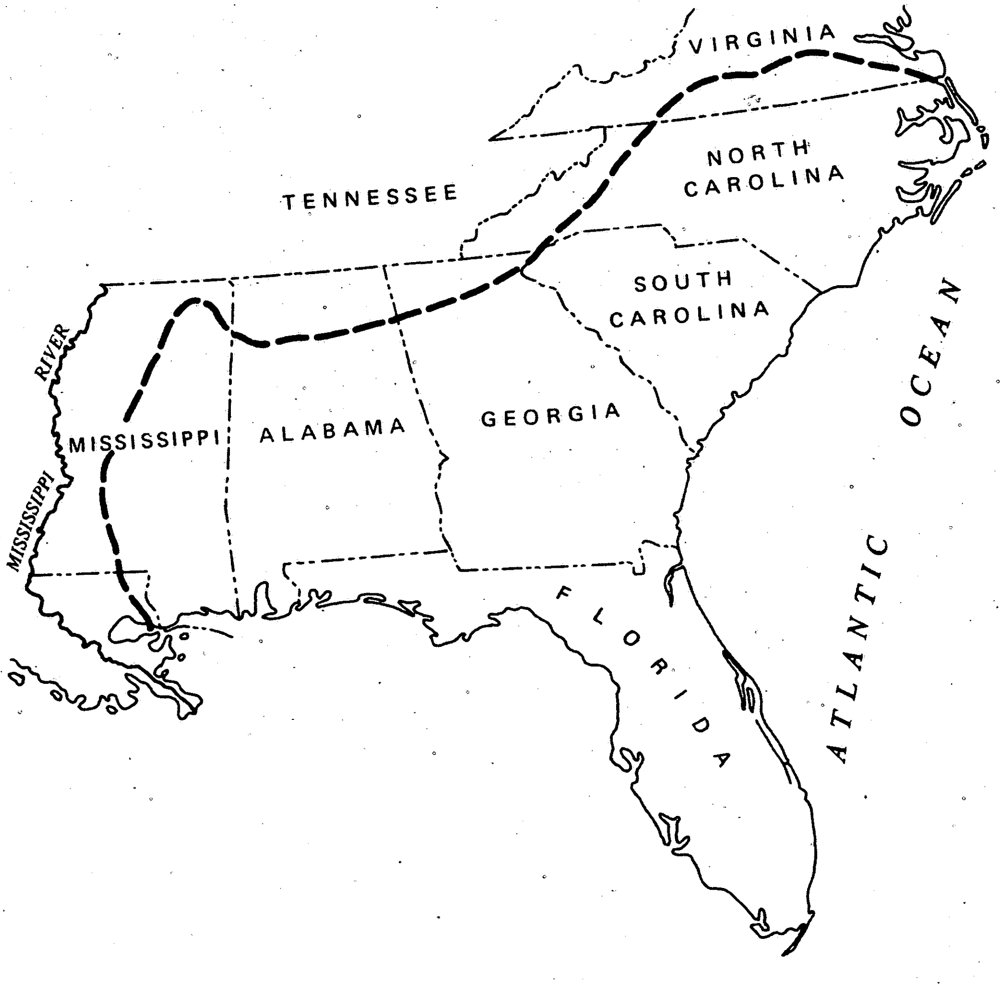
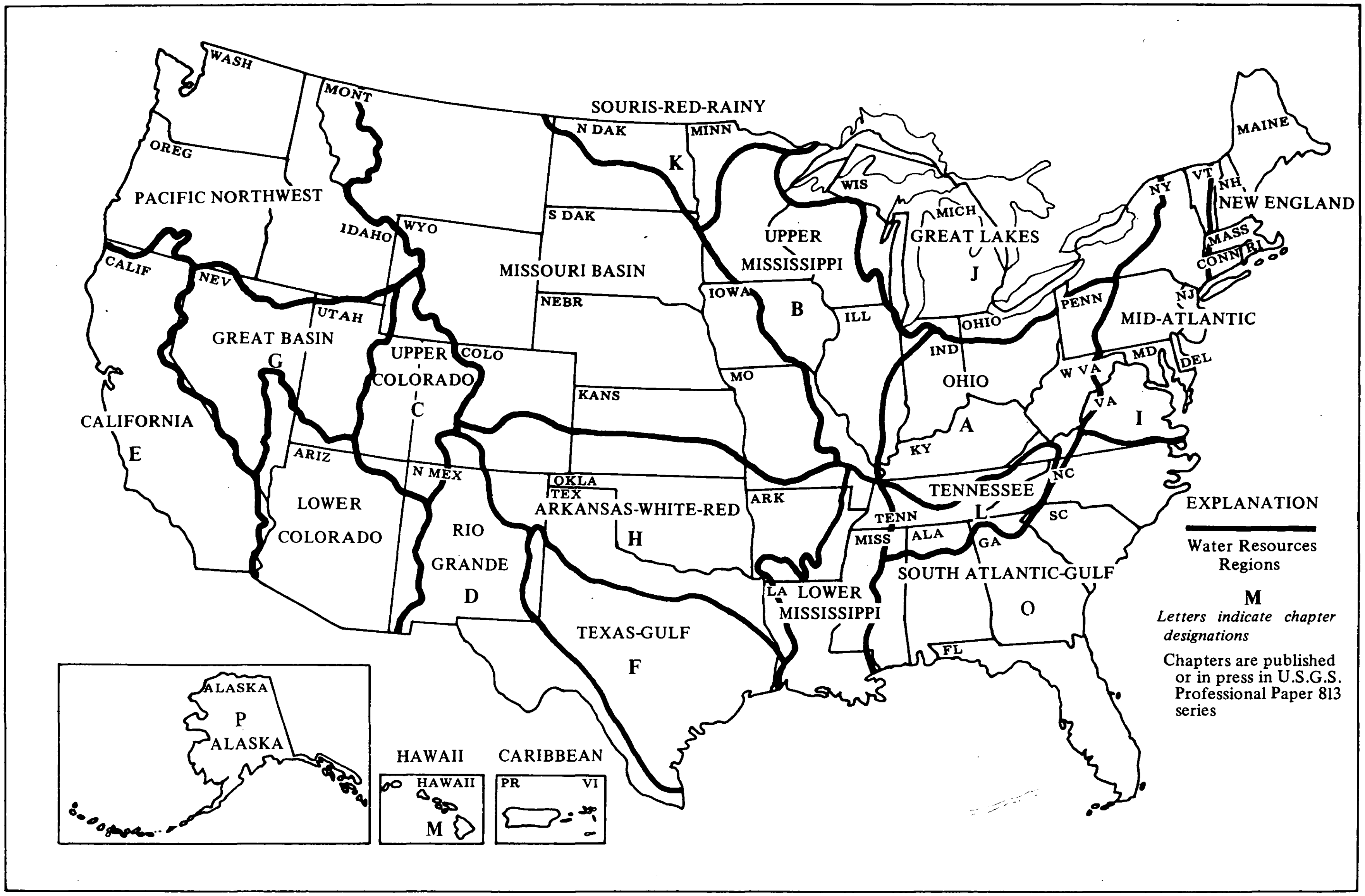
Summary Appraisals of the Nation's Ground-Water Resources—South Atlantic-Gulf Region

