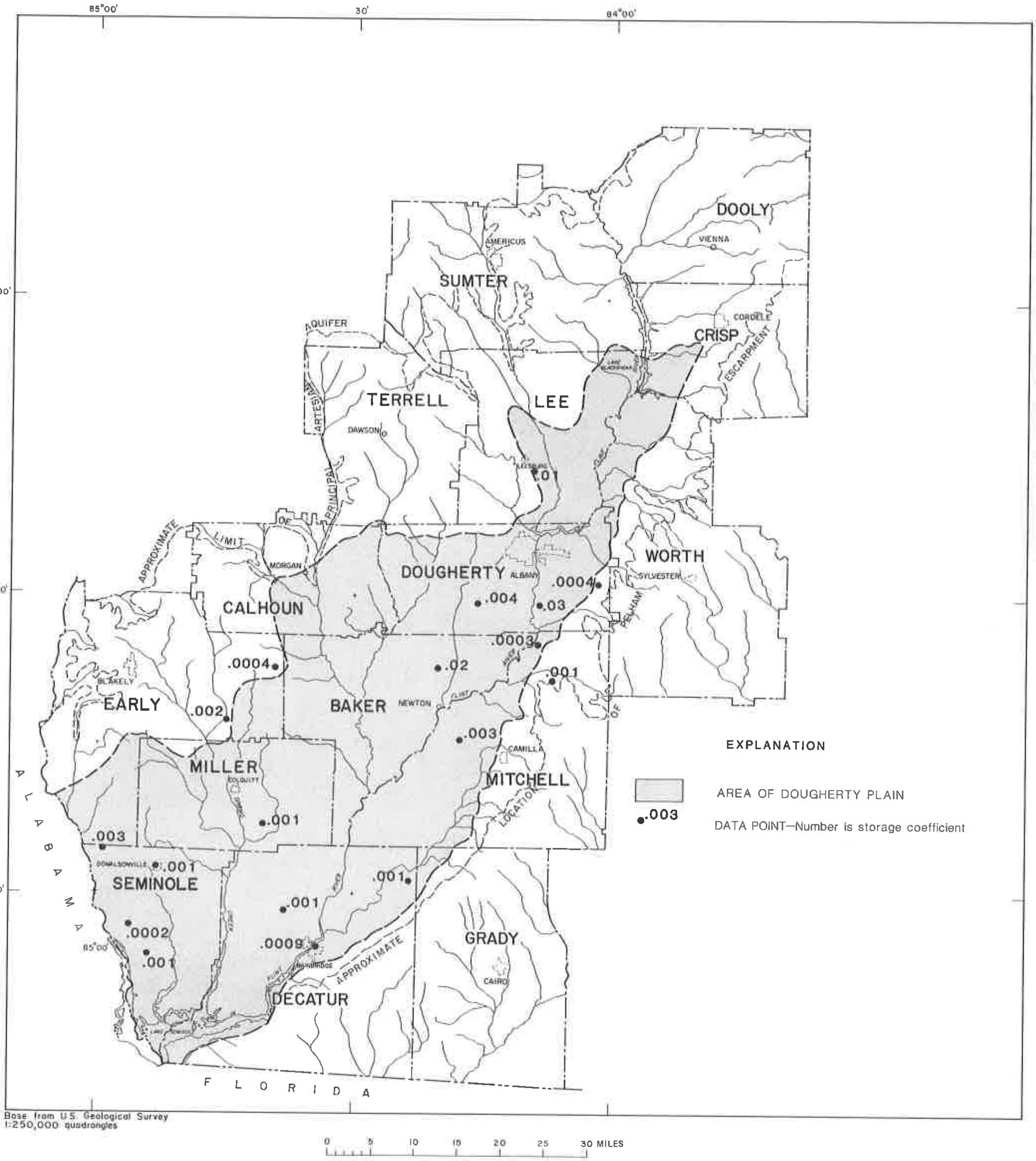
[R, reported]

Well No.	Diameter of well (in.)	Length of open hole (ft)	Aquifer thickness (ft)	Static water level (ft)	Drawdown (ft)	Duration of pumping (hrs)	Discharge (gal/min)	Specific capacity [(gal/min)/ft]	Estimated trans-missivity (1,000 ft^2/d)
007-34	16	108	150	19	11	8R	1,500	140	45
037-07	12	82	82	32	20	8	570	28	7
081-13	6	52	110	7	7	36	350	50	27
081-17	10	90	150	15	24	4R	400	17	6
087-25	12	140	277	46	4	8R	800	200	98
087-28	12	100	325	35.97	4.09	.017	700	170	86
087-35	12	100	330	22.22	2.78	.43	960	340	87
093-11	10	28	50	115	17	6R	90	5	2
093-12	10	38	50	97	20	6	230	12	3
095-17	10	168	208	41.33	2.5	8R	1,000	400	140
095-35	12	124	230	57	6	8R	1,500	250	120
095-45	16	109	180	32.50	1.45	48	1,400	960	440
095-47	16	100	202	55	1	1.0	1,000	1,000	460
095-62	16	55	150	17	54	8	210	4	2
095-66	12	64	64	21	71	144	400	6	2
099-29	16	41	60	17	5	8R	1,500	300	98
177-14	6	60	138	42	18	12	150	8	4
177-20	4	97	125	26	18	4R	225	12	4
177-44	8	26	75	25	18	4R	210	12	6
205-11	20	100	302	55	3	24	1,600	530	370
205-12	12	186	302	44	3	6	1,500	500	220
205-32	16	156	260	40	6	8R	1,500	250	100
321-04	4	97	120	.26	3.6	1	40	11	5

ured should be given. Measured specific capacities of wells in the principal artesian aquifer range from 4 to 1,040 (gal/min)/ft, with respective pumping durations of 8 and 1 hours (table 11).

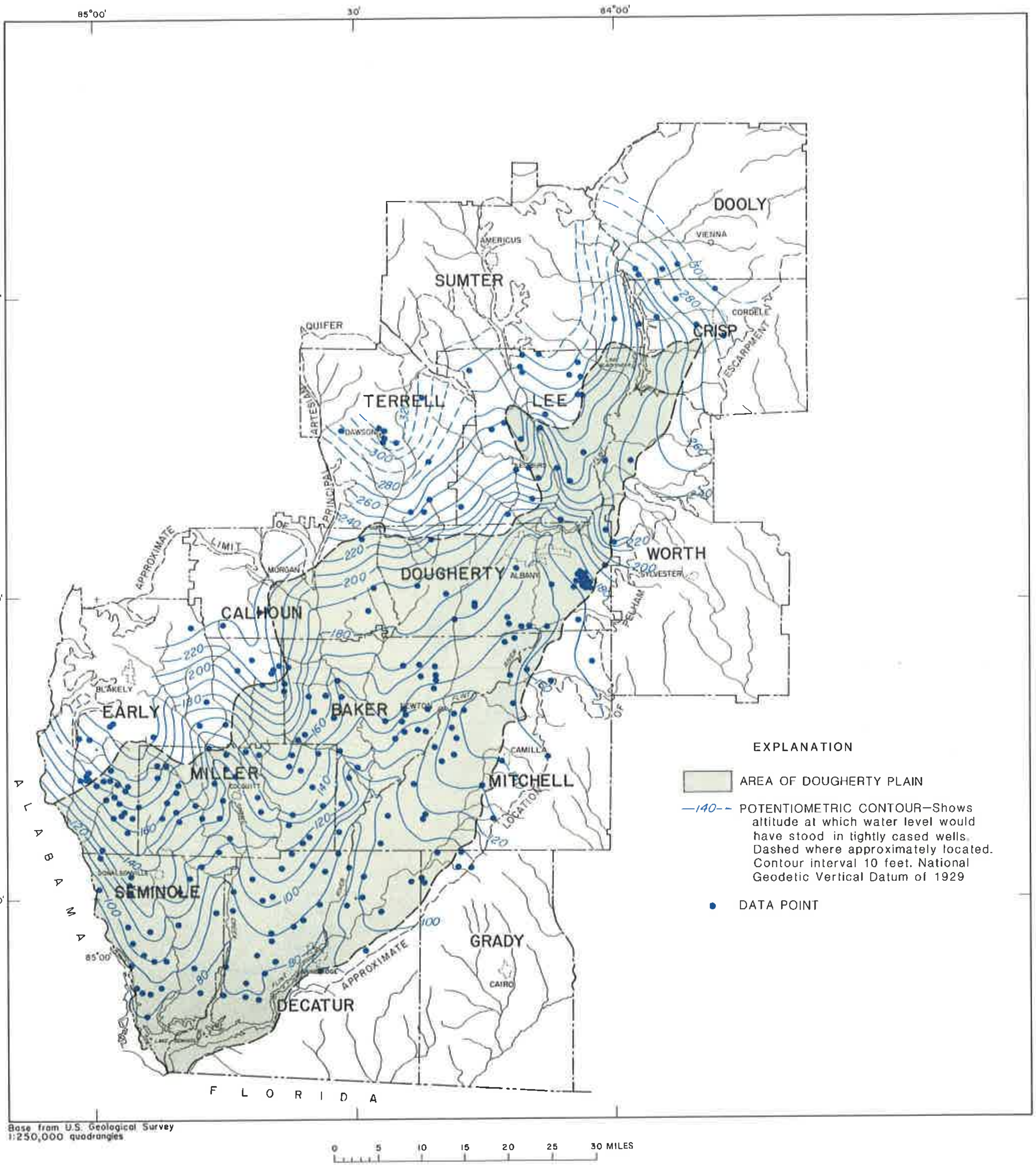
Water levels

Water-level measurements were made four times in the Dougherty Plain test wells and in about 200 privately owned wells between November 1979 and April 1981. (See Mitchell, 1981, table 47, for a listing of the 1979 and May 1980 measurements.) Maps showing the potentiometric surface of the principal artesian aquifer for November 1-5, 1979 (Mitchell, 1981, pl. 2), and May 12-16, 1980 (fig. 25), November 3-7, 1980 (Watson, 1980, p. 2), and March 30-April 3, 1981 (unpublished), were constructed from these measurements. Figure 25 shows the May 1980 potentiometric surface of the principal artesian aquifer, which reflects generally seasonal high levels following late-winter through early-spring recharge. November water levels are generally about 10 ft lower than in May because of seasonal summer declines (fig. 26). Because of a drought beginning in June 1980 and lasting through the summer



Base from U.S. Geological Survey
1:250,000 quadrangles

Figure 24.—Distribution of point values of storage coefficients of the principal artesian aquifer.



Base from U.S. Geological Survey
1:250,000 quadrangles

Figure 25.—Potentiometric surface of the principal artesian aquifer, May 1980. From Mitchell (1981).

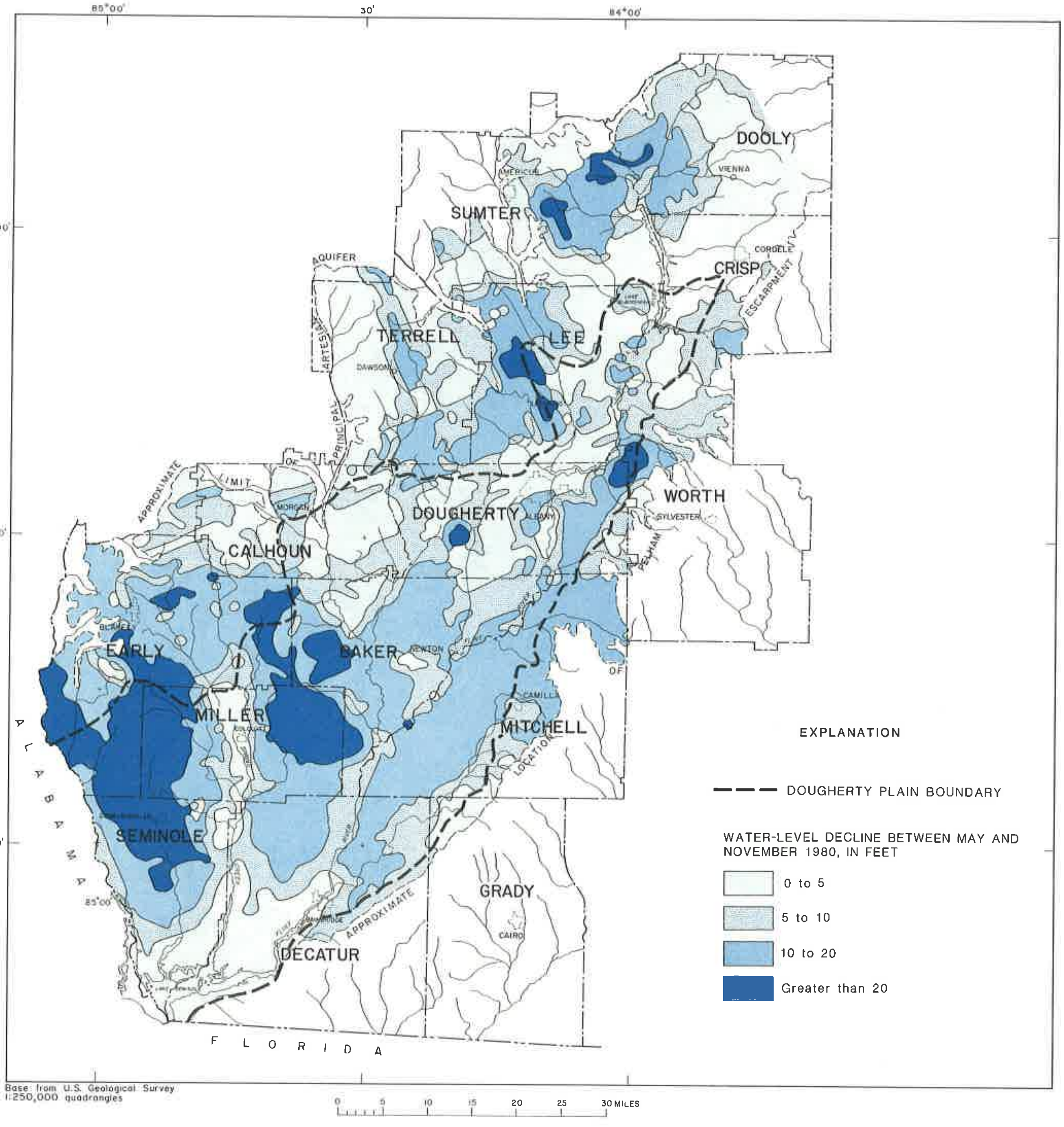


Figure 26.—Seasonal water-level declines in the principal artesian aquifer between May and November 1980.

of 1981, water levels for March 30-April 3, 1981, which should be about the same as May 1980, are generally about 10 ft lower than the May 1980 water levels (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. Water levels remained at about the November 1980 seasonal low.

Figure 28 shows long-term cyclic fluctuations of water levels in two wells open to the principal artesian aquifer. The water level in well 087-23, which is in an area of very high transmissivity, normally fluctuates about 5 ft. The water level in well 095-68, which is in an area of moderate transmissivity, normally fluctuates about 10 ft. The actual fluctuation for any particular year at a particular site depends primarily upon the timing and amount of spring rainfall that recharges the aquifer and the amount of subsequent summer decline. Summer declines are dependent upon natural discharge to streams, evapotranspiration rates, and, to a lesser degree, summer rainfall and pumpage.

Lisbon Formation

Because it has relatively low transmissivity compared with the principal artesian aquifer (Watson, 1981), the top of the Lisbon is considered to be the base of the principal artesian aquifer in the area of investigation. Although domestic supplies of water may be obtainable from the Lisbon south and east of the study area, no wells within the Dougherty Plain are known to yield more than a few gallons per minute.

Recharge, Discharge, and Flow Characteristics

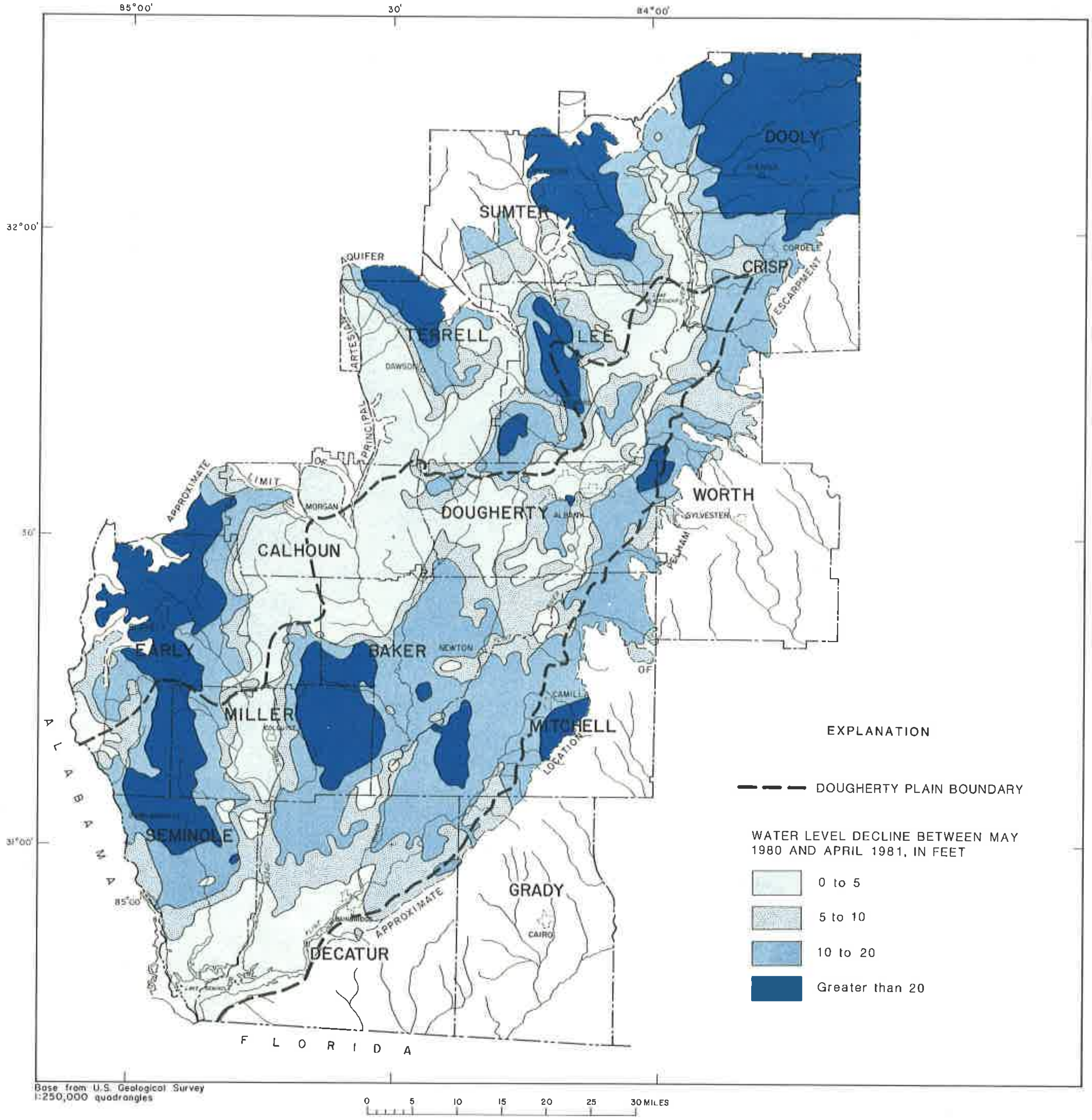
Annual mean recharge of about 2,800 Mgal/d to the residuum occurs chiefly from rainfall during January through May (fig. 21). Rainfall that is not evaporated, transpired, retained in the unsaturated zone as soil moisture, or discharged to streams, moves downward through the residuum to recharge the principal artesian aquifer. Most rainfall occurring during the summer months is lost to evapotranspiration or is retained as soil moisture in the unsaturated zone of the residuum. Consequently, little, if any, summer rainfall infiltrates to the water table or the principal artesian aquifer (fig. 29).