GEOLOGICAL SURVEY PROFESSIONAL PAPER 813-0

U.S. DEPARTMENT OF THE INTERIOR



SUMMARY APPRAISALS OF THE NATIONS GROUND-WATER RESOURCES— SOUTH ATLANTIC-GULF REGION



Geographic Index to the Series, U.S. Geological Survey Professional Paper 813, *Summary Appraisals of the Nations Ground-Water Resources.*

Boundaries shown are those established by the United States Water-Resources Council for Water-Resources Regions in the United States.

Summary Appraisals of the Nation's Ground-Water Resources—South Atlantic-Gulf Region

By D. J. CEDERSTROM, E. H. BOSWELL, *and* G. R. TARVER

GEOLOGICAL SURVEY PROFESSIONAL PAPER 813-0

A summary of the occurrence and quality of ground water and its present and potential significance in the regional water supply

U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON: 1979

UNITED STATES DEPARTMENT OF THE INTERIOR

CECIL D. ANDRUS, *Secretary*

GEOLOGICAL SURVEY

H. William Menard, *Director*

Library of Congress Cataloging in Publication Data

Cederstrom, Dagfin John, 1908-
Summary appraisals of the Nation's ground water resources–South
Atlantic-gulf region.

(Geological Survey professional paper 813-0)
Bibliography: p. 033-035.
Supt. of Docs. no.: I 19. 16P813-0
1. Water, Underground–Gulf States. 2. Water, Underground–Southern States.
I. Boswell, Ernest H., 1919- joint author. II. Tarver, George R., joint author.
III. United States. Geological Survey. IV. Title. V. Series: United States.
Geological Survey. Professional paper 813-0.
GB1018.C4 553'. 79'0976 78-23386

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402

Stock Number 024-001-03137-0

CONTENTS

ILLUSTRATIONS

TABLES

CONVERSION FACTORS

[The following factors may be used to convert the U.S. customary units published herein to the International System of Units (SI)]