The vertical hydraulic conductivity of the residuum confining zone is generally low--about 0.003 ft/d (table 9). Within the Dougherty Plain, however, the cross-sectional area of flow in the vertical direction is large--about 4,400 mi^2--and consequently large quantities of water are transmitted through the residuum confining zone to the principal artesian aquifer. Digital modeling results indicate that annual mean recharge to the artesian aquifer is about 2,200 Mgal/d (10 in.), whereas late-summer recharge is 1,400 Mgal/d (6 in.).

Recharge to the principal artesian aquifer varies considerably with location because of the highly variable leakance of the residuum (fig. 20). For example, digital modeling results indicate that recharge varies from about 0.1 to 2 $(Mgal/d)/mi^2$.

The principal artesian aquifer transmits water from interstream areas of recharge to natural areas of discharge and to wells. Natural outlets include springs, streams, and the overlying residuum or underlying Lisbon Formation, where hydrostatic pressure in them is less than in the principal artesian aquifer.

Hydrograph separation techniques (discussed previously) indicate that annual mean ground-water discharge to streams from the residuum and the principal artesian aquifer is about 2,600 Mgal/d, and late-summer mean discharge is about 1,500 Mgal/d. Additionally, annual mean discharge to wells from the principal artesian aquifer is about 225 Mgal/d (210 Mgal/d for irrigation and 15 Mgal/d for all other). As with recharge, discharge varies considerably with both areal location in the Dougherty Plain and time of year. (See section on Base Flow.)



Base from U.S. Geological Survey 1:250,000 quadrangles

Figure 27.—Difference in principal artesian aquifer water levels between May 1980 and April 1981.

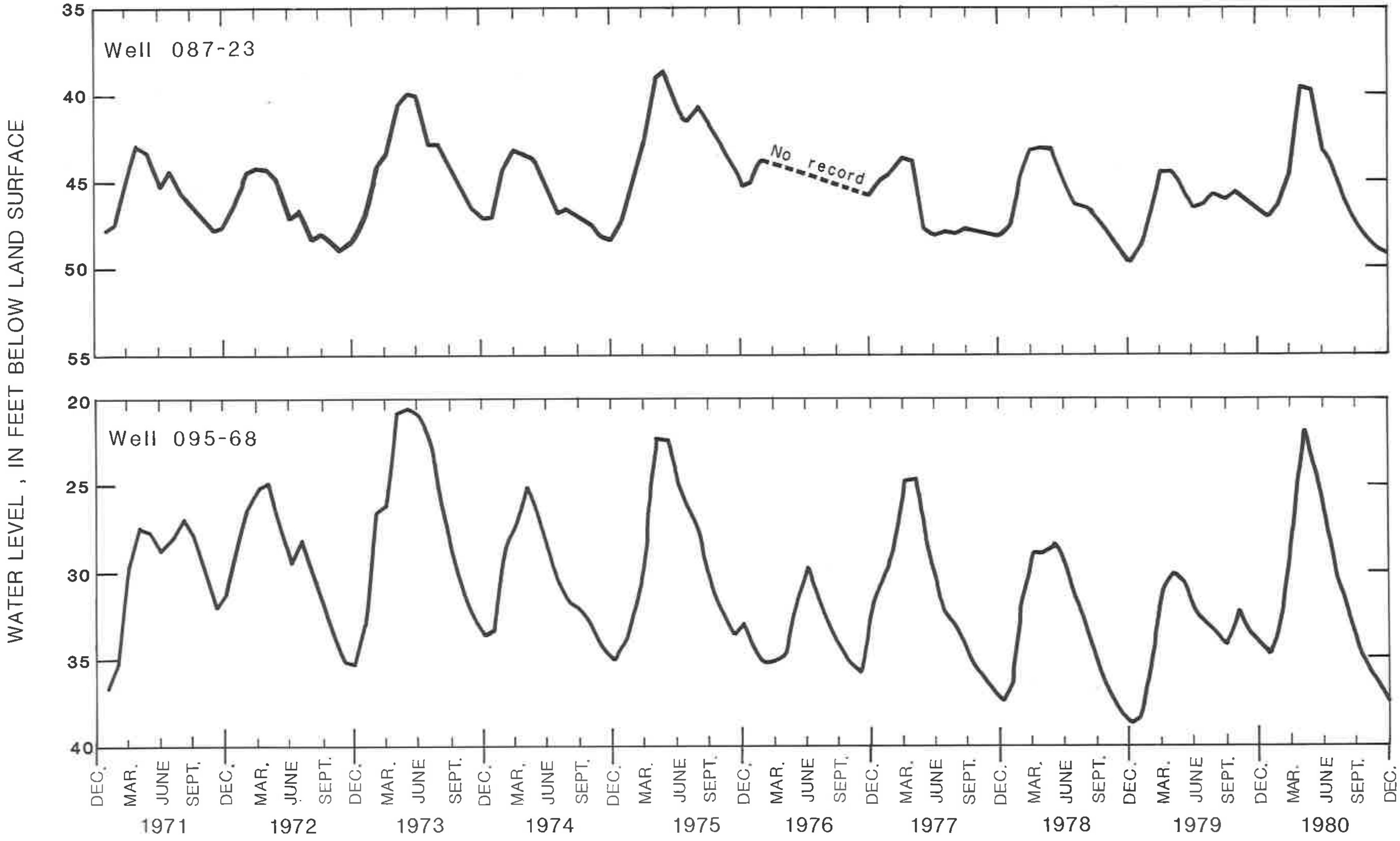


Figure 28.—Fluctuations of mean monthly water levels in the principal artesian aquifer at wells 087-23 and 095-68.

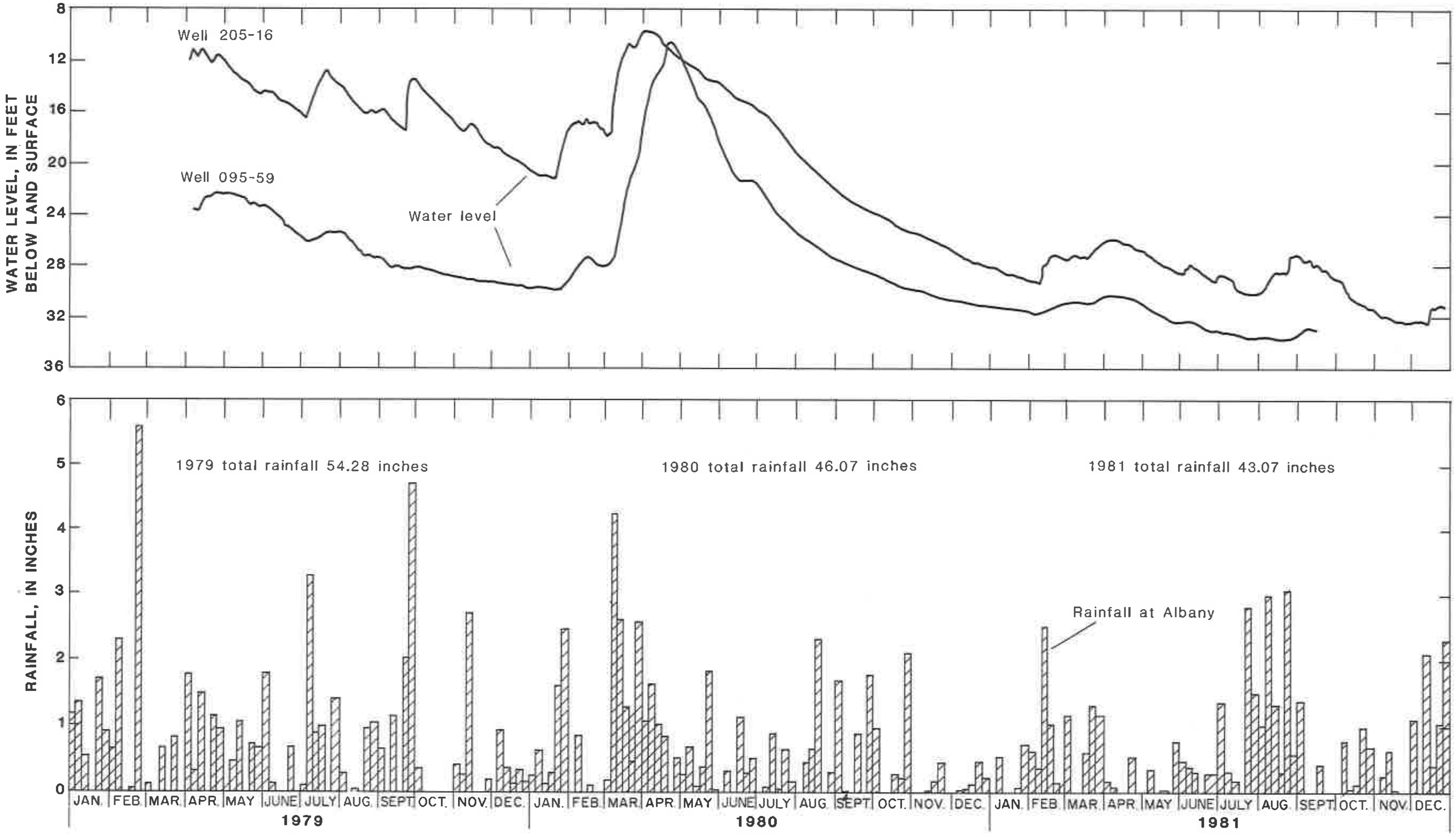


Figure 29.—Fluctuations of mean daily water levels in the principal artesian aquifer at wells 095-59 and 205-16 and 5-day rainfall totals at Albany and Camilla.

Long-term water-level records of the principal artesian aquifer indicate that except for cyclic seasonal fluctuations and hydrologic extremes, the potentiometric surface of the principal artesian aquifer has remained fairly constant. This implies that over the long term, aquifer storage changes have been minimal and recharge approximately equaled discharge.

The potentiometric map of the principal artesian aquifer (fig. 25) illustrates several hydrogeologic characteristics of the Dougherty Plain area. Regional ground-water flow direction within the principal artesian aquifer is from the northern part of the 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 digital modeling results indicate that about 90 percent of the annual ground-water discharge occurs as discharge to streams and springs.

Whereas the potentiometric contour map may be used to estimate the general direction of ground-water flow, the actual movement of a single water molecule may be very complex and may differ greatly from that which is implied by the two-dimensional potentiometric map. The actual flow of ground water is three dimensional and is affected not only by hydraulic gradient, but also by changes in aquifer properties (such as permeability, porosity, and thickness). Furthermore, aquifer properties of a limestone vary widely, depending upon the hydrogeologic characteristics of the aquifer.

White (1969) proposed a three-part classification of carbonate aquifers based upon recognizable physical features: (1) a diffuse-flow solutional modification; (2) a free-flow aquifer in which ground-water flow paths have been localized by solutional modification into well integrated systems of conduits; and (3) a confined-flow aquifer in which geologic boundaries rather than hydraulics are the flow-limiting factors. Ground-water movement through the diffuse—flow system is analagous to flow in a homogeneous aquifer and more nearly follows the "basic" assumptions upon which ground-water flow equations are based. In a free-flow system, flow occurs in distinct conduits or channels, while nearby rock may have little porosity or permeability. Flows in these conduits often have high velocities and may be turbulent.

The principal artesian aquifer generally functions as a free-flow system. However, it may function as a confined diffuse-flow aquifer where the surface water-ground water interaction is slight. Consequently, flow equations that assume laminar flow in an isotropic and homogeneous medium cannot be rigorously applied to the principal artesian aquifer. Nevertheless, if the limitations of basic flow equations as regards a particular set of geohydrologic conditions are considered, these flow equations used in conjunction with potentiometric maps may be used to indicate the general direction and average velocity of ground-water flow.

The average velocity of ground-water flow may be computed by the following equation:

$$\bar{v} = \frac{-K\ dh/dl}{\theta}, \qquad \text{(Lohman, 1979)}$$

where

$\bar{v}$ = average velocity, in feet per day

K = lateral hydraulic conductivity, in feet per day,

dh/dl = change in head with respect to change in distance, in feet per foot,

θ = porosity, as a decimal fraction,

and $-$ = the minus sign indicates that flow is in the direction of decreasing head.

It must be stressed that the solution of this equation is the average velocity, and may not correspond to the actual velocity of a discrete unit of water between any two points in the aquifer. Actual ground-water velocity may be more or less than this average value, depending upon the flow path followed and local geohydrologic conditions.

Because the principal artesian aquifer acts as both a free-flow and a diffuse-flow system, average velocities of ground-water flow vary greatly. The effective hydraulic conductivity of the upper part of the principal artesian aquifer adjacent to the Flint River above Bainbridge is believed to exceed 1,000 ft/d as a result of secondary solution (free-flow system). The effective porosity of this part of the aquifer is assumed to be about 20 percent, and the hydraulic gradient is about 3 ft/mi (fig. 25). Using the preceeding equation, the average velocity of ground-water flow is about 3 ft/d.

The effective hydraulic conductivity of the aquifer in the northern part of the study area, away from streams, is about 100 ft/d, based on data shown in figures 6 and 23 (diffuse-flow system). The effective porosity is estimated to be about 20 percent, and the hydraulic gradient is about 2 ft/mi (fig. 25). Thus, the average velocity of ground-water flow in this area is about 0.2 ft/d.

Water Budget

Very little ground-water development from the principal artesian aquifer has taken place in the Dougherty Plain except for irrigation purposes. During average hydrologic conditions, pumpage from the aquifer accounts for about 10 percent of its total ground-water discharge. Consequently, under average hydrologic conditions the principal artesian aquifer has not been significantly stressed, and over the long term, it is in a state of hydrologic equilibrium. Equilibrium, or steady state, implies that the rate of discharge from the hydrogeologic system is equal to the rate of recharge and that no change in ground-water storage takes place. Obviously, there are seasonal changes in recharge, discharge, and ground-water storage (fig. 28), but on an annual average basis the water budget becomes balanced--that is, there are no long-term or permanent changes in storage.

The ground-water budget can be estimated by assuming the steady-state condition that inflow is equal to outflow. Table 12 presents a simplified water budget for the residuum and the principal artesian aquifer hydrogeologic system in the Dougherty Plain area in which precipitation is equal to the sum of overland runoff, base runoff, evapotranspiration, and ground-water pumpage. Assuming steady-state and average conditions, water is estimated to circulate through the hydrogeologic system at the rate of 4,300 ft^3/s (2,800 Mgal/d), plus or minus about 860 ft^3/s (560 Mgal/d).

The volume of ground water in storage in the principal artesian aquifer within the study area cannot be accurately determined, because sufficient

Table 12.--Estimated mean annual hydrologic budget factors for the principal artesian aquifer system

Factor	Estimated quantity (in.)	Accuracy of estimate (percent)	Variability of factor (in.)
Precipitation	53	± 5	±2.6
Overland runoff	4	±20	± .8
Base runoff [1/]	12	±20	±2.4
Evaporation-transpiration	36	±17	±6.0
Pumpage [2/]	1	±20	± .2

[1/] Primarily ground-water discharge to streams from principal artesian aquifer, but also includes some contribution from the residuum.

[2/] Total 1980 pumpage from principal artesian aquifer. No significant pumpage occurs from residuum.

specific-yield and storage-coefficient data are not available. However, estimates of average specific yield (0.15), aquifer thickness (200 ft), storage coefficient (0.003), and potentiometric head (20 ft) indicate that about 3,700 billion cubic feet (28,000 billion gallons) of water is presently (1981) in storage.

Water in storage in the principal artesian aquifer could, in theory, supply the entire present (1981) pumpage requirements of the Dougherty Plain for a number of years. In practice, however, reducing water levels below the top of the principal artesian aquifer for any period of time could increase the possibility of sinkhole collapse, reduce or eliminate base flow to streams, and increase well construction and pumping costs. In fact, most existing wells could not be pumped if water levels declined more than 10 to 20 feet below the top of the aquifer. Therefore, the desirable limit to water available from storage alone is about 50 billion gallons, or about half of the 1981 total pumpage of 113 billion gallons.

GROUND-WATER QUALITY

All ground water contains inorganic and, in some instances, organic constituents in solution. The type and concentration of constituents depend upon the surface and subsurface environment through which the water moves, the rate of movement, and the acidity of the water. Concentrations of naturally occurring dissolved constituents generally increase with depth and distance from the area where the water entered the subsurface.

Excess concentrations of dissolved solids may affect the suitability of ground water for various uses. Water-quality criteria or standards have been established for various uses and serve as a basis for assessing the chemical suitability of water for its intended use. The most important water-quality standards are public health standards which have been established for drinking water.

Selected chemical constituents of interest to this study are those for which recommended and mandatory drinking water standards have been established by the U.S. Environmental Protection Agency (1975, 1977, and 1979). (See table 13.)

Table 13.--Recommended and maximum concentrations of selected constituents in public drinking water supplies

[From U.S. Environmental Protection Agency, 1979; 1980]

Constituent	Recommended concentration limit in milligrams per liter, except where noted
Inorganic	
Total dissolved solids	500
Chloride (Cl)	250
Sulfate (SO_4)	250
Nitrate (NO_3-N)	10
Iron (Fe)	.3
Manganese (Mn)	.05
Copper (Cu)	1.0
Zinc (Zn)	5.0
Hydrogen sulfide (H_2S)	.05
	Maximum permissible concentration
Arsenic (As)	0.05
Barium (Ba)	1.0
Cadmium (Cd)	.01
Chromium (Cr + 6)	.05
Lead (Pb)	.05
Mercury (Hg)	.002
Fluoride (F)	(See comments.)
Organic	
Cyanide	0.05
Endrine	.0002
Lindane	.004
Methoxychlor	.1
Toxaphene	.005
2, 4-D	.1
2, 4, 5-TP silvex	.01
Phenols	.001
Carbon chloroform extract	.2
Synthetic detergents	.5

Fluoride: When the annual average of the maximum daily air temperatures for the location in which the water-supply system is located is the following, the maximum permissible concentration (MPC) for fluoride is:

Temperature, in degrees Fahrenheit	Temperature, in degrees Celsius	MPC, in milligrams per liter
53.7 and below	12.0 and below	2.4
53.8 to 58.3	12.1 to 14.6	2.2
58.4 to 63.8	14.7 to 17.6	2.0
63.9 to 70.6	17.7 to 21.4	1.8
70.7 to 79.2	21.5 to 26.2	1.6
79.3 to 90.5	26.3 to 32.5	1.4

Recommended standards apply to those constituents which may adversely affect public health, the taste, color, or turbidity of the water, or may impart some other undesirable characteristic to the water. Consumption of water having concentrations somewhat above the recommended limits is generally not harmful to humans. Mandatory limits, however, establish maximum permissable concentrations in drinking water, and human consumption of water having concentrations above these limits may produce specific toxic or adverse physiological effects.

Water samples were collected from 16 residuum and 14 principal artesian aquifer wells (table 14). These samples were analyzed for concentrations of major inorganic constituents and for agricultural pesticides, herbicides, insecticides, and fungicides commonly used in southwest Georgia (table 15). Analyses for the trace elements arsenic, lead, mercury, copper, and zinc were not made because previous studies (Radtke and others, 1980; Pollard and others, 1978) found none of these elements in concentrations exceeding the recommended or maximum limits in either surface or ground water in the Dougherty Plain.

The chemical quality of ground water in the Dougherty Plain area varies both within and among the separate geohydrologic units. Statistical analyses of concentrations of selected constituents in water from the residuum and principal artesian aquifer are listed in table 16. These data indicate that water from these units usually meet U.S. Environmental Protection Agency recommended or mandatory standards.