Multiply U.S. customary units	*By*	*To obtain SI units*
	Length	
Inches (in.)	25.4	Millimeters (mm)
Feet (ft)	.3048	Meters (m)
Miles (mi)	1.609	Kilometers (km)
	Area	
Square miles (mi^2)	2.590	Square kilometers (km^2)
	Flow	
Cubic feet per second (ft^3/s)	28.32	Liters per second (L/s)
	.02832	Cubic meters per second (m^3/s)
Gallons per minute (gal/min)	.06309	Liters per second (L/s)
	6.309×10^{-5}	Cubic meters per second (m^3/s)
Million gallons per day (Mgal/d)	3,785	Cubic meters per day (m^3/d)
Cubic feet per second per square mile [(ft^3/s)/mi^2]	.0109	Cubic meters per second per square kilometer [(m^3/s)/ km^2]
Gallons per day per square mile [(gal/d)/mi^2]	.00146	Cubic meters per day per square kilometer [(m^3/d)/km^2]
	Volume	
Cubic feet (ft^3)	0.02832	Cubic meters (m^3)
	Gradient	
Feet per mile (ft/mi)	18.9	Centimeters per kilometer (cm/km)
	.189	Meters per kilometer (m/km)
	Hydraulic conductivity	
Feet per day (ft/d)	0.3048	Meters per day (m/d)
	Transmissivity	
Feet squared per day (ft^2/d)	0.0929	Meters squared per day (m^2/d)

The conversion from temperature in degrees Farenheit (°F) to temperature in degrees (Celsius (°C) is expressed by: °C= (5/9) (°F−32).

SUMMARY APPRAISALS OF THE NATION'S GROUND-WATER RESOURCES—SOUTH ATLANTIC-GULF REGION

By D. J. CEDERSTROM, E. H. BOSWELL, and G. R. TARVER

ABSTRACT

Precipitation in the 270,000-square-mile South Atlantic-Gulf Region ranges from 44 to 80 inches, and the average runoff is about 15 inches. The ground-water discharge that forms the base flow of streams is conservatively estimated to be about 78,000 million gallons per day—the equivalent of about 6 inches of precipitation. On this basis, the regional sustained ground-water supply is about 286,000 gallons per day per square mile. Projected water use through 2020 indicates that about 10 percent of the supply will meet the region's requirement for ground water.

Enormous quantities of ground water are available in the South Atlantic-Gulf States in the extensive aquifers that underlie the Coastal Plain province. Large supplies of ground water can be developed also in places in the Cumberland Plateau and the Valley and Ridge provinces. In the Piedmont and Blue Ridge provinces ground water is available only in modest quantities.

The principal Coastal Plain aquifers consist largely of deltaic sand and gravel deposits of Cretaceous to Quaternary age; however, a notable exception is the highly permeable Tertiary limestone aquifer, which underlies parts of four States. Ground water in the Blue Ridge and the Valley and Ridge provinces is available from openings along fissures and joints in consolidated rocks and from the unconsolidated sand and gravel in the residuum and alluvium that overlie the bedrock. In parts of these areas faulting and folding has created favorable conditions for the development of moderate supplies of ground water. In the Piedmont province modest quantities of water are available from joints and fractures. Solution cavities in massive limestone units in some areas underlying the Cumberland Plateau section yield very large quantities of ground water.

Most of the major Coastal Plain aquifers are recharged where they are exposed and water moves downdip to the south. The general direction of ground-water movement in the Coastal Plain aquifers is seaward. There is, however, movement of water vertically and laterally that affects pressure and quality in every aquifer.

Ground water of good chemical and physical quality is available generally except in a small area in western Alabama and eastern Mississippi and in some small coastal areas. Freshwater extends to depths of slightly more than 3,000 feet in some areas. In many areas, water can be produced that does not require any treatment for general use. The more common objectionable constituents or properties are excessive iron, fluoride, hardness, color, and acidity. Contamination or pollution of ground water is not a major regional problem, but it is significant in local areas. Many of these local problems of contamination were the result of earlier improper disposal of oil-field and industrial waste. Saltwater intrusion either directly from the sea or from estuaries has been reported in every State in the region, and the potential for the proliferation of this problem is very large.

The relationship of ground water and surface water is significant at many places in the region where large ground-water withdrawals affect swamps, lakes, and the flow of streams and springs. There is a potential in some areas for using ground water during dry periods for low-flow augmentation of stream supplies. In other areas it is feasible to recharge ground-water reservoirs artificially by means of injection wells, pits, and water spreading.

Although large water-level declines caused by withdrawals have occurred locally, water-level changes have been small or modest when considered on a regional basis owing to the abundant rainfall and favorable recharge conditions.

The saline-water resources of the region are known to be extremely large. In some areas where the availability of freshwater is limited, saline ground water is available for desalinization to supplement freshwater supplies. Also, the saline aquifers are potential storage sites for injected freshwater.