Pesticides

Rapid growth in agricultural use of large-acreage irrigation systems has resulted in increases in the use of fertilizers and pesticides, some of which are toxic to humans, long-lasting, and tend to accumulate in the hydrogeologic system.

Pesticides were detected in water from 11 residuum wells and 4 principal artesian aquifer wells. Total pesticide concentrations were usually greater in water from the residuum than in water from the principal artesian aquifer. Water from two of the principal artesian aquifer wells contained pesticide concentrations only slightly above detection limits, whereas water from the other two principal artesian aquifer wells contained concentrations of pesticides within detection limits.

The presence or absence of pesticides in water from principal artesian aquifer wells as reported herein is valid only for the times that the samples were taken. Concentrations of pesticides could be greater or less in samples from these same wells at other times. As discussed previously, water flow in the aquifer may range from about 0.2 ft/d to 3 ft/d. Consequently, pesticides can quickly move through the aquifer in areas where flow velocities are relatively high. Thus, pesticide detection is strongly time dependent.

The areal extent, severity, and the long-term affects of pesticides upon quality of water from the principal artesian aquifer cannot be determined from the available data. The U.S. Geological Survey and the U.S. Environmental Protection Agency currently are conducting further investigations and analyses of pesticide movement in the Dougherty Plain area.

GROUND-WATER FLOW MODEL

Model Description

A two-dimensional numerical model developed by Trescott and others (1976) was used to simulate water levels in the principal artesian aquifer. Water levels in the aquifer are affected by pumpage and variations in natural recharge and leakage to and from streams. The digital model utilizes a central finite-difference scheme to evaluate the partial differential ground-water flow equations in which the head is the dependent variable.

Three reasons underlie the choice of a two-dimensional ground-water model to simulate ground-water conditions in the Dougherty Plain: (1) the flow system in and around the Dougherty Plain area can be conceptualized (without significant simulation error) as a two-dimensional flow system; (2) during a drought period in which substantial amounts of agricultural pumping is occurring, the aquifer

Table 14.--Selected water-quality data for wells from which water was analyzed for major inorganic constituents and pesticides

[Geohydrologic unit: PCPA, principal artesian aquifer; RSDM, residuum]

Well No.	Well name	Geo-hydro-logic unit	Date sampled	Water level (ft below land surface)	Tempera-ture (°C)	pH	Specific conduc-tance at 25°C	Alkalinity as $CaCO_3$ (mg/L)		Hydrogen sulfide (mg/L)
								Unfiltered	Filtered	
Baker County										
29	T. Rentz TW 1	PCPA	04-23-81	17.29	20.5	7.66	280	118	118	--
Calhoun County										
24	B. Jordan TW 1	RSDM	04-14-81	26.30	21.0	6.40	60	26	21	--
25	B. Jordan TW 2	PCPA	04-14-81	20.98	20.4	7.74	270	180	107	0.4
Decatur County										
10	A. Newton, North TW	PCPA	04-22-81	43.81	20.5	7.78	220	95	93	.4
43	DP 5	PCPA	04-22-81	54.17	20.6	7.79	210	107	104	--
44	DP 6	RSDM	08-20-80	--	--	5.60	50	--	--	--
Dougherty County										
15	Nilo, North TW 2	PCPA	04-14-81	31.25	20.6	7.60	230	138	--	--
71	Nilo, South TW 3	RSDM	04-15-81	36.13	20.5	6.60	125	52	44	--
72	USMC Supply TW 1	RSDM	04-13-81	23.47	--	5.75	34	--	--	--
Early County										
39	I. Newberry TW 1	PCPA	04-23-81	--	20.3	7.44	265	116	116	.0
45	I. Newberry TW 2	RSDM	04-15-81	25.72	21.0	7.30	160	75	72	--
46	V. Evans TW 1	RSDM	04-23-81	8.97	18.7	6.36	110	43	43	--
Lee County										
15	M. Moorman TW 1	PCPA	04-20-81	27.51	20.1	7.60	200	95	85	.0
40	Piedmont Plant Farm TW 1	RSDM	04-20-81	34.00	21.5	6.80	83	20	21	--
41	S. Stocks TW 1	RSDM	04-20-81	14.07	20.5	6.80	77	7	7	--
43	H. Usry TW 1	RSDM	04-16-81	23.80	19.0	6.10	63	16	16	--
Miller County										
15	DP 2	PCPA	04-22-81	20.79	21.0	7.61	270	184	135	.2
16	DP 3	RSDM	04-22-81	34.94	21.1	6.90	320	740	--	.7
33	J. Fleet TW 2	RSDM	04-23-81	32.37	--	6.78	320	148	148	--
Mitchell County										
16	C. Holton TW 1	PCPA	04-15-81	28.21	20.7	7.95	185	103	87	--
35	C. Holton TW 2	RSDM	04-15-81	43.50	20.0	6.30	55	20	18	--
36	H. Davis TW 1	RSDM	04-21-81	31.78	20.0	6.10	160	11	--	--
38	DP 11	PCPA	04-15-81	44.92	20.3	7.90	195	90	80	--
40	H. Davis TW 2	PCPA	04-21-81	45.35	20.7	7.80	210	103	102	--
Seminole County										
08	Roddenberry TW 1	PCPA	04-22-81	28.51	20.8	7.60	265	129	126	.8
26	D. Harvey TW 1	PCPA	04-23-81	57.07	21.1	7.72	230	107	107	.0
Sumter County										
22	E. Stephens TW 1	RSDM	04-16-81	14.95	19.0	6.00	70	14	15	--
Worth County										
04	DP 8	PCPA	04-16-81	12.53	20.6	7.75	215	117	113	--
05	DP 9	RSDM	04-16-81	22.68	20.0	7.90	155	1,070	71	--
09	C. Odom TW 1	RSDM	04-16-81	24.90	19.5	5.20	60	14	15	--

becomes partly unconfined and the two-dimensional model is capable of simulating an aquifer which is changing states (from confined to unconfined); and (3) the amount of data available could not justify the use of a three-dimensional model.

Heads simulated by the model were compared with measured heads from wells in the project area. The comparisons were made to evaluate the concepts used in the calibration process and to measure the accuracy of the model in response to hypothetical changes in the geohydrologic system. The calibrated model was used to predict the effects of pumpage ranging from 113 to 408 billion gallons per year under hypothetical hydrologic drought conditions and 287 billion gallons per year under long-term, average hydrologic conditions.

Table 15.--Agricultural pesticides commonly used in southwest Georgia, 1976-77

[From Radtke and others, 1980]

Chemical name	Class	Crop	Pounds of active ingredients/acre	Residual
HERBICIDES				
Translated (systemic) herbicides				
2,4-D	Phenoxy acid	Corn, grain sorghum	0.5	1 week
2,4-DB	do.	Peanuts	.25	1 week
Atrazine	Triazine	Corn, grain sorghum	2-3	3-12 weeks
Proazine	do.	Grain sorghum	2	2-8 weeks
Simazine	do.	Corn	2-3	2-3 weeks
Chloroxuron	Substituted urea	Soybeans	1-1.5	1-2 weeks
Linuron	do.	Grain sorghum, soybeans	1	3 weeks
Butylate	Carbamate	Corn	3-6	3-8 weeks
Vernolate	do.	Peanuts	2-2.25	3-8 weeks
Alachlor	Substituted aniline	Peanuts, corn, soybeans	3	3 weeks
Benefin	do.	Peanuts	1-1.5	2-4 months
Trifluralin	do.	Soybeans, vegetables	.5-1	--
Contact herbicides				
Dinoseb	Phenol	Peanuts, soybeans	2	2 weeks
Paraquat	Pyridylium	Corn	.25	none
INSECTICIDES				
Dicofol	Chloronated hydrocarbon	Peanuts, soybeans	.8	--
Carbofuran	Carbamate	Peanuts	1.5	--
Diazinion	Organophosphate	Peanuts, soybeans	1.5	--
Malathion	do.	Peanuts, tobacco	1.0	--
Disulfoton	do.	Peanuts	.75	--
NEMATOCIDES				
Dibromochloropropane	Fumigant	Peanuts	6 qts.	--
Ethoprop	Nonfumigant organophosphate	Peanuts, corn, soybeans	2	--
Carbofuran	Nonfumigant carbamate	Peanuts, corn	1.5	--
FUNGICIDES				
Benomyl	Carbamate	Vegetables, peanuts	.5	--
Chlorothalonil	Chloronated hydrocarbon	Peanuts	1.0	--
Quinrozene	Chloronated benzene	Peanuts	10.0	--

System Concepts

To numerically model the principal artesian aquifer flow system, a conceptual flow model of the aquifer flow system in southwest Georgia was developed. The aquifer may be conceptualized as being confined from above by the residuum (described previously in this report) and from below by the Lisbon Formation. Furthermore, the aquifer is assumed to be homogeneous and isotropic. Water recharges the aquifer by moving vertically downward through the residuum and discharges from the aquifer to pumping wells and to streams that are hydraulically connected to the aquifer. This conceptual flow model is illustrated in figure 30.

Table 16.--Statistical summary of water-quality data pertinent to the residuum (RSDM) and the principal artesian aquifer (PCPA)

			Statistical analysis					
Source	Constituent	Number of samples	Minimum	Maximum	Mean	Standard deviation	Median	Mode
RSDM	Temperature (degree C)	14	18.7	21.5	20.1	0.9	20.0	19.0
PCPA	do.	20	17.0	21.1	19.9	1.3	20.5	20.5
RSDM	Specific conductance (umhos)	19	34.0	490.0	145	118	110	60
PCPA	do.	20	150.	280	220	35	212	200
RSDM	pH (units)	18	5.2	7.9	--	--	--	--
PCPA	do.	16	7.4	8.0	--	--	7.7	7.6
RSDM	Alkalinity field (mg/L, as $CaCO_3$)	15	7.0	210	61	64	26	14
PCPA	do.	16	9.5	184	112	39	108	103
RSDM	Alkalinity (mg/L, as $CaCO_3$)	13	7.0	1070	159	338	20	14
PCPA	do.	13	90	184	119	30	107	95
RSDM	Hardness (mg/L, as $CaCO_3$)	18	11	240	61	60	38	17
PCPA	do.	20	89	140.0	105.0	15.3	105.0	100.0
RSDM	Calcium, dissolved (mg/L, as Ca)	18	3.4	87.0	22.0	22.0	14.0	7.9
PCPA	do.	20	35.0	53.0	42.1	6.0	40.0	40.0
RSDM	Magnesium, dissolved (mg/L, as Mg)	18	.3	4.3	1.2	1.0	.9	1.0
PCPA	do.	20	.2	3.3	.9	.6	.8	.5
RSDM	Sodium, dissolved (mg/L, as Na)	18	1.3	6.8	2.8	1.5	2.4	2.6
PCPA	do.	20	1.3	6.0	2.2	1.1	1.9	2.1
RSDM	Sodium adsorption ratio	18	.1	.3	.2	.1	.2	.2
PCPA	do.	20	.1	.3	.1	.1	.1	.1
RSDM	Potassium, dissolved (mg/L, as K)	18	.2	5.9	.9	1.3	.4	.3
PCPA	do.	20	.1	1.1	.3	.2	.3	.3
RSDM	Chloride, dissolved (mg/L, as Cl)	18	2.0	14.0	4.3	2.7	3.7	3.0
PCPA	do.	20	1.5	6.2	3.2	1.3	3.0	1.6
RSDM	Sulfate, dissolved (mg/L, as SO_4)	18	0	6.1	2.5	2.0	1.8	1.3
PCPA	do.	20	0	8.8	1.8	2.2	1.0	.1
RSDM	Fluoride, dissolved (mg/L, as F)	18	.1	.5	.2	.1	.1	.1
PCPA	do.	20	0	.2	.1	.03	.1	.1
RSDM	Silica, dissolved (mg/L, as SiO_2)	18	.1	12.0	6.07	3.1	6.3	3.0
PCPA	do.	20	5.2	20.0	8.2	3.6	7.0	5.2
RSDM	Iron, suspended recoverable (mg/L, as Fe)	10	.160	73.0	20.9	23.7	12.1	.160
PCPA	do.	12	.08	15.0	31.8	53.7	.71	.80
RSDM	Iron, total recoverable (mg/L, as Fe)	16	.180	73.0	18.2	20.1	12.5	2.80
PCPA	do.	16	.100	15.0	3.55	5.08	.755	.100
RSDM	Iron, dissolved (mg/L, as Fe)	17	.010	3.20	.289	.779	.020	.010
PCPA	do.	16	.000	.510	.051	.123	.020	.010

Table 16.--Statistical summary of water-quality data pertinent to the residuum (RSDM) and the principal artesian aquifer (PCPA)--Continued

Source	Constituent	Number of samples	Statistical analysis					
			Minimum	Maximum	Mean	Standard deviation	Median	Mode
RSDM	Manganese, suspended recoverable (mg/L, as Mn)	13	.000	9.90	2.13	3.24	.500	.000
PCPA	do.	9	.000	.770	.148	.247	.030	.030
RSDM	Manganese, total recoverable (mg/L, as Mn)	14	.030	30.0	4.58	7.95	1.42	.030
PCPA	do.	14	.010	1.10	.189	.330	.030	.030
RSDM	Manganese, dissolved (mg/L, as Mn)	14	.001	33.0	2.80	8.73	.135	.280
PCPA	do.	14	1.0	30.0	7.30	10.2	2.0	1.0
RSDM	Nitrogen, dissolved (mg/L, as N)	3	.3	1.7	.8	--	--	--
PCPA	do.	10	.1	3.6	2.0	1.3	1.9	1.9
RSDM	Nitrogen, organic dissolved (mg/L, as N)	3	.1	.5	.2	--	--	--
PCPA	do.	10	0	.3	.1	.1	.1	0
RSDM	Nitrogen ammonia, dissolved (mg/L, as N)	16	.02	1.5	.2	.4	.06	.05
PCPA	do.	16	.01	.3	.09	.08	.06	.04
RSDM	Nitrogen nitrate, dissolved (mg/L, as N)	13	.01	.02	.01	.005	.01	.01
PCPA	do.	14	.01	.01	.01	0	.01	.01
RSDM	Nitrogen nitrite, dissolved (mg/L, as N)	5	0.08	0.6	0.4	--	--	--
PCPA	do.	2	2.5	3.3	2.9	--	--	--
RSDM	Nitrogen ammonia + organic, dissolved (mg/L, as N)	3	.2	.6	.3	--	--	--
PCPA	do.	10	.3	.4	.2	.1	.2	.03
RSDM	Nitrogen, NO_3 + NO_2, dissolved (mg/L as N)	16	.02	3.1	.8	.9	.4	.02
PCPA	do.	16	.02	3.3	1.5	1.2	1.4	.04
RSDM	Phosphorus, dissolved (mg/L, as P)	17	.01	.03	.02	.008	.01	.01
PCPA	do.	16	.01	.07	.02	.02	.02	.02
RSDM	Carbon, organic, total (mg/L as C)	14	1.6	120	15.2	30.7	5.8	1.6
PCPA	do.	14	.8	4.3	2.3	1.2	2.1	1.0
RSDM	Sulfide, total (mg/L, as S)	1	.7	.7	.7	--	--	--
PCPA	do.	9	0	.8	.2	.3	0	0
RSDM	Nitrogen ammonia, dissolved (mg/L, as NH_4)	16	.03	1.9	.2	.4	.08	.06
PCPA	do.	16	.01	.4	.1	.1	.07	.05
RSDM	Nitrogen nitrate, dissolved (mg/L, as NO_3)	5	.4	2.7	1.6	--	--	--
PCPA	do.	2	11.0	15.0	13.0	--	--	--
RSDM	Nitrogen nitrite, dissolved (mg/L, as NO_2)	5	.07	.07	.06	--	--	--
PCPA	do.	2	.03	.03	.03	--	--	--

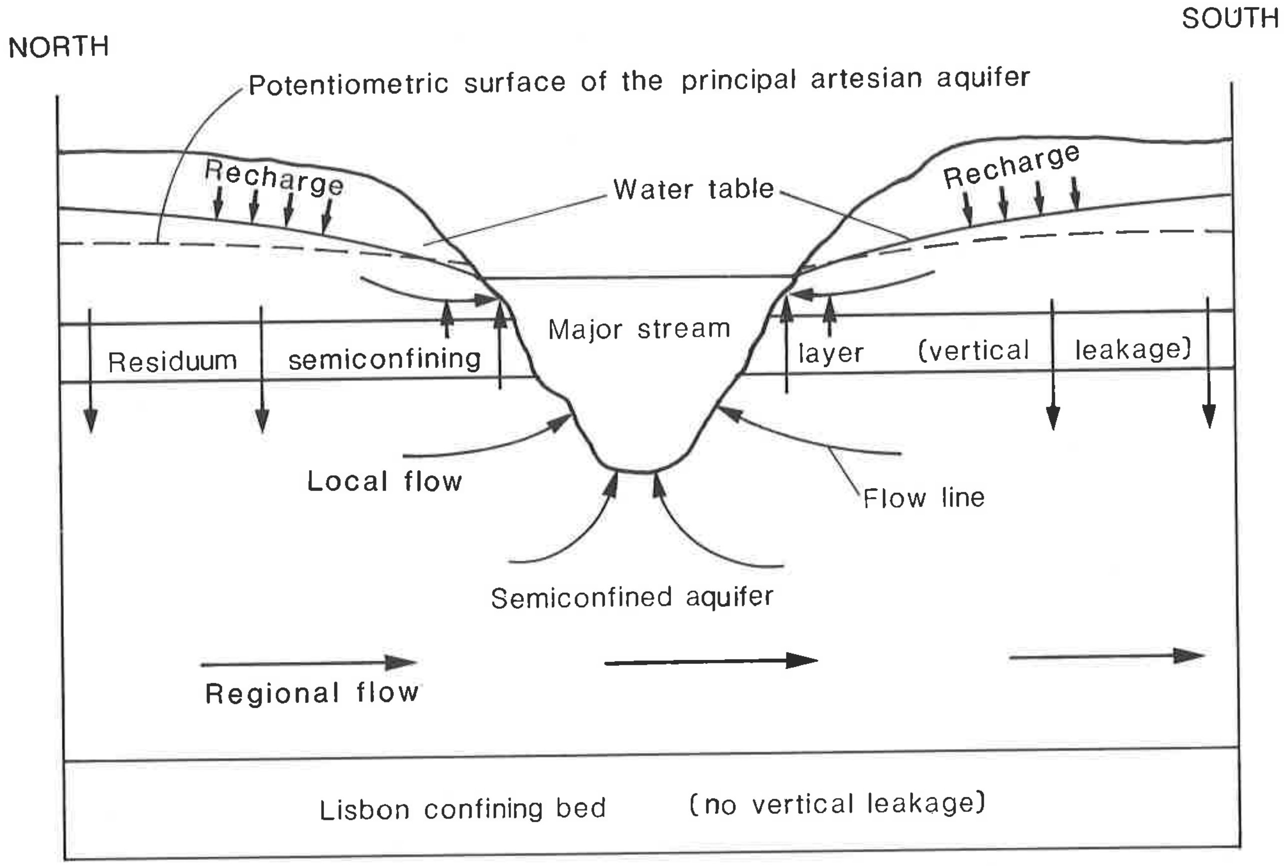


Figure 30.—Conceptual flow model of the principal artesian aquifer system.

Ground-Water Flow Analysis

Two-dimensional transient ground-water flow in a confined aquifer can be described by

$$\frac{\partial}{\partial x}(Txx\frac{\partial h}{\partial x})+\frac{\partial}{\partial y}(Tyy\frac{\partial h}{\partial y}) = S\frac{\partial h}{\partial t}+W(x,y,t), \qquad (1)$$

in which

T_{xx}, T_{yy} are the principal components of the transmissivity tensor, in the x and y directions, respectively (L^2t^{-1}),

h is the hydraulic head (L),

S is the storage coefficient (dimensionless),

and

W(x,y,t) is the volumetric flux of recharge or withdrawal per unit surface area of the aquifer system (Lt^{-1}).