Ground-water problems generally are not severe. Critical situations are restricted to areas where large quantities of ground water are being withdrawn or where aquifers are contaminated by oil-field or industrial waste. Large withdrawals in coastal areas have caused some saltwater intrusion. In other localities, highly mineralized water may have migrated along fault zones to freshwater aquifers. Many of the present problems can be resolved or ameliorated by redistributing withdrawals or developing alternative water sources.

INTRODUCTION

This report describing the ground-water resources of the South Atlantic-Gulf Region is one of a series of regional ground-water appraisals that summarize data in many published reports and unpublished data in the files of Federal, State, and other agencies. The report discusses the enormous quantities of ground water that can be obtained by conventional development methods in many areas in the region and suggests that, by conjunctive use of surface water and ground water, larger volumes of water can be made available.

About three-fourths of the region is in the Atlantic and Eastern Gulf Coastal Plains where the geologic units that make up the aquifers are limestone or unconsolidated sand and gravel. The remainder of the region is underlain by the older consolidated rocks of the Appalachian Highlands which contain ground water in fractures and solution cavities.

Freshwater at some localities is known to occur at depths greater than 3,000 feet. There are only a few areas of very limited extent where freshwater is not available in usable quantities. Water-quality problems are those usually amenable to simple treatment.

The largely undeveloped ground-water resources in the region will be one of the controlling factors in future economic development. Industrial expansion and intensive agricultural development will place increasing demands on water. It is, therefore, essential that sound appraisals of the water resources be available to planners and managers to meet the need for additional demands for water.

GEOGRAPHIC SETTING

The South Atlantic-Gulf Region, which comprises an area of about 270,000 square miles in the southeastern part of the United States, is drained by streams flowing to the Atlantic Ocean and the Gulf of Mexico between the James River drainage in Virginia and the lower Mississippi River drainage. It includes all of Alabama, Florida, Georgia, North Carolina, South Carolina, and parts of Mississippi and Virginia (fig. 1). The region includes parts of the Appalachian Highlands and the Coastal Plain—two of the eight major physiographic divisions of the United States (Fenneman, 1938).

The Coastal Plain province occupies about 70 percent of the region, the Piedmont province about 25 percent, and the Blue Ridge province, Valley and Ridge province, and Cumberland Plateau section together constitute about 5 percent. The Coastal Plain is separated from the rest of the region by the Fall Line, the irregular topographic boundary between the coastal deposits and the older rocks of the Appalachian Highlands.

Precipitation extremes in the South Atlantic-Gulf Region range from about 44 inches in parts of the Coastal Plain to 80 inches in small areas in the mountains of North Carolina and South Carolina (fig. 2). Thunderstorms are particularly common in Florida, occurring 70 days or more a year. As much as 5 inches of rain in 24 hours along the Gulf Coast and as much as 3½ inches in 24 hours on the Coastal Plain along the Atlantic and inland from the Gulf is not uncommon. Such storms frequently result in floods of short duration.

Average runoff in the region is 15 inches per year (Murray and Reeves, 1977, p. 19). Runoff ranges from about 10 inches per year along the Atlantic Coast up to 30 inches along the panhandle of Florida and the Alabama-Mississippi coast, where thick permeable sands in the coastal areas absorb much of the heavy rainfall. Runoff is about 15 inches in the more inland areas where the annual rainfall is 45 to 50 inches. In the mountainous areas, runoff is about half the total precipitation. The difference of about 35 inches between average runoff and the average rainfall over the Coastal Plain and Piedmont provinces is lost by evaporation and transpiration.

The flow of streams varies with precipitation and is generally highest in February and March and lowest in October, except in central and southern Florida where flows are highest in October and low in late fall and in May.

Average annual air temperature ranges from about 60°F (16°C) in southern Virginia to 70°F (21°C) in the northern Gulf Coast, and to 77°F (25°C) in southern Florida.

GEOLOGIC FRAMEWORK

STRUCTURE

The Piedmont province is made up of ancient sedimentary rocks that have been intruded by igneous rocks and subjected to repeated stress. Throughout the area rocks have been fractured, faulted, and folded. The Triassic basins within the Piedmont province are infaulted blocks of younger sedimentary rocks.

The Coastal Plain has been subjected to repeated somewhat gentle differential movements. There are now a series of highs and intervening sags in the basement rock surface and overlying sediments along the entire coastline (fig. 3). Irregularities in the basement surface may be due to movement in pre-Cretaceous times; however, persistent movement in places has affected the younger sediments.

The northernmost major structural high in the South Atlantic-Gulf Region is the Cape Fear Arch (fig. 3). To the south a definite sag in the basement is known as the Southeast Georgia Embayment. Crossing the neck of Florida the basement rises again across the Ocala Uplift and then falls away in the Southwest Georgia Embayment. The Chattahoochee Anticline, more or less parallel to the river of the same name, passes to the west of the Southwest Georgia Embayment.