For steady-state conditions, equation (1) can be reduced to

$$\frac{\partial}{\partial x}(Txx\frac{\partial h}{\partial x})+\frac{\partial}{\partial y}(Tyy\frac{\partial h}{\partial y}) = W(x,y) \qquad (2)$$

Equations (1) and (2) are approximated by the use of a finite-difference scheme which is described in detail by Trescott and others (1976).

The numerical model utilizes the following equation to calculate leakage into and out of the aquifer

$$Q = \frac{K'v}{M'} \cdot (h_r-h_a) \cdot A, \qquad (3)$$

in which

Q is the leakage (L^3t^{-1}),

k'_v is the vertical hydraulic conductivity of the residuum confining layer (Lt^{-1}),

M' is the thickness of the residuum confining layer (L),

A is the unit surface area (L^2),

h_r is the head in the residuum (water table, L),

and

h_a is the head in the principal artesian aquifer (L).

For a stream that cuts into the principal artesian aquifer, leakage was estimated in a slightly different manner. Where the stream cuts into the aquifer, water flows laterally toward the stream and, in the immediate vicinity of the stream, flows vertically upward into the stream as shown in figure 30. Assuming that the aquifer has homogeneous geologic properties, its average head occurs one-half the distance from the streambed to the bottom of the aquifer (Johnston, 1977, p. 12). Thus, the discharge into a stream may be calculated by conceptualizing the upper half of the aquifer as a confining unit and the head in the confining unit as the head in the aquifer. However, since a stream occupies a much smaller surface area than does a cell block (described in the following section and illustrated in figure 32), and since the leakage computation is for an entire cell area, the quantity of leakage must be reduced in accordance with the ratio of stream surface area to cell block surface area. This is accomplished by reducing the values of vertical hydraulic conductivity by the ratio of stream area to cell block area. Therefore, discharge into the stream is calculated by

$$q_1 = \frac{A_s}{A_n} \cdot K_v \cdot \frac{(h_r-h_2)}{b/2}, \qquad (4)$$

where

q_1 = leakage (L^3t^{-1}),

A_s = surface area of stream (L^2),

A_n = surface area of cell block (L^2),

K_v = vertical hydraulic conductivity (L^2t^{-1}),

h_r = head in the confining layer (water table) (L),

h_2 = head of the aquifer at the stream (L),

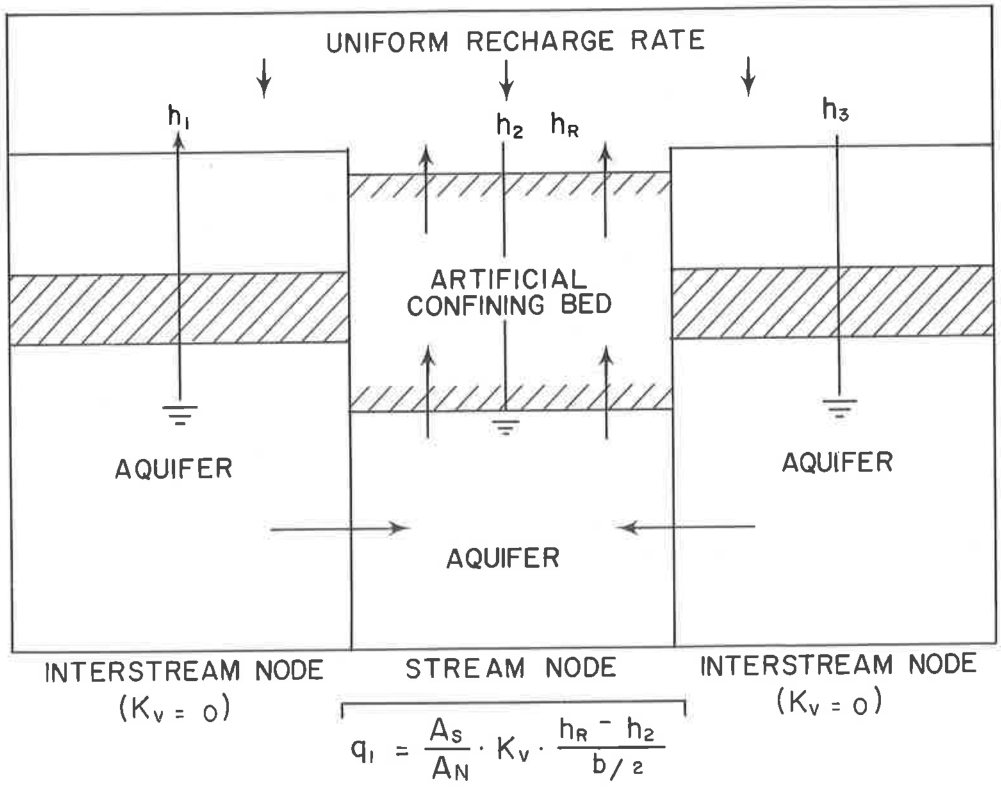
and

b/2 = 1/2 thickness of the aquifer (thickness of the artificial confining bed, L).

Equation (4) is described in detail by figure 31.

Finite-Difference Grid and Boundary Conditions

The principal artesian aquifer was idealized by using a 78-row by 105-column finite-difference grid, shown in figure 32. Each cell block of the grid occupies



$$q_1 = \frac{A_S}{A_N} \cdot K_v \cdot \frac{h_R - h_2}{b/2}$$

Where q_1 = Leakage, A_S = Surface Area of Stream, A_N = Surface Area of Node, K_V = Vertical Hydraulic Conductivity, h_R = River Head (constant), h_1, h_2, h_3 = Heads in Aquifer, and $b/2$ = Thickness of Artificial Confining Bed ($1/2$ Aquifer Thickness).

Figure 31.—Conceptual flow model of hydraulic connection between the principal artesian aquifer and the Flint River. Modified from Johnston (1977).

a 1-square mile area throughout the grid with the node located at the center of the cell block. The following boundary conditions (shown in figure 32) were imposed on the model:

(1) Constant-head boundary: Along the Chattahoochee River to the west and below Lake Seminole, the aquifer head at a specified cell block was held constant for a specific simulation. Along the Chattahoochee River, the aquifer head ranged from 75 ft above sea level near Lake Seminole to 144 ft above sea level at the model's northern boundary.

(2) Constant-flux boundary: The Dougherty Plain is separated from the Tifton Upland on the east by a topographic and ground-water divide across which no water is assumed to flow. Furthermore, the updip limit of the principal artesian aquifer generally coincides with the northern physiographic boundary of the Dougherty Plain. Thus, the eastern and northern boundaries of the model were assigned a constant flux value of zero for all simulations.

These boundary conditions are realistic for both steady-state and transient simulations and are factual representations of existing field geologic and hydrologic conditions. Presently, there are no centers of major pumping along the zero flux boundaries.

Data Requirements

The data requirements of the model are aquifer and confining bed hydraulic parameters and initial conditions. Aquifer transmissivity (T) and vertical hydraulic conductivity (K'_v) and thickness (b') of the residuum confining unit are required for each cell block. Aquifer storage coefficient (S) is required only for transient analysis. Furthermore, initial heads of the residuum and the aquifer, and stages of streams must be specified for each block in the aquifer for both steady-state and transient simulations.

Hydraulic properties

Transmissivity values for the principal artesian aquifer used in the model ranged from 3,000 ft^2/d to 300,000 ft^2/d, and are within the limits of the field data, as previously discussed.

Storage coefficients for the principal artesian aquifer calculated from 18 aquifer tests range from 2×10^{-4} to 3×10^{-2}. A storage coefficient of 5×10^{-4} was assumed for confined conditions throughout the modeled area. Where water levels declined below the top of the principal artesian aquifer (a water-table condition) as a result of pumping or other stress, a specific yield value of 0.2 was used.

The vertical hydraulic conductivity and thickness of the residuum confining unit were combined to form the parameter known as leakance. Thus

$$L' = \frac{K'_v}{b'}, \qquad (5)$$

where

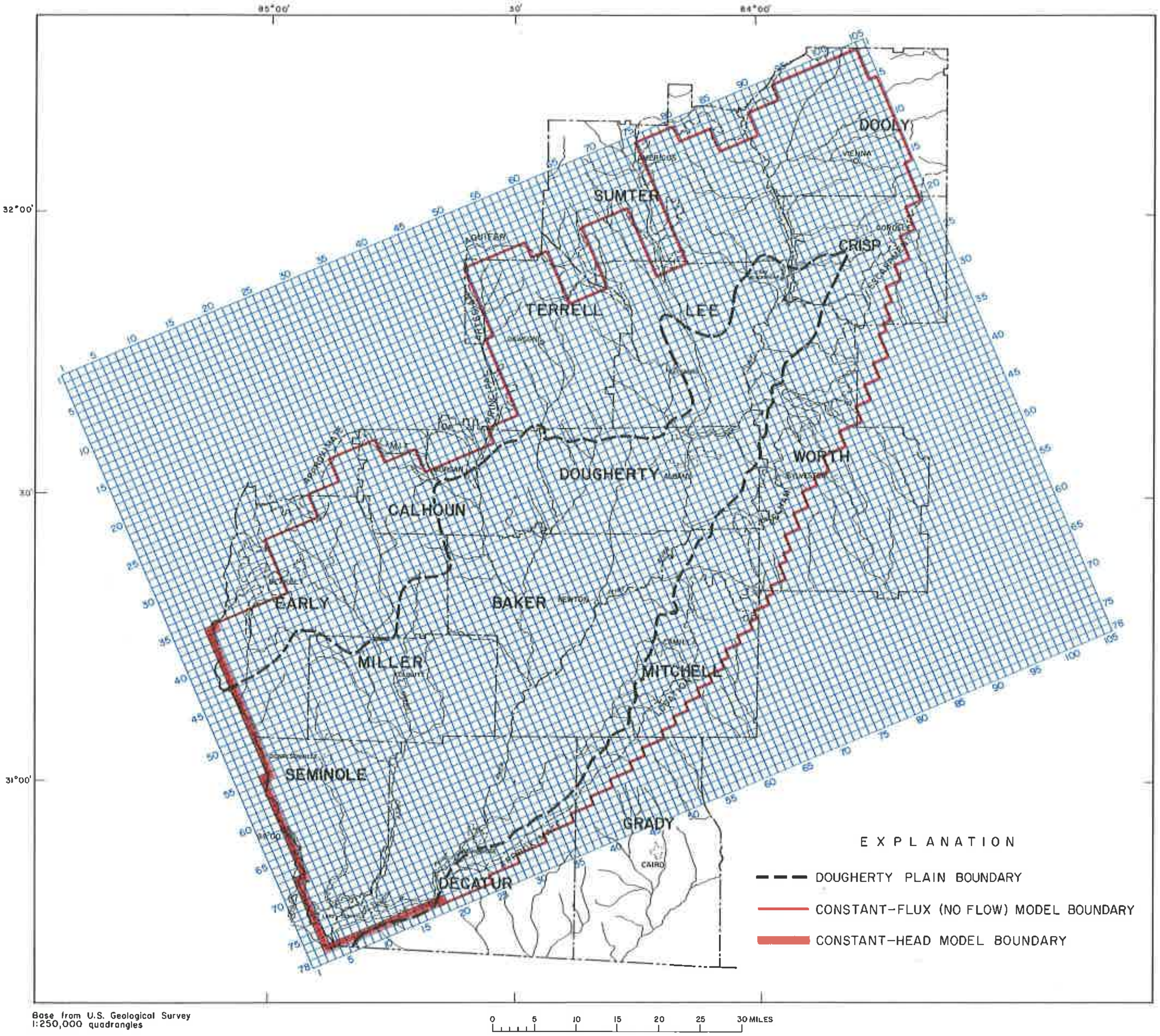
L' is the leakance (t^{-1}),

K'_v is the vertical hydraulic conductivity of the residuum confining layer (Lt^{-1}),

and

b' is the thickness of the residuum confining layer (L).

Figure 20 illustrates the areal range of leakance (K'_v/b') of the residuum used in the calibrated model. Preliminary values of leakance were estimated by dividing estimated vertical hydraulic conductivity values by residuum confining layer thickness, which is considered to be equivalent to the bottom half of the residuum. An initial leakance map based on these results was modified during the steady-state calibration of the digital model. Consequently, the resulting map presents estimated ranges of leakance based on test-drilling data and digital modeling analyses. The values presented in figure 20 are considered realistic and within the range of accuracy of the field data.



Base from U.S. Geological Survey 1:250,000 quadrangles

Figure 32.—The model area with finite-difference grid and boundary conditions. No flow where boundary and grid lines coincide; constant head where boundary line bisects cell block.

The method used in calculating the vertical hydraulic conductivity of nodes dedicated to streams is described below. The thickness of confining beds underlying all streams was assumed to be 10 ft. Measurements were made to estimate the amount of ground water discharged to the largest (perennial) streams (fig. 33). This process yielded four different classifications of streams:

(1) For streams that gained ground water at a rate of less than 0.1 $(ft^3/s)/mi^2$, the confining layer between the streams and the aquifer was assigned a vertical hydraulic conductivity value of 0.005 ft/d. This was the median value of hydraulic conductivities obtained from field tests. These streams were considered to be minor streams that had little or no effect on the aquifer.

(2) The confining layer under streams that had gains ranging from 0.1 to 0.25 $(ft^3/s)/mi^2$ were assigned a vertical hydraulic conductivty value of 0.01 ft/d and a stream node ratio of 0.02.

(3) The confining layer under streams that had gains greater than 0.25 $(ft^3/s)/mi^2$ were assigned a vertical hydraulic conductivity value of 0.05 ft/d and a stream node ratio of 0.04.

(4) Streams that cut into the aquifer (such as the Flint and Chattahoochee Rivers) were assigned vertical hydraulic conductivity values of 40 ft/d.

Initial model runs indicated that these values were generally acceptable. Leakance values were changed only slightly to achieve a calibrated model.

Another required hydraulic input parameter is the altitude of the water table in the residuum (or riverhead) (fig. 22). The water-table altitude varies, depending on climatic conditions and the time of year. Data from 29 residuum wells were used as control points. Regionalization of these data is based on topography, lithologic character of the residuum, stream and surface drainage features, and data trends. For purposes of steady-state model calibration, the November 1979 water-table altitudes (riverheads) were used. Furthermore, water-table altitudes assigned to stream nodes were average stream surface altitudes obtained from 1:24,000-scale topographic maps and from gaging-station data.

The digital model used in these simulations has the ability to simulate unconfined and confined aquifers. Unconfined or water-table conditions occur in the principal artesian aquifer where the potentiometric surface in the aquifer falls below the base of the residuum confining layer. In order to simulate an unconfined aquifer, three additional hydraulic parameters are required:

(1) Horizontal hydraulic conductivity of the principal artesian aquifer. This value was determined by dividing the transmissivity (fig. 23) of the aquifer by its thickness for each cell block (fig. 6).

(2) Altitudes of the top and base of the aquifer. These values were determined from structure contour maps of the tops of the principal artesian aquifer (fig. 5) and the Lisbon Formation (fig. 7).

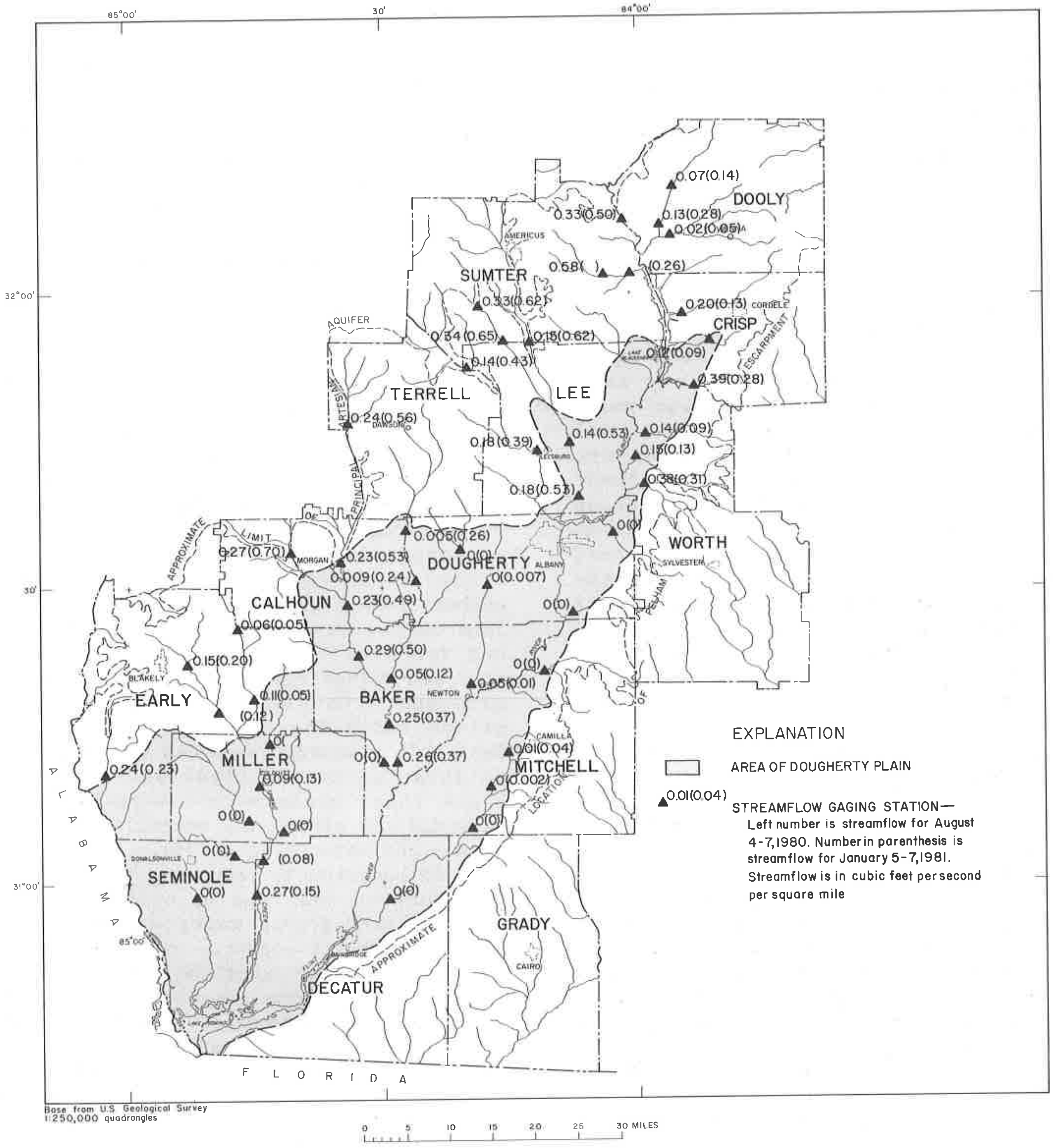
(3) Specific yield of the principal artesian aquifer. A constant value of 0.2 was used in the model. While this value may seem high for a limestone, it was believed that the large solution channels occurring as secondary porosity justified the use of the large value.

Initial conditions

Initial potentiometric values were assigned to each cell block of the principal artesian aquifer being modeled. Measured water levels were used to construct the potentiometric surface map for November 1979 (Mitchell, 1981, pl. 2), and values for each cell block were derived from this map.

Model Calibration

The purpose of a calibration procedure is to represent natural ground-water flow conditions with a digital model as accurately as possible, within existing



Base from U.S. Geological Survey 1:250,000 quadrangles

Figure 33.—Measured stream discharge for August 1980 and January 1981.

limits of available data. The process of adjusting model input parameters until realistic results are obtained is termed calibration. The digital model was calibrated for November 1979 steady-state conditions. The model calibration was then tested by simulating transient conditions during May to November 1980.

Calibration Procedures

The error criterion selected for calibration required the mean error between simulated and derived cell-block values to approach zero for all cell blocks and the standard deviation to be less than ± 5.0 ft. Assuming a normal error distribution, this would assure that 95 percent of all simulated heads would be within ± 10 ft of derived heads which themselves are considered accurate to generally ± 10 ft. Since input head values are derived from potentiometric maps based on measured heads, the errors computed by the model (drawdown) are the input heads minus the simulated heads.

During the calibration procedure, aquifer transmissivity, leakance of the residuum confining unit, and water-table altitudes (riverheads) were varied. Calibrated transmissivity values ranged from about 3,000 to 300,000 ft^2/d. These compared well with measured values, and none were more than 2 times the measured values.

Leakance (K'_v/b') was varied more than the transmissivity during the calibration process; however, care was taken to assure that the final calibrated values agreed, in general, with values determined from test drilling and general data trends (fig. 20).

Because few water-table altitudes were available, this parameter was least accurately known and was the most varied. However, in all areas the data were checked to assure that water-table altitudes were above the top of the artesian aquifer and below land surface.

November 1979 Steady-State Simulation

The simulated steady-state potentiometric surface and measured water levels (heads) for November 1979 are shown in figure 34. From the figure it is apparent that the simulated values compare favorably with the measured data. Average simulation error was 0.6 foot with a standard deviation of error of 4.6 ft. This was within the desired criterion that 95 percent of all the simulated heads be within ±10 ft of input data.

The distribution of the head error (difference between cell-block values derived from measured heads and simulated heads) is shown in figure 35. The error in the heads approximates a normal distribution at a class interval of 4.0 ft. The difference between the simulated potentiometric surface and the potentiometric surface constructed from measured water levels is shown in figure 36. The areas of greatest difference usually occur along or near the streams. This is probably due to the required application of stream leakage over an entire cell block, as discussed previously. The authors considered it necessary to simulate quantities of water discharged to and received from streams that would approach values obtained from field measurements. Consequently, at several stream nodes the drawdown required to leak this discharge exceeded the desired calibration error criterion. However, since these nodes were few in number, they did not affect the overall calibration significantly (fig. 35).

In addition to requiring the simulated heads to meet the error criterion, the simulated ground-water discharge to streams must also compare acceptably with measured ground-water discharge. Although no seepage-run measurements were available for November 1979, two sets of measurements were made at selected sites during August 4-7, 1980, and January 5-7, 1981 (fig. 33). Comparison of these measured flows with simulated flows for November 1979 indicates that the simulated values are reasonable because stream baseflow and ground-water conditions were similar for November 1979 and August 1980. The field measurements for these months are compared with simulated results for November 1979 in table 17. Allowing for the changes in ground-water levels and slight climatic differences between November 1979 and August 1980,

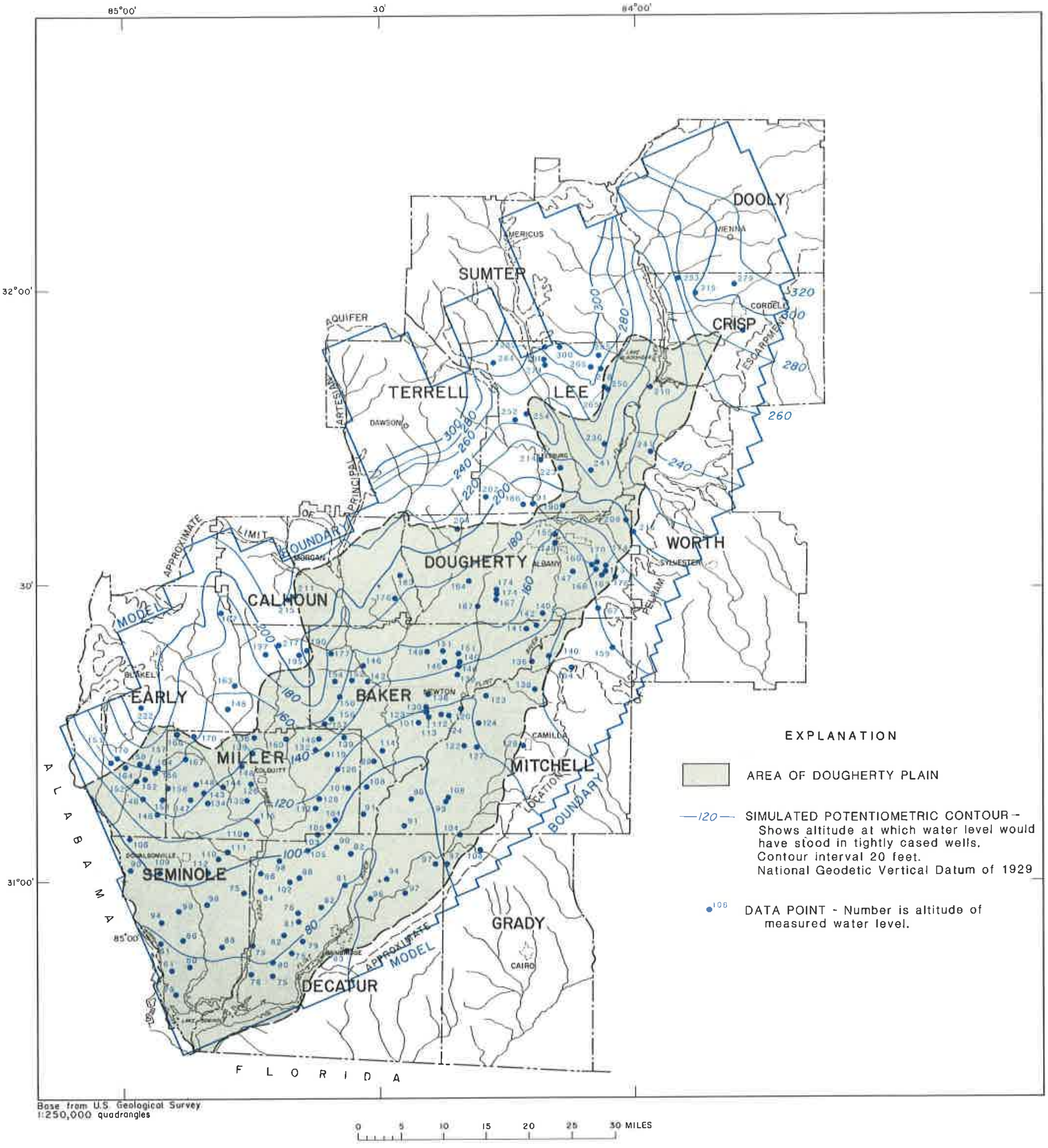


Figure 34.—Measured water levels and simulated potentiometric surface of the principal artesian aquifer, November 1979.

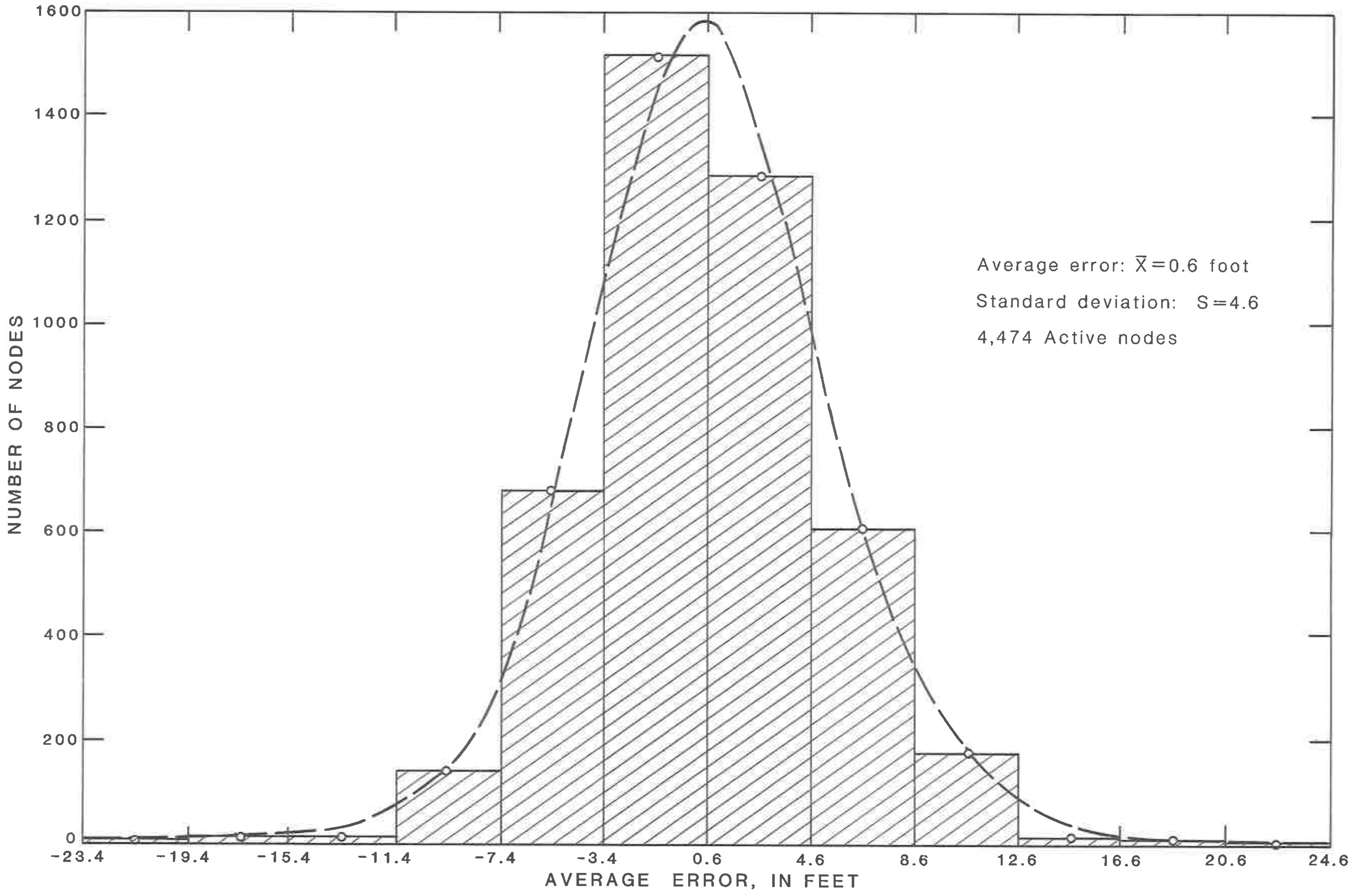


Figure 35.—Distribution of head error for the November 1979 calibration of steady-state simulation.

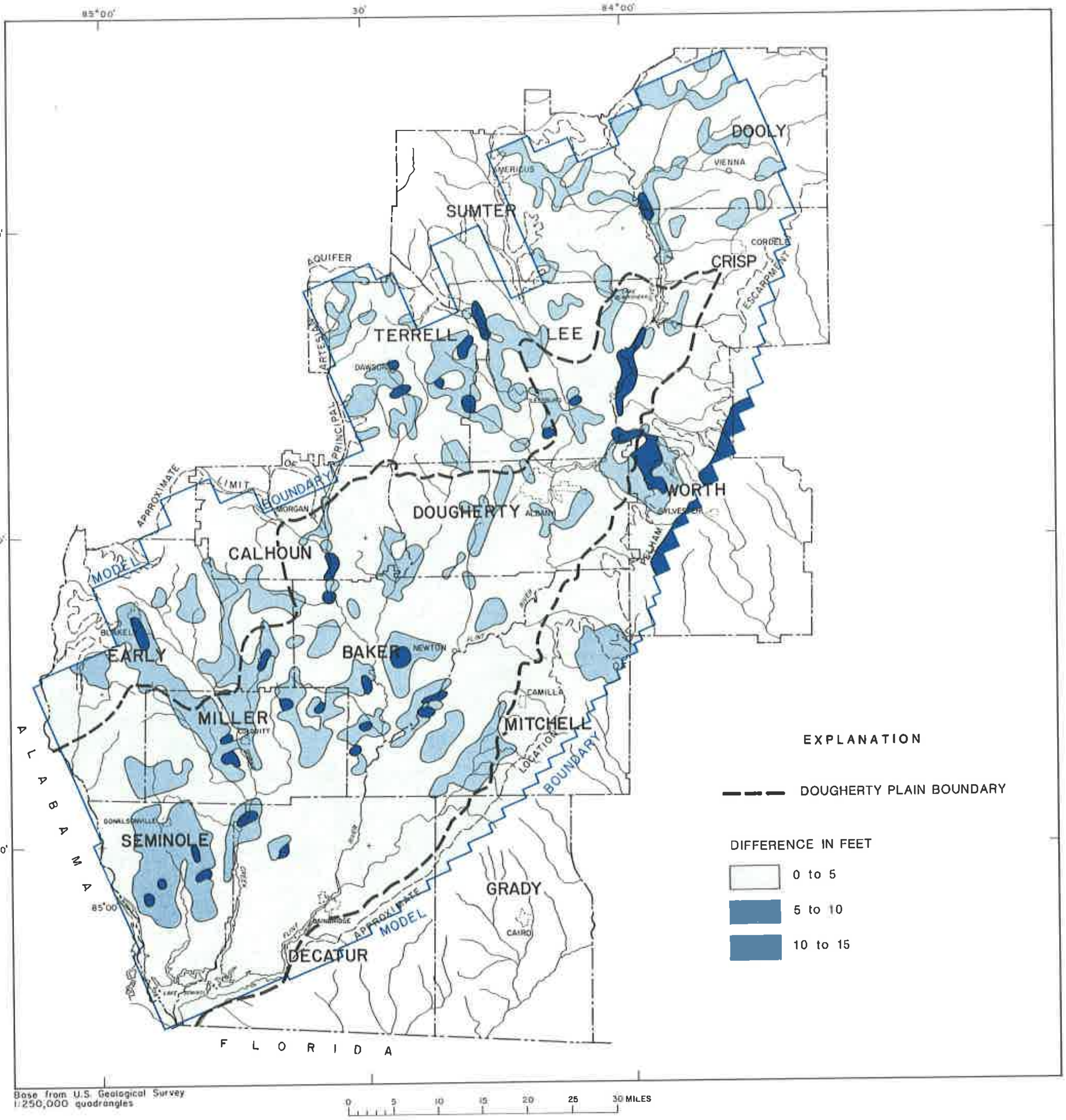


Figure 36—Areal distribution of difference between the November 1979 simulated potentiometric surface and the potentiometric surface constructed from measured water levels.

Table 17.--Measured and simulated ground-water discharge to selected streams

Stream	Flow, in ft^3/s Measured Aug. 4-7, 1980	Jan. 5-7, 1981	Simulated Nov. 1979	Stream reach Upstream station	Downstream station
Dry Creek	—	12	14	Headwater	56290
Spring Creek	—	71	55	56100	57050
Ichawaynochaway Creek	132	53	80	53266	55350
Chickasawhatchee Creek	15	38	29	Headwater	54500
Kinchafoonee Creek	39	20	20	50860	51000
Muckaloochee Creek	7.1	14	7.2	51780	51800
Lime Creek	—	16	15	Headwater	50100
Turkey Creek	7	15	12	49900	49910
Pennahatchee Creek	1.5	5.2	3.7	Headwater	49980
Muckalee Creek	22	29	65	51700	51920
Jones Creek	7.1	4.4	6.2	Headwater	50509
Flint River	[1] 1,200	—	1,300	49500	53000

[1] Net gain in Flint River flow between Montezuma (station 49500) and Newton (station 53000), after subtracting tributary inflow to Flint River between Montezuma and Newton.

and the effects of irrigation pumpage from the stream, the agreement between measured flows and simulated flows was acceptable.

Another factor to consider in evaluating calibration validity is the total ground-water budget for the Dougherty Plain area. Base-flow analysis was used for eight watershed areas comprising the Dougherty Plain. (Refer to section on Base Flow.) Over a 10-year period (water years 1959-70) late-summer (Sept., Oct., and Nov.) mean base runoff derived primarily from the principal artesian aquifer was calculated to be about 2,300 ft^3/s. Because the simulation was pertinent only to November 1979 and because November base flow is slightly less than the average of September through November flows, the simulated ground-water flow should be slightly less than estimated late-summer values. In fact, the simulated ground-water discharge was 2,200 ft^3/s, which was considered an acceptable comparison with the hydrograph analysis.

To measure the sensitivity of the calibrated model to changing transmissivity, leakance, and water-table altitudes (riverheads), a sensitivity analysis was conducted by varying these parameters. Transmissivity and leakance values were varied from 25 percent to 400 percent of the calibrated value. Water-table altitudes were varied from 80 percent to 120 percent of the values used in the calibration. Ten different computer runs were made varying the calibrated parameters. The average error, standard deviation, and simulated ground-water discharge for each run are given in table 18.

Several conclusions may be drawn from table 18.

(1) By varying transmissivity and leakance, acceptable average simulated head errors and standard deviations could be achieved. However, these new parameters could not simulate an acceptable water budget.

(2) Even though the altitude of the water table in the residuum (riverhead) was varied by only ± 20 percent, it produced drastic changes in simulated heads--values that would be unacceptable if they were used in a calibrated model.

(3) The model is most sensitive to changes in water-table altitude. Thus, the accuracy of the calibrated model could be most improved by additional field data that better define the water table in the residuum.

Table 18.--Sensitivity of aquifer transmissivity (T), confining zone leakance (L), and riverhead (R) on the calibrated model for November 1979

Run No.	Parameters	Average error (ft)	Standard deviation	Water budget [ft^3/s (in./yr)]
C [1]	T, L, R	+0.6	4.6	2,207 (6.4)
1	0.25T, L, R	-2.0	4.4	934 (2.7)
2	0.50T, L, R	-.9	4.2	1,458 (4.2)
3	2.0T, L, R	+2.6	5.7	3,213 (9.3)
4	4.0T, L, R	+5.4	7.7	4,491 (13.0)
5	T, 0.25L, R	+5.4	7.7	1,127 (3.3)
6	T, 0.50L, R	+2.7	5.7	1,610 (4.6)
7	T, 2.0L, R	-.8	4.2	2,817 (8.1)
8	T, 4.0L, R	-2.0	4.4	3,700 (10.7)
9	T, L, 0.8R	+38.2	18.0	3,056 (8.8)
10	T, L, 1.2R	-37.0	18.0	3,943 (11.4)

[1] Calibrated model run for November 1979.

May-November 1980
Transient Simulation

Because of the increasing demand on ground-water supplies for agricultural irrigation in the Dougherty Plain, the utility of the model would be considerably enhanced if it were capable of accurately (within the established error criterion) reproducing ground-water conditions during a given irrigation season. With measurements of the altitude of the water surface in the principal artesian aquifer available during May and November 1980, ground-water conditions were simulated by the model for the period of May 15 to November 5, 1980.

This total period was simulated in stages by using 3 time periods. During the first period of 17 days (May 15-31, 1980), only municipal pumpage of 24 ft^3/s was considered. Starting heads were those obtained from measured values for May 1980. Water-table altitudes in the residuum (riverhead) were obtained in a manner described below.

Because an areal distribution of measured water-table altitudes was not available for May 1980, the authors calibrated a steady-state model using available May 1980 potentiometric surface measurements to obtain water-table riverhead) values. The May 1980 steady-state calibration utilized aquifer transmissivity and leakance values determined from the November 1979 steady-state calibration. The May 1980 steady-state simulation produced water-table altitudes (riverheads) that were greater in magnitude than those used in the November steady-state simulation. This was in agreement with existing hydrologic conditions at the simulation time, since an increase in precipitation had occurred during the winter months (Dec.-Apr. 1980). The calibrated steady-state model for May 1980 (using the simulated water-table values) met the calibration error criterion required of all model calibrations (average simulation error of 1 ft and standard deviation of error of 4.7 ft). Furthermore, all water-table data were checked to assure that values were above the top of the principal artesian aquifer and below land-surface altitudes.