The major structures have created irregularities in the outcrop pattern, the most marked being the pattern over the Cape Fear Arch.

GEOLOGY

The South Atlantic-Gulf Region may be divided into two broad components: (1) the Coastal Plain province, about 196,000 square miles, made up of soft unconsolidated sand, gravel, and clay and consolidated or semiconsolidated limestone and (2) the remainder (Piedmont province, Blue Ridge province, Valley and Ridge province, and Cumberland Plateau section), about 74,000 square miles, consisting for the most part of hard consolidated rocks—indurated and metamorphosed sedimentary rocks and crystalline igneous rocks.

FIGURE 1.—Map showing location, major drainage, and principal physiographic subdivisions of the South Atlantic-Gulf Region.

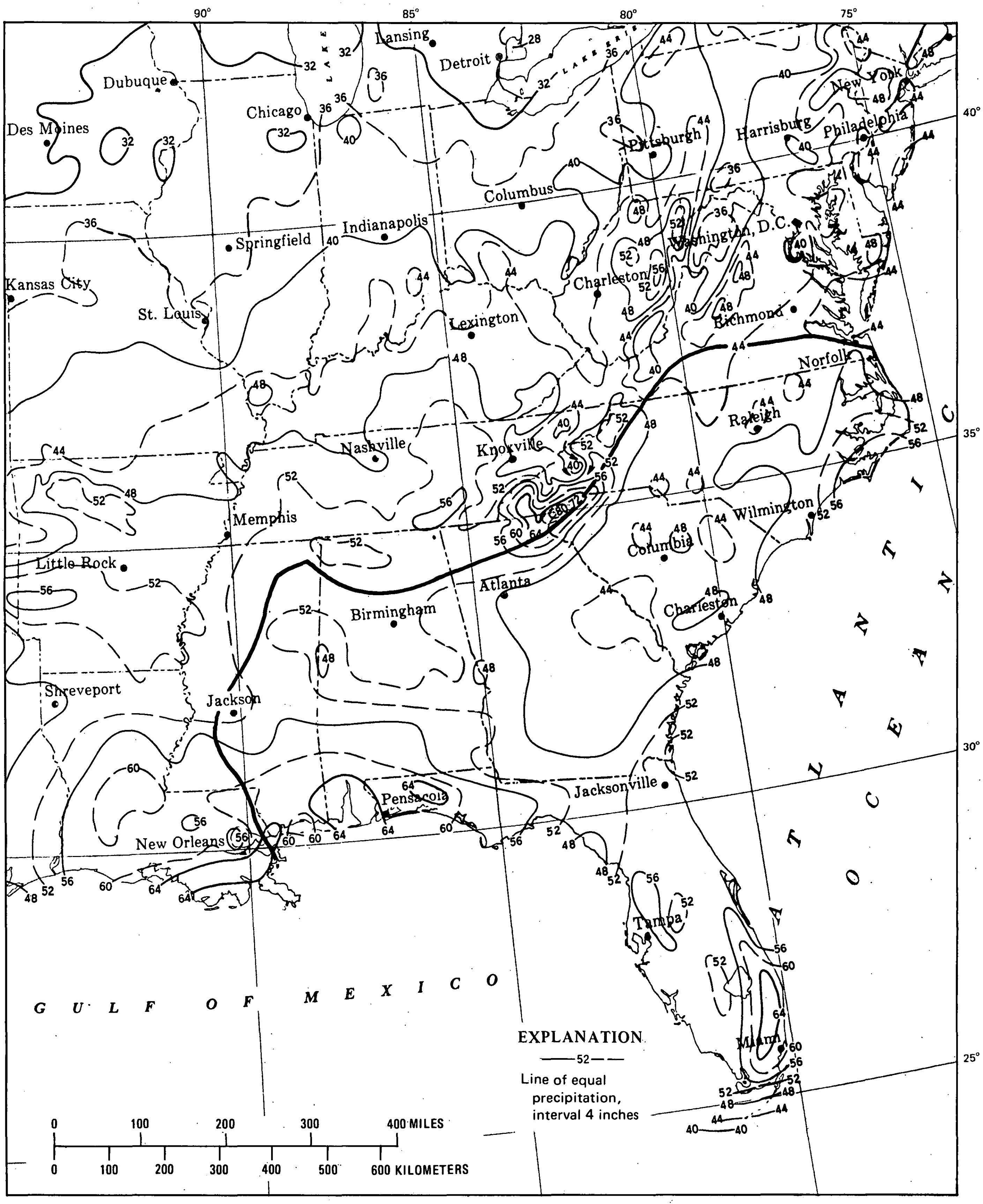


FIGURE 2.—Average annual precipitation in the South Atlantic-Gulf Region.