The second time period of 107 days began on June 1, 1980, and ended on September 15, 1980. This period included most of the 1980 growing season when agricultural pumping reached a very high level in the Dougherty Plain (H. E. Gill, U.S. Geological Survey, oral commun., Nov. 1981). In terms of an annualized rate, ground water was used for agricultural irrigation at the rate of about 1,100 ft^3/s during 1980. For modeling purposes, all irrigation systems within a 1-square mile grid-block area were summed and assumed to be at the center of the block. Data on the number and capacity of irrigation systems in the Dougherty Plain were obtained through a field survey of existing irrigation systems during the spring of 1980 (R. R. Pierce, U.S. Geological Survey, oral commun., 1981). The locations of agricultural irrigation systems in the modeled area, as of the spring of 1980, are shown in figure 37. In addition to agricultural use, municipal pumpage of 24 ft^3/s was also included during the second time period.

The simulated head values calculated at the end of the first time period were used as the starting head values for the second time period. However, constant-head nodes (Chattahoochee River and Lake Seminole) were assigned a value between the measured potentiometric water-levels of May 15 and November 5, 1980. The values assigned to the constant head nodes for September 15, 1980, were estimated by inspection of ground-water hydrographs from wells located near the Chattahoochee River and Lake Seminole. The assumption was made that all constant-head nodes would have similar ground-water-level declines as did the wells where measurements were available. Therefore, the amount of water-level decline occurring from May 15 to September 15, 1980, in the measured water levels was applied to all constant-head nodes.

The third time period, September 16 to November 5, 1980 (51 days), was simulated by using only the 24 ft^3/s of municipal pumpage. The simulated potentiometric heads computed at the end of the second time period were used as the starting heads for this period. Constant head nodes were assigned the poten-

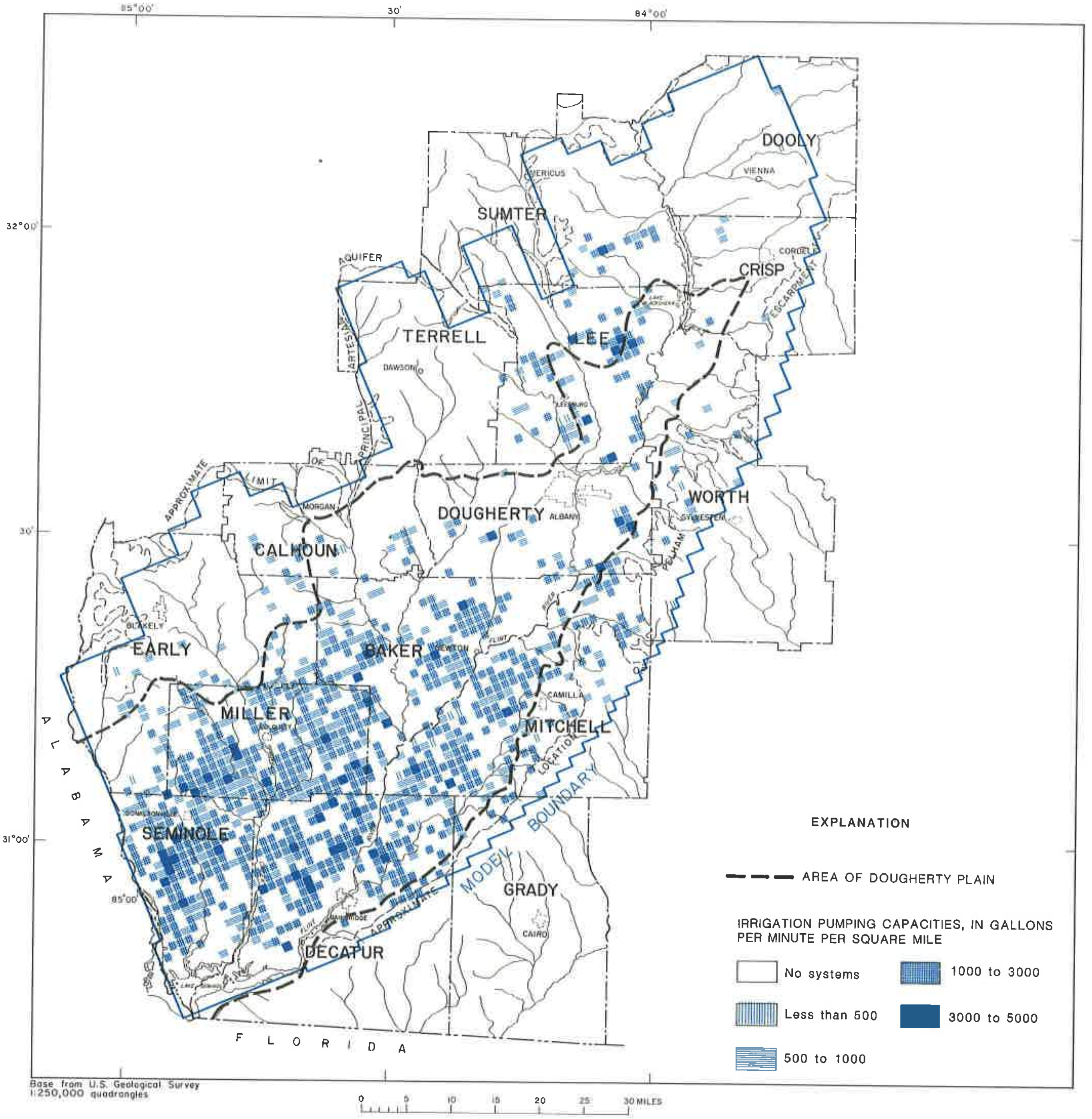


Figure 37.—Locations and capacities of agricultural irrigation systems in the Dougherty Plain area as of spring 1980.

tiometric surface values at those locations for November 1980.

Areal measurements of water-table altitudes in the residuum (riverheads) were also not available for the second and third pumping periods (June 1 to Nov. 5, 1980). However, based upon a review of hydrographs, water-table values were set equal to the starting potentiometric head values of the principal artesian aquifer for pumping periods two and three. For grid nodes identified as river nodes, the water-table values were set equal to what was believed to be a reliable surface-water altitude of the stream or river at the start of the pumping period.

The storage coefficient of 5×10^{-3} was assumed not to vary significantly throughout the Dougherty Plain. Therefore, this value was used throughout the modeling area for all three pumping periods.

Measured water levels in the principal artesian aquifer for November 1980 and those simulated at the end of the transient simulation are presented in figure 38. The simulation error for November 1980 averaged 0.2 ft with a standard deviation of 3.4 ft. This was well within the desired criterion that 95 percent of all simulated heads be within ± 10 ft of the derived data.

The simulated water levels for eight wells in the Dougherty Plain during May 15 to November 5, 1980, compare satisfactorily with measured water levels for this time period. Measured and simulated water levels in wells 087-10, 087-23, and 095-68 are shown in figure 39, and measured and simulated water levels in wells 201-05, 205-16, 253-08, and 253-26 are shown in figure 40.

It should be noted that the measured water levels represent a point value; whereas, the simulated water levels represent an average value for a 1 mi^2 block. Therefore, while the fluctuation with time of simulated and measured values should be similar, actual simulated and measured values may differ considerably.

Simulated Effects of Pumpage During A Hypothetical Drought and During Normal Recharge Conditions

Transient model analyses were used to simulate changes in the potentiometric surface of the principal artesian aquifer and discharge to or recharge from overlying streams resulting from three sets of hydrologic conditions: (1) 1981 pumpage (municipal, industrial, and irrigation) during a hypothetical 3-year hydrologic drought, (2) 1981 pumpage plus the projected potential increase in irrigation pumpage during a hypothetical 3-year hydrologic drought, and (3) 1980 pumpage plus the projected potential increase in irrigation pumpage during a 10-year period of long-term average recharge conditions.

The transient model was used as previously calibrated for all predictive simulations with the exception of water-table altitude (riverhead) and storage coefficient, as explained below. Model results are presented as a series of maps showing ranges of water-level declines resulting from drought conditions (reduced recharge) and increased irrigation pumpage.

All simulations were made by using the water-table conversion option of the model (Trescott and others, 1976, p. 11-12). As simulated water levels in the aquifer drop below the top of the aquifer, the initial artesian storage coefficient (0.005) converts to a predetermined water-table specific yield value (0.2). Also, to treat leakage more realistically, if parts of an artesian aquifer change to water-table conditions, the maximum head difference across the confining bed is limited to the difference between the altitude of the water table in the residuum (riverhead) and the top of the aquifer.

In the modeled area, ground-water withdrawals from the principal artesian aquifer for irrigation use increased from 47 billion gallons per year in 1977 to about 76 billion gallons in 1980. Partly because of constantly increasing irriga-

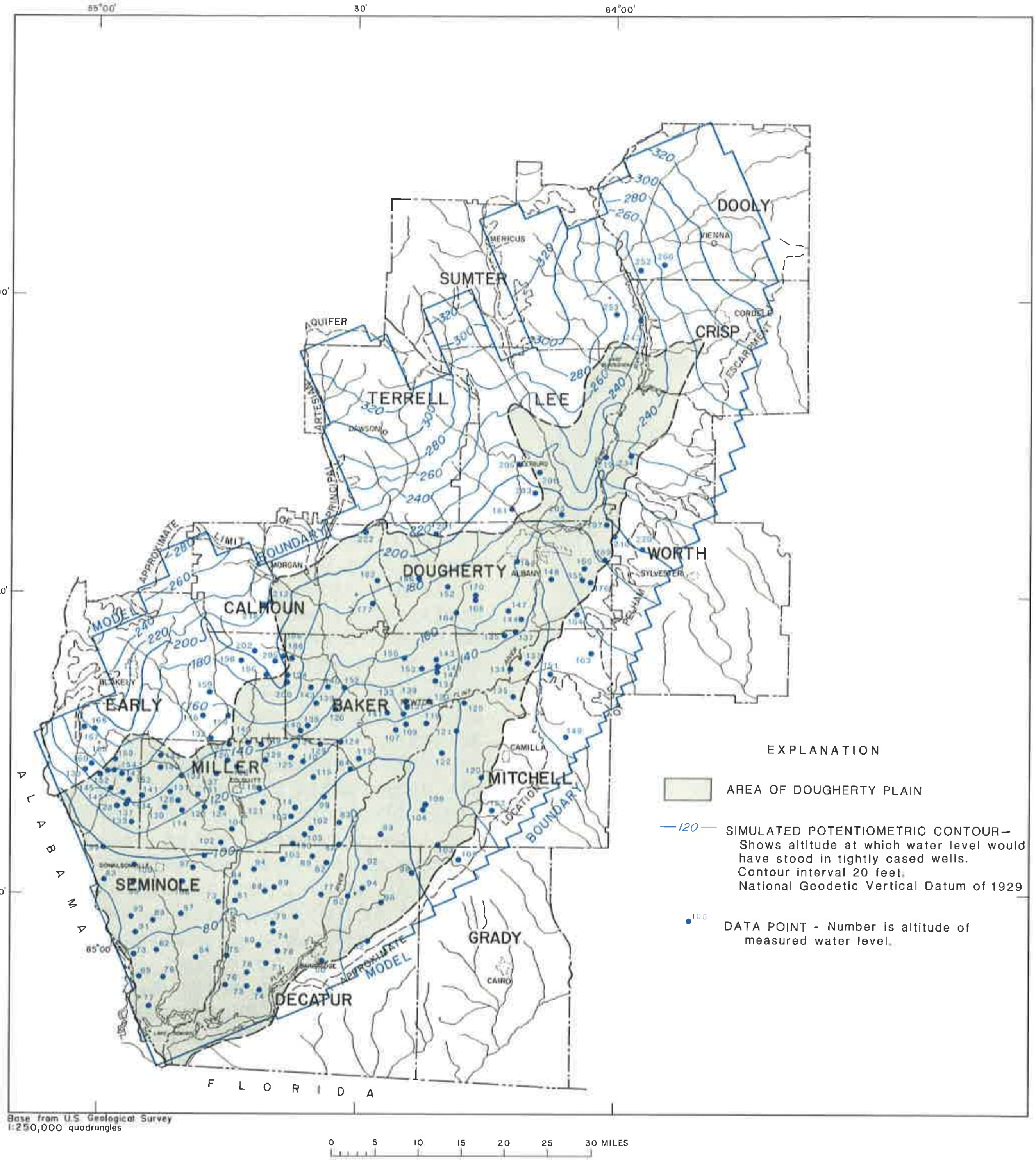


Figure 38.—Measured water levels and simulated potentiometric surface of the principal artesian aquifer, November 1980.

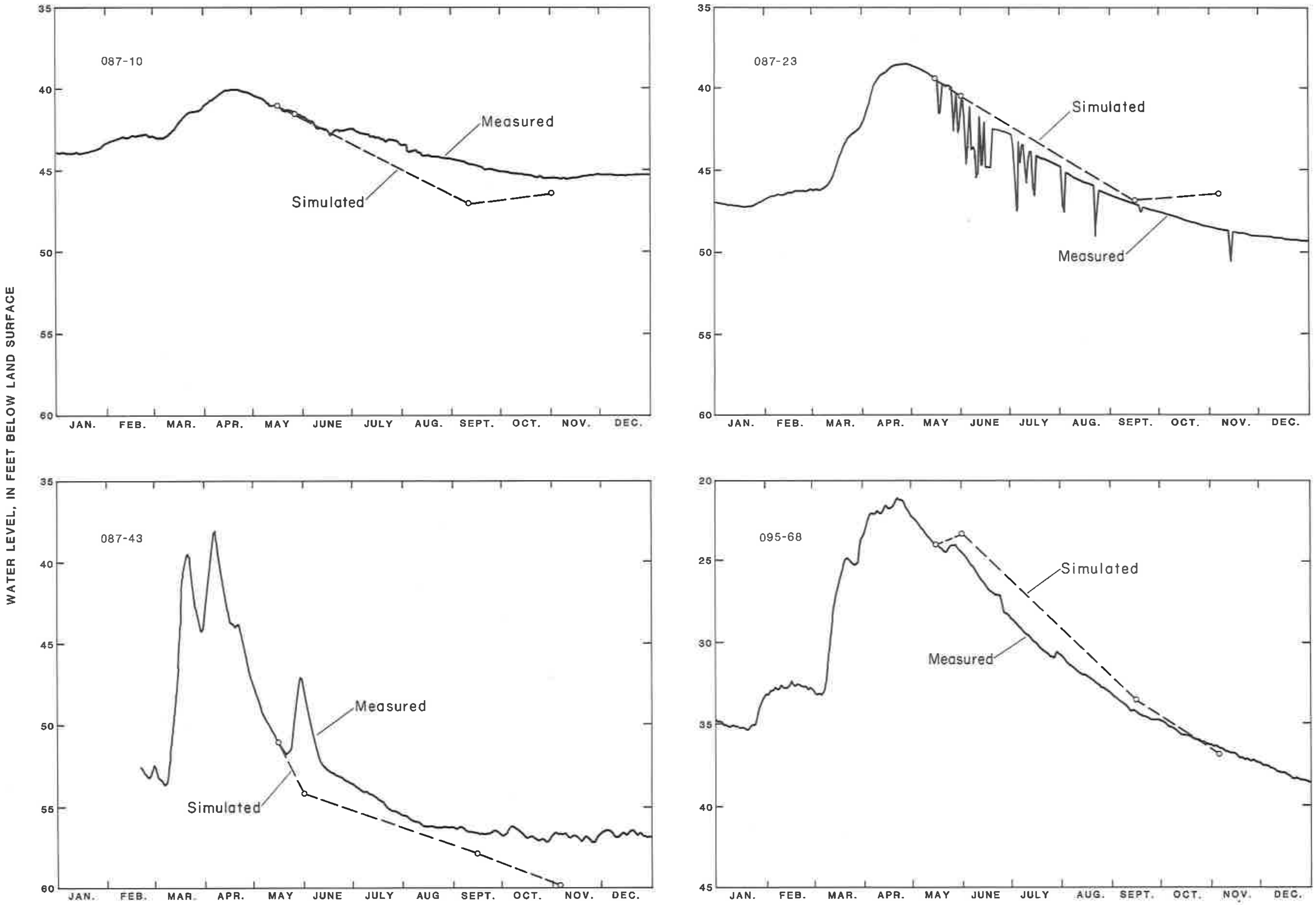


Figure 39.—Measured and simulated water levels in wells 087-10, 087-23, 087-43, and 095-68, 1980.

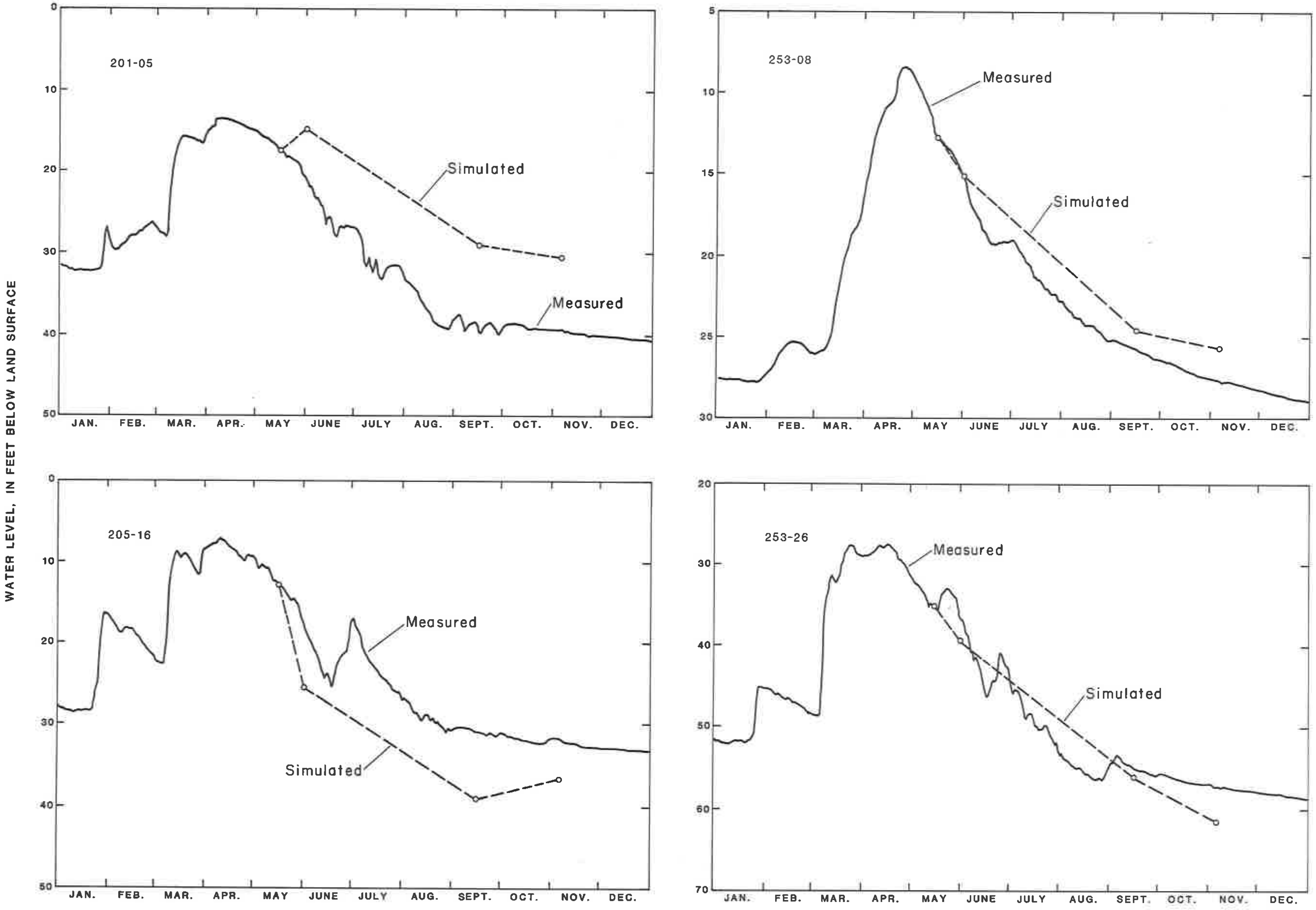


Figure 40.—Measured and simulated water levels in wells 201–05, 205–16, 253–08, and 253–26, 1980.

tion use, and partly because of a hydrologic drought that occurred from the summer of 1980 through the summer of 1981, irrigation withdrawals are estimated to have increased to about 107 billion gallons in 1981. 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 insure successful growth of two or three crops yearly. Average yearly water use for all purposes, other than irrigation, is about 6 billion gallons.

Projected potential increase in agricultural land within the Dougherty Plain area was estimated from county land-use maps prepared by the Soil Conservation Service (R. R. Pierce, U.S. Geological Survey, written commun., 1981). Projected pumpage was assigned to each square-mile block in the model based on the number of acres of potential agricultural land still available in that node for new or additional irrigation and an average application rate per acre (fig. 41). Potential additional irrigation pumpage was not assigned to urban or urbanizing areas, areas not suitable for irrigation by center-pivot systems, or in those counties that lie mostly outside of the Dougherty Plain. The potential additional projected irrigation pumpage under normal recharge conditions is estimated to be about 205 billion gallons per year and, under drought conditions, is estimated to be about 295 billion gallons per year.

Effects of Irrigation Pumpage During a Hypothetical 3-Year Drought

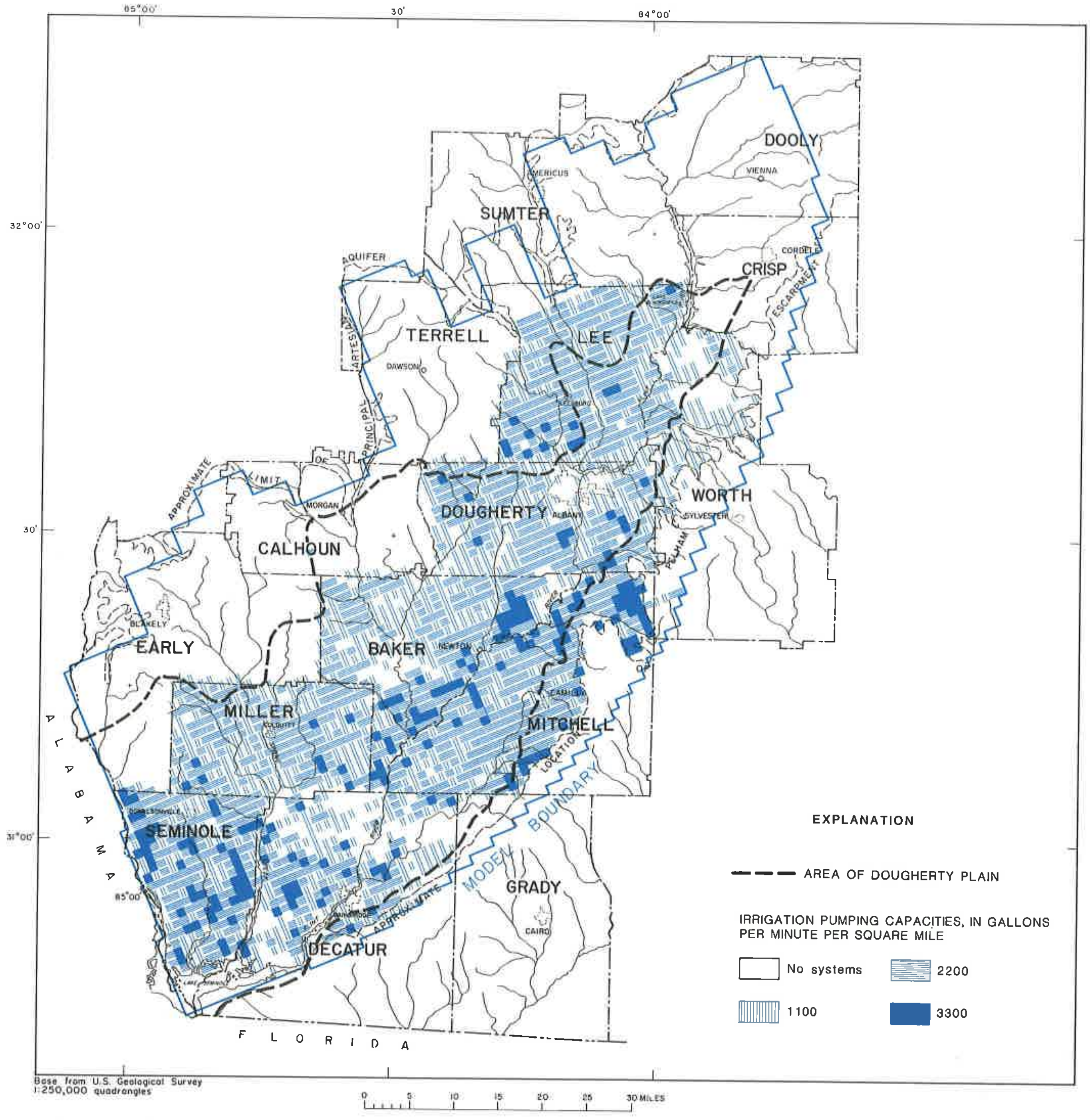
Model runs were made simulating water-level declines from initial low water levels (Nov. 1979) resulting from reduced recharge and from increased irrigation pumpage during two 3-year drought periods. A single irrigation season of 154 days (May-Sept.) was simulated for each year.

Recharge used in the model for the two drought simulations was estimated as follows: estimated mean recharge for 1981 (a drought year) was used as recharge for the year-1 simulation; 80 percent and 60 percent of the 1981 recharge were input as year-2 and year-3 recharge, respectively. The assumption was made that as the drought continued, water levels in the residuum would decline and, consequently, recharge (leakage from the residuum into the principal artesian aquifer) would decline accordingly. Actual recharge for years 2 and 3 of a 3-year drought is unknown. The figures given here are, however, believed to be reasonable, based on the limited residuum water-level data available before and during the first year of the 1980-81 drought. Nevertheless, it must be emphasized that the simulation results to be discussed are valid only for the given set of recharge conditions. If recharge conditions during a concurrent 3-year drought are significantly different from those described above, simulation results would also be significantly different.

Pumpage of 113 billion gallons per year

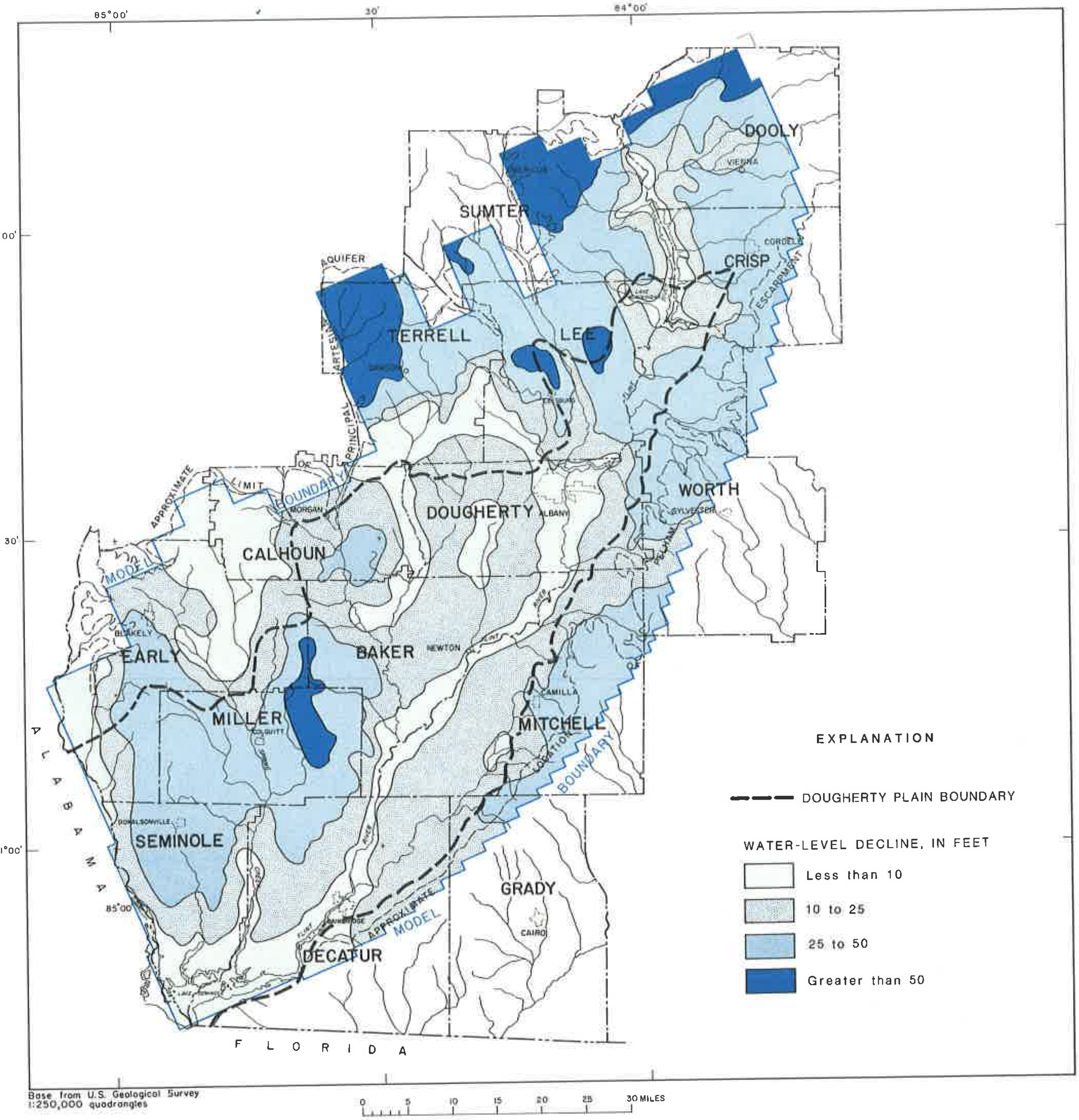
The simulated mean declines in the potentiometric surface of the principal artesian aquifer for drought years 1, 2, and 3 were, respectively, 18, 22, and 26 ft below the starting potentiometric surface. Simulated declines at the end of the hypothetical 3-year drought were generally less than 43 ft, but ranged from 43 to 61 ft in about 15 percent of the modeled area (fig. 42). In some areas, water levels fell from a few feet to 10 ft below the top of the aquifer (fig. 43). Figure 44 shows hydrographs of actual water-level declines due to the 1980-81 drought and projected water-level declines resulting from the simulated 3-year drought.

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) was derived from aquifer storage and half from recharge. Aquifer discharge to streams was considerably reduced, and all streams originating within the Dougherty Plain stopped flowing. Simulated flow of the Flint



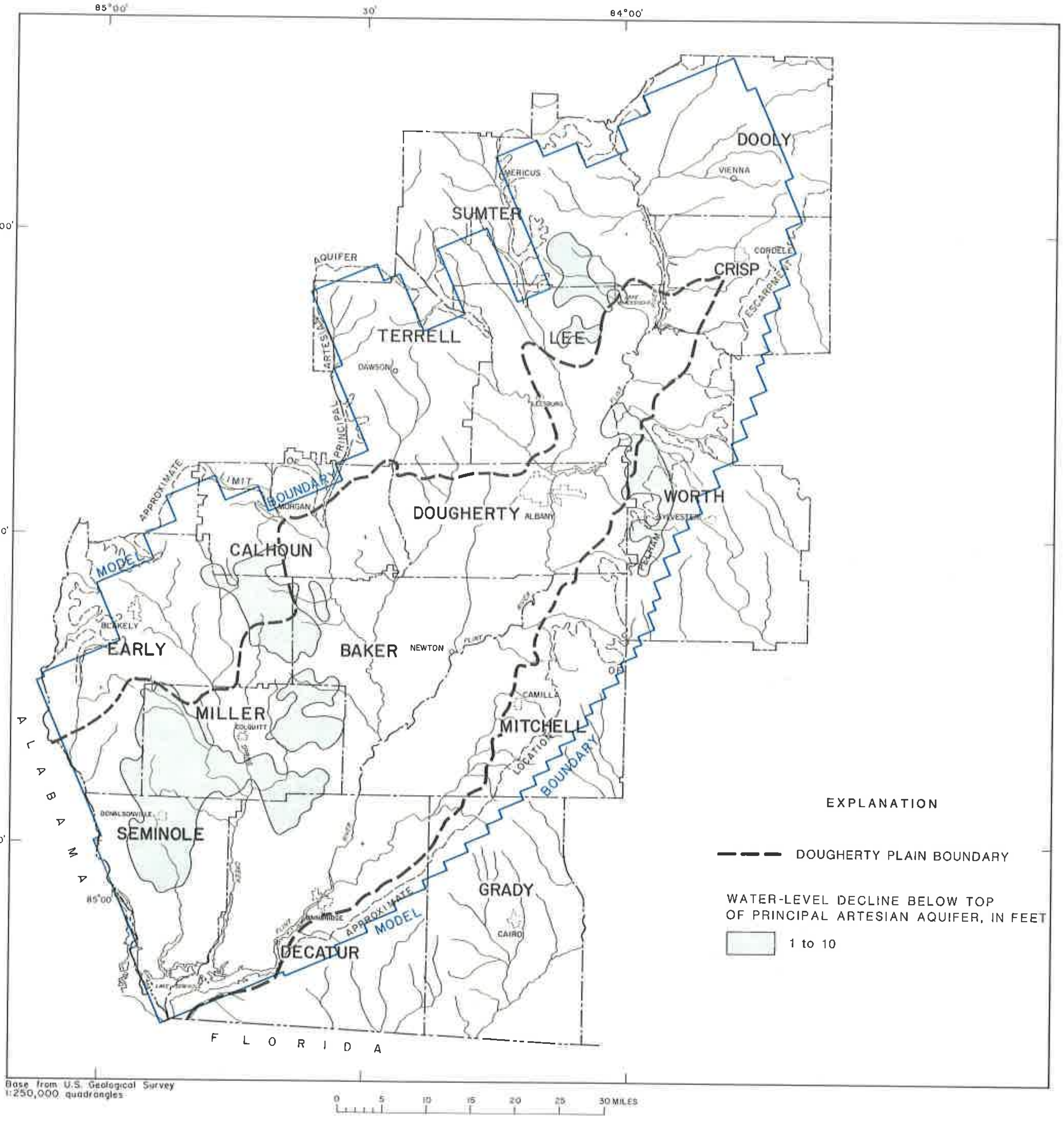
Base from U.S. Geological Survey 1:250,000 quadrangles

Figure 41.—Locations and capacities of projected potential irrigation systems in the Dougherty Plain area.



Base from U.S. Geological Survey 1:250,000 quadrangles

Figure 42.—Simulated water-level declines in the principal artesian aquifer after pumping 113 billion gallons per year for 3 years during a hypothetical hydrologic drought.



Base from U.S. Geological Survey 1:250,000 quadrangles

Figure 43.—Simulated water-level declines below the top of the principal artesian aquifer after pumping 113 billion gallons per year for 3 years during a hypothetical hydrologic drought.

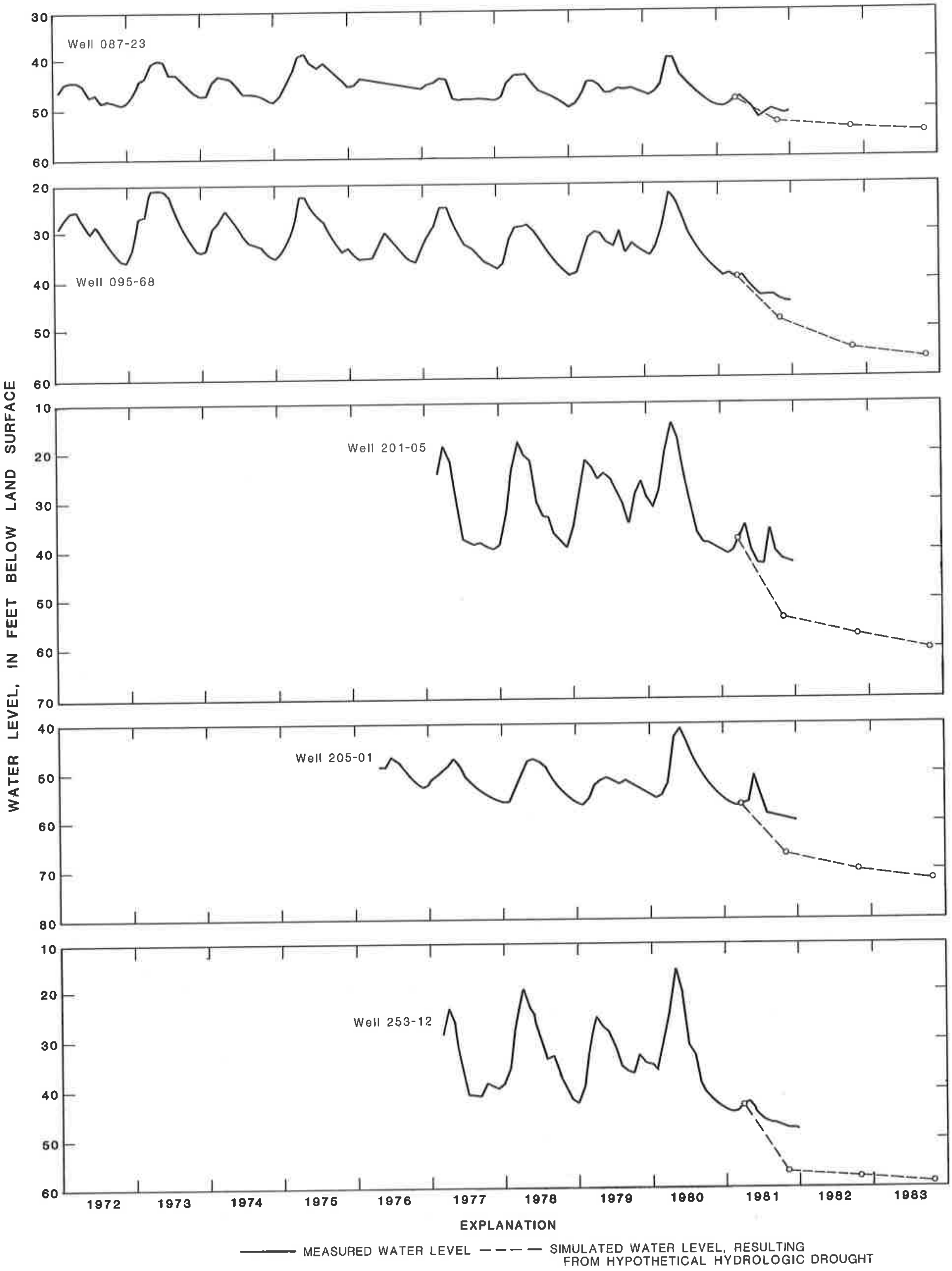


Figure 44.— Measured and simulated water levels in the principal artesian aquifer in wells 087-23, 095-68, 201-05, 205-01, and 253-12.

River at the end of the 3-year drought declined to about 800 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, respectively, in August 1980, and were 144, 83, and 37 ft^3/s, respectively, in July 1981. The effects upon streamflow of direct withdrawal of water from rivers for irrigation were not modeled. Consequently, quantitative comparisons of streamflow measurements with simulated streamflows should not be made.