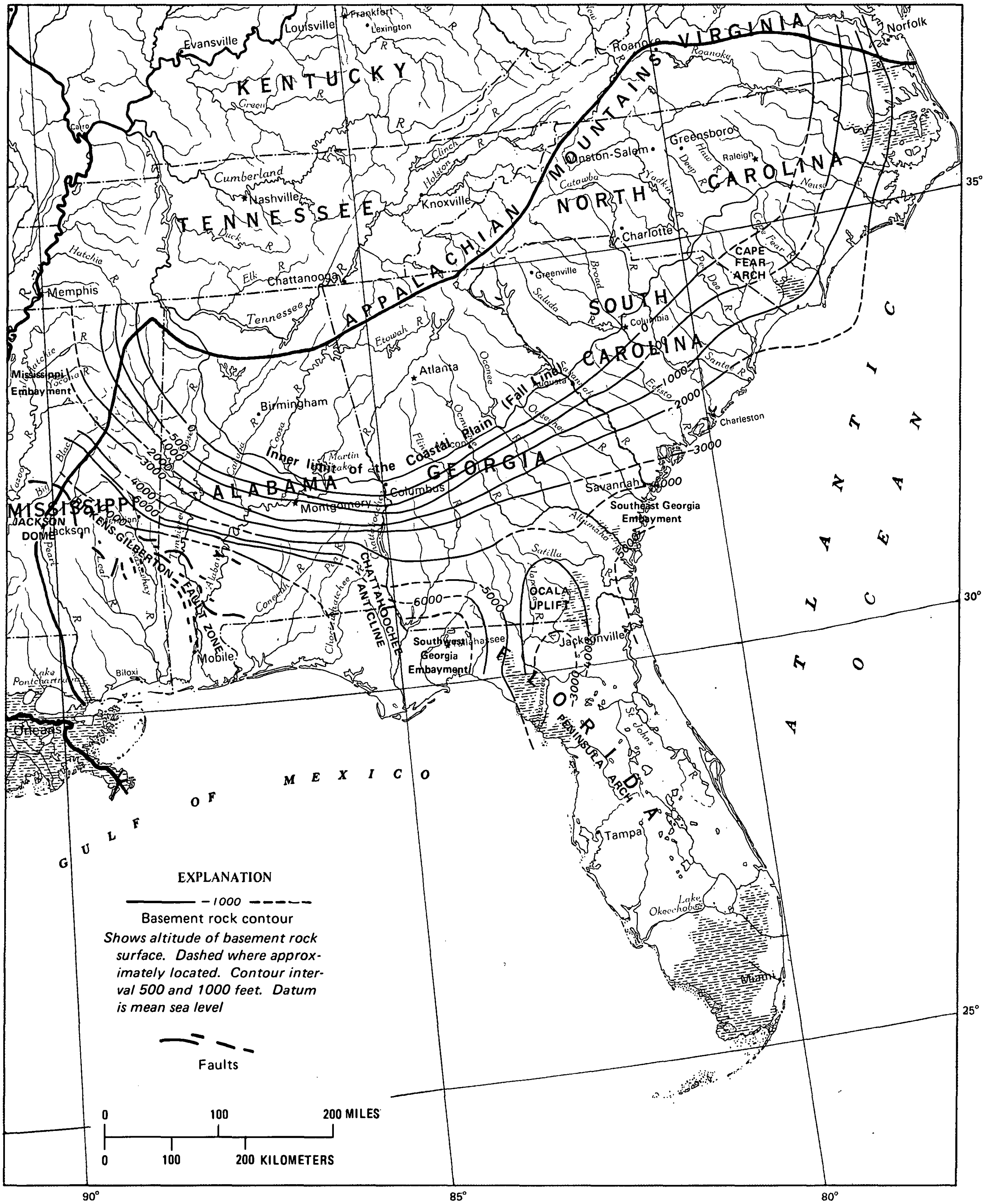


FIGURE 3.—Major structural features and depth below sea level of basement in the Coastal Plain province.

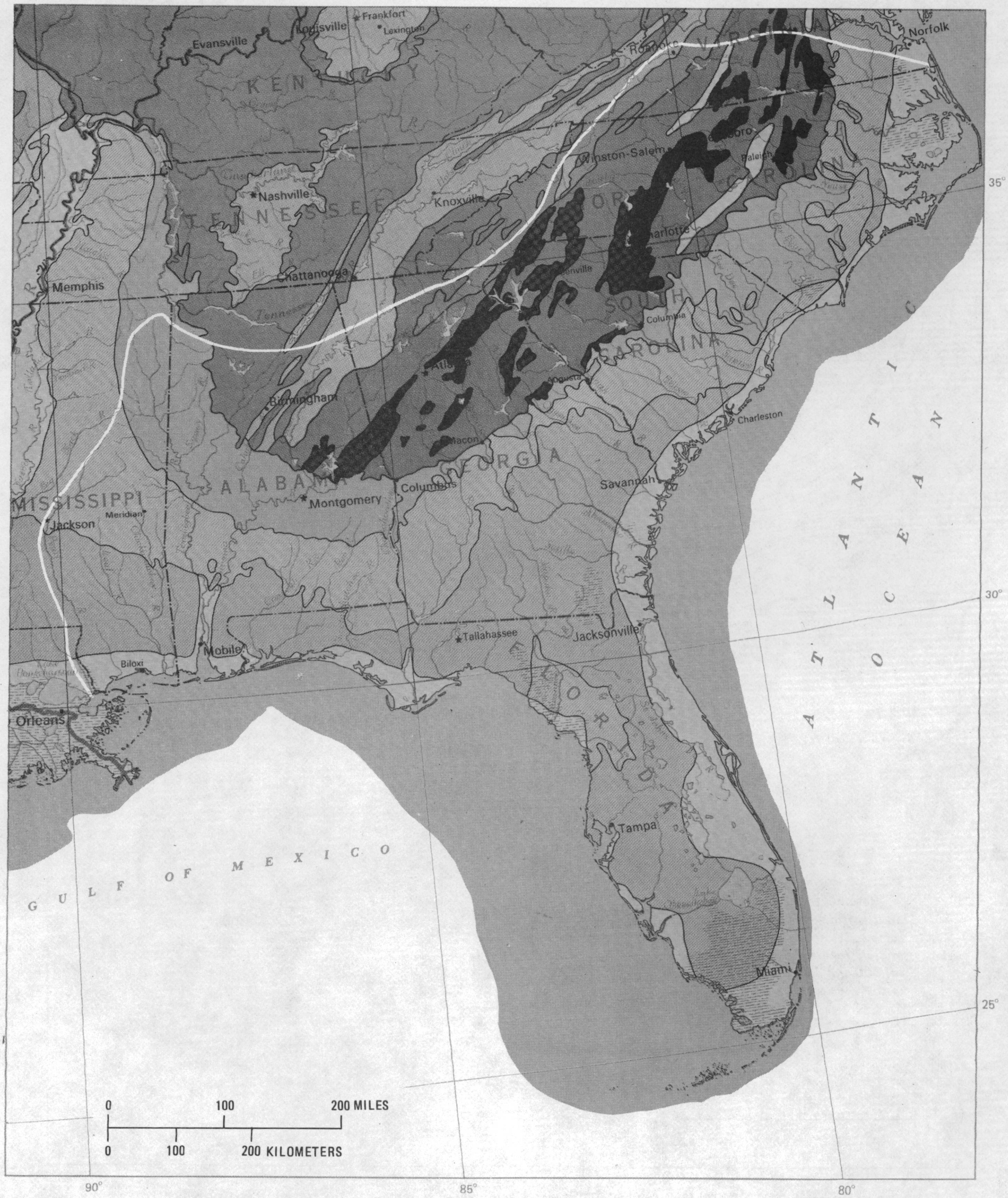


FIGURE 4.—Geologic map of the South Atlantic-Gulf Region.

The Coastal Plain province is underlain by unconsolidated clay, sand, and gravel and consolidated or semiconsolidated limestone. The deposits, which range in age from Cretaceous to Holocene, form a hugh arc extending from southern Virginia through the Carolinas, Georgia, Alabama, and into eastern Mississippi (fig. 4). From a thin edge at the Fall line, most of the deposits thicken seaward; a southward projection forms the peninsula of Florida.

In most places, the Coastal Plain beds have a gentle dip seaward. Each formation was generally overlapped by the next younger formation and their eroded edges are now exposed in a succession of older (inland) to younger (seaward) arcuate belts. The surface exposures of some formations are irregular. For instance, in northern North Carolina the inner edges of older strata were beveled by the advancing seas, and younger formations extend to the Fall Line.

The Coastal Plain formations are rarely uniform laterally (along the strike) or downdip. Nearshore sandy deltaic continental sediments thicken downdip and grade into deeper water silty or limy marine deposits. Laterally, sediments may also change in proportions of sand and clay, or may become limy.