Pumpage of 408 billion gallons per year

The simulated mean declines in the potentiometric surface of the principal artesian aquifer for drought years 1, 2, and 3 were, respectively, 25, 29, and 33 ft below the starting potentiometric surface. Simulated declines at the end of the hypothetical 3-year drought were generally less than 53 ft, but ranged from 53 to 73 ft in about 15 percent of the modeled area (fig. 45). Water levels declined from a few feet to 10 ft below the top of the aquifer in about 30 percent of the modeled area and more than 10 ft in some places (fig. 46).

During the hypothetical 3-year drought simulation, the total pumpage of 1,224 billion gallons (1,206 billion gallons for irrigation and 18 billion gallons for all other) was supplied by aquifer storage (634 billion gallons), induced recharge from surface water (410 billion gallons), and recharge from the residuum (180 billion gallons). Most of the surface-water input to the aquifer was from the Flint River (water entering the Flint River upstream of the Dougherty Plain) and Lake Seminole (from lake storage and input from the Chattahoochee River). Mean flows of the Chattahoochee and Flint Rivers and Kinchafoonee Creek were severely reduced. All other streams stopped flowing.

Effects of Pumping 287 Billion Gallons Per Year with Normal Recharge

A 10-year transient simulation using mean annual hydrologic conditions and previously calibrated hydraulic parameters was made to determine the effects of long-term irrigation pumpage on water levels. Water-level declines are the difference between simulated water levels at the end of the 10-year simulation and yearly average water levels, as determined from November 1979 (low levels) and May 1980 (high levels) potentiometric maps. Pumpage input to the model consisted of 1980 pumpage (76 billion gallons for irrigation and 6 billion for other pumpage) plus projected potential irrigation pumpage (205 billion gallons per year).

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 pumpage from the principal artesian aquifer would be slightly lowered water levels and about a 30-percent reduction in aquifer discharge to streams resulting in significantly reducing streamflow throughout the Dougherty Plain area.

SUMMARY AND CONCLUSIONS

The hydrologic character of the principal artesian aquifer in the Dougherty Plain, an area of about 4,400 mi^2 in southwest Georgia, was investigated to determine if this aquifer is capable of supplying expected future increases in agricultural pumpage, especially during hydrologic droughts.

The Dougherty Plain, part of the Georgia Coastal Plain, is underlain by

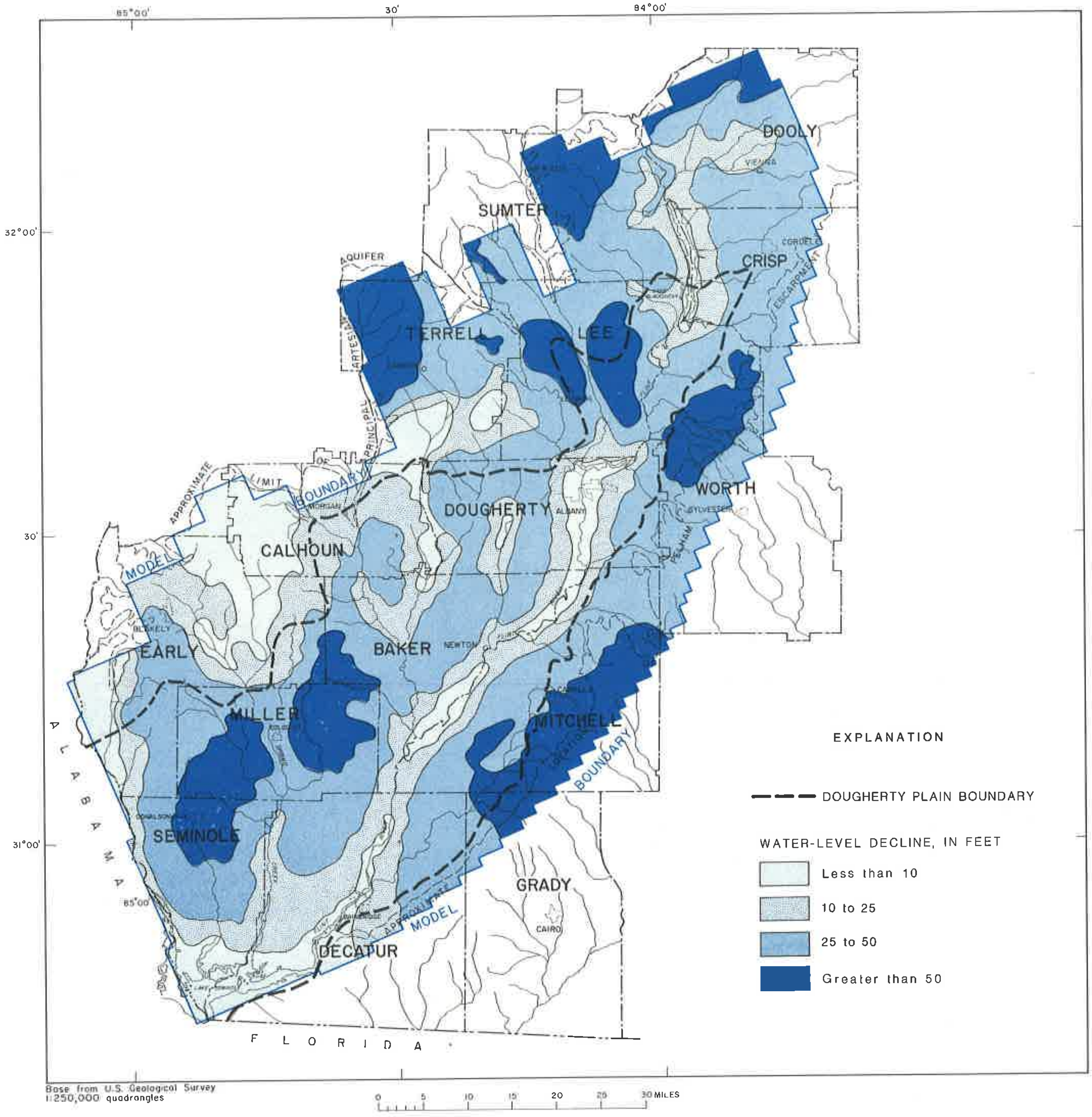
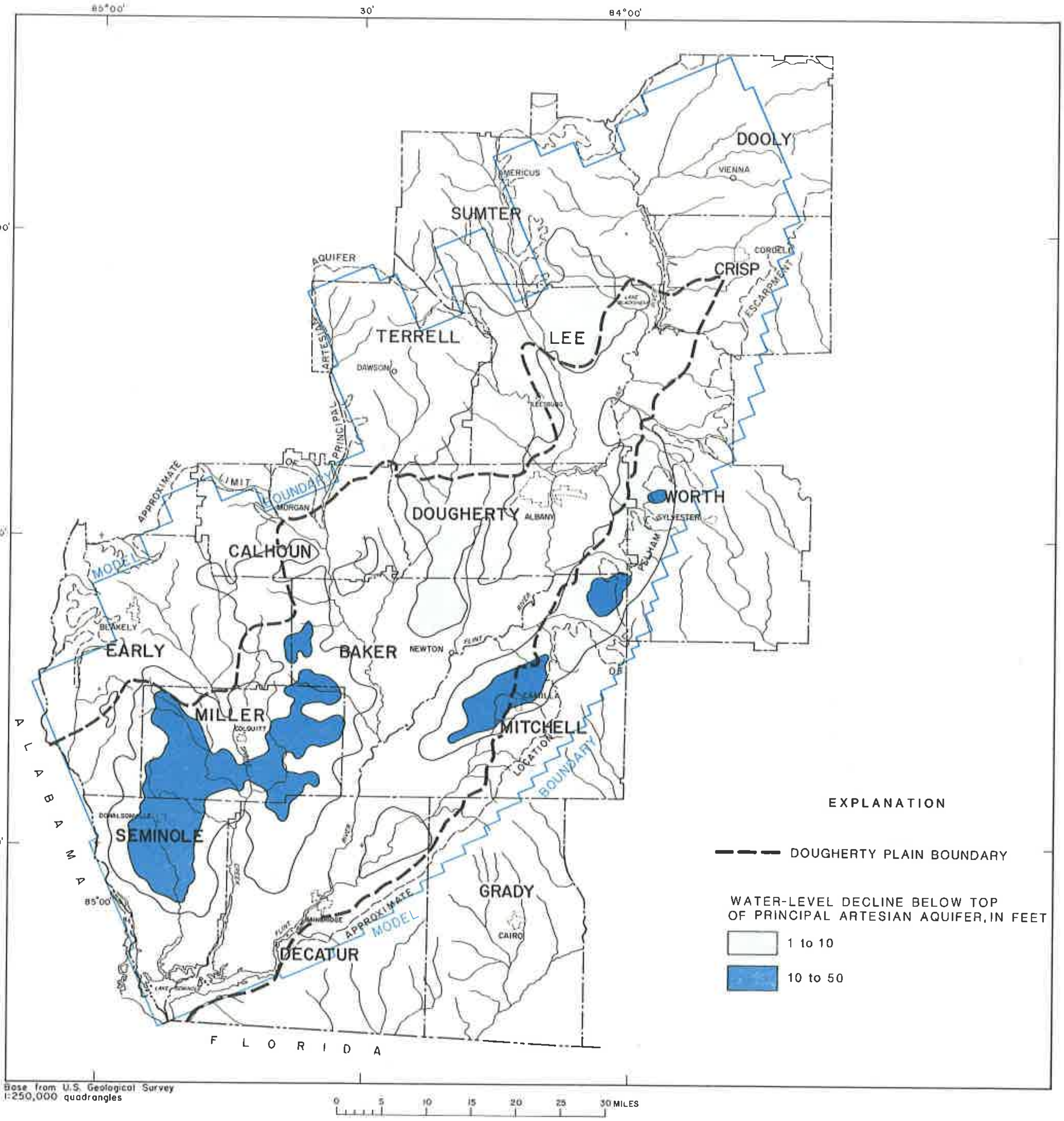


Figure 45.—Simulated water-level declines in the principal artesian aquifer after pumping 408 billion gallons per year for 3 years during a hypothetical hydrologic drought.



Base from U.S. Geological Survey
1:250,000 quadrangles

Figure 46.—Simulated water-level declines below the top of the principal artesian aquifer after pumping 408 billion gallons per year for 3 years during a hypothetical hydrologic drought.

sediments ranging in age from Upper Cretaceous to Holocene. The sediments consist of sand, clay, and carbonate rocks to thicknesses of more than 5,000 ft. The Dougherty Plain slopes gently to the south or southeast and averages about 160 ft above sea level. The plain is characterized by karst topography marked by numerous depressions or sinkholes, and is covered by about 25 to 125 ft of sandy clay residuum that contains silicified boulders. The plain is drained by the Chattahoochee and Flint Rivers.

Annual rainfall in the Dougherty Plain averages about 53 in. Rainfall for January through March and for June through August is about equal in magnitude (15 in.), but differs greatly in duration and distribution. Rainfall in the winter months is generally of long duration and moderate intensity; rainfall in the summer months is usually of short duration and high intensity. Most ground-water recharge from precipitation occurs from January through March. Rainfall during the summer months is generally lost to overland runoff to streams or to evapotranspiration.

Average annual runoff of eight watersheds was weighted by the basin drainage area within the study area. The sum of the weighted products give an annual mean runoff rate for the Dougherty Plain area of 5,200 ft^3/s; a spring high of 9,200 ft^3/s; and a late-summer low of 2,700 ft^3/s. These quantities are the approximate average total annual, spring high, and late-summer low water yields of the Dougherty Plain area under average climatic and hydrologic conditions.

The base flow of streams in the Dougherty Plain is primarily ground-water discharge from the principal artesian aquifer. Therefore, base flow is a measure of the perennial ground-water yield of the principal artesian aquifer. Average annual mean base flow in the area of investigation was calculated as 4,000 ft^3/s. Average late-summer (Sept., Oct., and Nov.) mean base flow is considerably less--about 2,300 ft^3/s. Total stream base flow during 7-day, 10-year minimum annual flows occurring within the Dougherty Plain area is about 1,600 ft^3/s and is, probably, almost entirely discharge from the principal artesian aquifer.

Estimated vertical hydraulic conductivity of the residuum, which is generally sandy clay or clayey sand, varies from as low as 0.0001 ft/d to a high of 9 ft/d, the median being 0.003 ft/d. Estimated horizontal hydraulic conductivity varies from a low of 0.0004 ft/d to a high of 30 ft/d, with the median being 0.02 ft/d.

Small quantities of water are obtained from residuum wells throughout the study area. As to be expected, yields are highly variable and range from generally less than 1 gal/min to, in a few places, as much as 50 gal/min. Water levels ranged from about 1 to 38 ft below land surface from January to September 1981. Water-level fluctuations in individual wells ranged from about 2 to 14 ft, with an average fluctuation for all wells of about 6 ft.

Within the study area, the principal artesian aquifer consists primarily of the Ocala Limestone of late Eocene age. The Ocala, which is a light-colored, fossiliferous limestone, is a wedge-shaped formation trending from northeast to southwest across Georgia, thickening to the southeast. The Ocala ranges in thickness from a few feet at the updip limit to about 350 ft in the southeastern part of the Dougherty Plain. The limestone is exposed along sections of major streams such as the Chattahoochee and Flint Rivers and Spring Creek, where erosion has removed the residuum.

Transmissivity of the principal artesian aquifer calculated from aquifer tests and estimated from specific capacities of wells ranges from 2,000 to 1,300,000 ft^2/d. Transmissivity is lowest in the northern part of the report area where the aquifer is relatively thin, and increases to the south where the aquifer is thicker. Transmissivity is high near the Chattahoochee and Flint Rivers and Spring Creek, because water moving between the surface-water system and the ground-water system adjacent to these major recharge-discharge areas has accelerated the solution of ground-water conduits.

Storage coefficients for the aquifer range from 2×10^{-4} to 3×10^{-2}, but are generally in the 10^{-3} to 10^{-4} range. The storage values indicate that the principal artesian aquifer generally can be considered semiconfined: water in the aquifer is confined by a leaky confining bed (residuum) that allows significant vertical movement of water into or out of the aquifer.

Measured well yields in the Dougherty Plain area range from about 40 to 1,600 gal/min. Many wells in the area do not penetrate the full thickness of the aquifer and, consequently, yield less than the maximum possible rate. Yields of 1,000 to 2,000 gal/min, however, are common in areas where transmissivity exceeds 50,000 ft^2/d, and where transmissivity exceeds 75,000 ft^2/d yields of more than 2,000 gal/d may be expected. Measured specific capacities of wells, which are common measures of well yield, range from 4 to 1,000 (gal/min)/ft.

Recharge occurs chiefly from rainfall that leaks downward through the residuum during January through May. Most rainfall occurring during the summer months is lost to evapotranspiration or to soil moisture in the unsaturated zone of the residuum. Although the vertical hydraulic conductivity of the residuum confining zone is generally low (about 0.003 ft/d), the cross-sectional area of flow in the vertical direction is large (about 4,400 mi), and consequently large volumes of water can be transmitted through the residuum confining zone. Annual mean recharge to the principal artesian aquifer is estimated to be about 2,200 Mgal/d (10 in.). Late-summer recharge is considerably less--about 1,400 Mgal/d (6 in.).

Because of a hydrologic drought that began in June 1980 and lasted through the summer of 1981, water levels in April 1981 were generally about 10 feet lower than water levels in May 1980. The small amount of rain that fell between June 1980 and April 1981 was not enough to recharge the aquifer to its normal spring level, and water levels remained about the same as in November.

The principal artesian aquifer transmits water from areas of recharge to natural areas of discharge and to wells. Natural outlets include springs, streams, and the overlying residuum or underlying Lisbon Formation, where hydrostatic pressure in them is less than in the principal artesian aquifer. About 90 percent of the annual ground-water discharge is to streams and springs.

Very little ground-water development has taken place in the Dougherty Plain except for irrigation. Under normal hydrologic conditions the ground-water system has not been significantly stressed, and over the long term is in a state of hydrologic equilibrium. Water is estimated to circulate through the steady-state hydrologic system at the rate of 4,300 ft^3/s (2,800 Mgal/d) plus or minus about 860 ft^3/s (560 Mgal/d).

Water in storage in the principal artesian aquifer could, in theory, supply the present pumpage requirements of the Dougherty Plain for a number of years. In practice, however, it would be unwise to reduce water levels below the top of the principal artesian aquifer for any period of time because of increased possibility of sinkhole collapse, reduction or elimination of base flow to streams, and increased well construction and pumping costs (most existing wells could not be pumped if water levels declined more than 10 to 20 ft below the top of the aquifer). Therefore, the desirable limit to water available from storage alone is about 50 billion gallons, or about half of the 1981 pumpage of 113 billion gallons.

Water samples from 16 residuum and 14 principal artesian aquifer wells were analyzed for concentrations of major inorganic constituents and for agricultural pesticides, herbicides, insecticides, and fungicides commonly used in southwest Georgia. While overall quality of water from the residuum and principal artesian aquifer is good, pesticides were detected in water from 11 residuum and 4 principal artesian aquifer wells. None of the water samples from the principal artesian aquifer, however, contained pesticide concentrations that exceeded the recommended limits for public drinking water.

A two-dimensional numerical model was constructed and calibrated to simulate water levels in the principal artesian aquifer. The digital model utilizes a finite-difference scheme to evaluate the partial differential ground-water flow equations in which the head is the dependent variable.

The digital model was initially calibrated for steady-state water levels occurring as of November 1979. Model calibration was verified by a transient simulation of the period May to November 1980. Most heads simulated by the calibrated model were within 5 ft of measured heads. Simulated ground-water discharges were within 10 percent of discharges estimated from base-flow analyses.

Transient model analyses were used to simulate changes in the potentiometric surface of the principal artesian aquifer and discharge to or recharge from overlying streams resulting from applying three sets of hydrologic conditions: (1) 1981 pumpage of 113 billion gallons per year during a hypothetical 3-year hydrologic drought, (2) 1981 pumpage plus the projected potential increase in irrigation pumpage of 295 billion gallons per year during a hypothetical 3-year drought, and (3) 1980 pumpage of 82 billion gallons per year plus the projected potential increase in irrigation pumpage of 205 billion gallons per year during a 10-year period of normal recharge conditions.

Simulated declines at the end of a 3-year drought with present pumpage of 113 billion gallons per year averaged about 26 ft and were generally less than 43 ft. Declines of from 43 to 61 ft occurred in about 15 percent of the modeled area. In some areas, water levels fell from a few feet to 10 ft below the top of the aquifer. Aquifer discharge to streams was considerably reduced, and all streams originating within the Dougherty Plain stopped flowing.

Simulated declines at the end of a 3-year drought with pumpage of 408 billion gallons per year averaged about 33 ft and were generally less than 53 ft. Declines of from 53 to 73 ft occurred in about 15 percent of the modeled area. Water levels declined from a few feet to 10 ft below the top of the aquifer in about 30 percent of the modeled area and more than 10 ft in some places. Stream discharge to the aquifer exceeded aquifer discharge to streams. About half of the pumpage came from aquifer storage and half came from surface-water discharge to the aquifer and leakage through the residuum.

A 10-year transient simulation using mean annual residuum water-table levels and previously calibrated hydraulic parameters was made to determine the effects of increasing irrigation pumpage under normal hydrologic conditions. Pumpage input to the model consisted of 1980 pumpage (82 billion gallons) plus projected potential irrigation pumpage (205 billion gallons per year).

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. Over the 10-year simulation period, only 6 Mgal/d was removed from storage--about 1 percent of the amount pumped. Net discharge to streams, however, was reduced by 30 percent. Consequently, a major effect of increased pumping would be to reduce the base flow of streams in the Dougherty Plain area during the irrigation season.

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