EXPLANATION

SEDIMENTARY ROCKS

▨ QUATERNARY
HOLOCENE AND PLEISTOCENE

▨ UPPER TERTIARY
PLIOCENE AND MIOCENE

▨ LOWER TERTIARY
OLIGOCENE, EOCENE, AND PALEOCENE

▨ CRETACEOUS

▨ JURASSIC AND TRIASSIC

▨ UPPER PALEOZOIC
PERMIAN, PENNSYLVANIAN, AND MISSISSIPPIAN

▨ LOWER PALEOZOIC
ORDOVICIAN AND CAMBRIAN

▨ YOUNGER PRECAMBRIAN
In southeastern United States includes metamorphosed Paleozoic

▨ *OLDER PRECAMBRIAN*
Metamorphic and igneous rocks

INTRUSIVE ROCKS

▩ PALEOZOIC
Chiefly granitic rocks

FIGURE 4.—Continued.

Sandy terrace deposits were superimposed upon the older formations throughout the Atlantic and Gulf Coastal regions during the Pleistocene Epoch.

Table 1 shows the stratigraphic units and aquifers of Cretaceous to Quaternary age that underlie the Coastal Plain province.

The Blue Ridge province is underlain by igneous and metamorphic rocks of older age which have been subjected to repeated stress.

The provinces outside the Coastal Plain are underlain by consolidated sedimentary rocks. In the Valley and Ridge province, these rocks have been greatly folded and faulted. In the adjacent Cumberland Plateau section the rocks have been subjected to less folding and faulting.

GROUND-WATER SUPPLIES

Most of the South Atlantic-Gulf Region is underlain by aquifers that are generally capable of yielding to wells 50 gal/min or more of water containing less than 1,000 milligrams per liter (mg/L) of dissolved solids (fig. 5 and table 1). Lower yields are characteristic of aquifers in the consolidated rocks that underlie the Blue Ridge, Valley and Ridge, and Piedmont provinces. In the Piedmont, Blue Ridge, Valley and Ridge provinces, and the Cumberland Plateau section, wells may intersect openings that result from structural deformation and solution, and yields range from substantial to meager.

The most prolific sources of ground water in the South Atlantic-Gulf Region are the highly permeable clastic and limestone aquifers in the Coastal Plain province. In small areas in western Alabama, eastern Mississippi, southeastern North Carolina, and northeastern South Carolina, these aquifers contain only saline water.

The aquifers occurring within each physiographic province in the South Atlantic-Gulf Region generally are not separate units operating independently; rather, each is a part of a complex system. Because of this interrelation, it is generally irrelevant to estimate quantities of water that are available from the individual aquifers. It is more meaningful to estimate the quantity available from the entire system.

Because the base flow of streams is supported almost entirely by ground-water outflow, the quantity of ground water available can be estimated by separating the total amount of streamflow from a region into its component parts—overland flow and base flow. The base-flow component is the approximate yield of the ground-water reservoirs under the existing hydrologic conditions.

TABLE 1.—*Generalized correlation of Coastal Plain stratigraphic units and aquifers*

System	Series	Mississippi		Alabama			Florida		Georgia		South Carolina	North Carolina	Southern Virginia
				Western		Southeastern	Panhandle	Peninsula					
Quaternary	Holocene and Pleistocene		Alluvium and terrace deposits		Alluvium and terrace deposits		Terrace deposits	Alluvium and terrace deposits upper part of Biscayne aquifer		Alluvium and terrace deposits	Alluvium and terrace deposits Waccamaw Formation	Alluvium and terrace deposits	Alluvium and terrace deposits
Tertiary	Pliocene		Citronelle Formation Graham Ferry Formation[1]		Citronelle Formation	Absent	Citronelle Formation	Caloosahatchee Marl Alachua Formation Tamiami Formation		Charlton Formation Duplin Marl	Duplin Marl	Duplin Marl Yorktown Formation	Yorktown Formation
	Miocene		Pascagoula Formation Hattiesburg Formation Catahoula Sandstone ?——?——?		Undifferentiated		Unnamed coarse clastic Shoal River Formation Pensacola clay Chipola Formation	Miccosukee Formation Hawthorn Formation		Hawthorn Formation	Hawthorn Formation	Pungo River Formation	St. Marys Formation Choptank Formation Calvert Formation
							Tampa Limestone and equivalents			Tampa Formation	Tampa (?) Limestone[2]		
	Oligocene		Paynes Hammock Sand Chickasawhay Limestone		Paynes Hammock Sand Chickasawhay Limestone	Absent	Chickasawhay Limestone Suwannee Limestone			Flint River Formation Suwannee Limestone	Flint River Formation Cooper Marl (upper part)	Undifferentiated	Undifferentiated
		Vicksburg Group	Byram Formation Marianna Limestone Forest Hill Sand Red Bluff Clay	Vicksburg Group	Byram Formation Marianna Limestone	Absent Red Bluff Clay	Byram Formation Marianna Limestone						
	Upper Eocene	Jackson Group	Yazoo Clay Moodys Branch Formation	Jackson Group	Yazoo Clay Moodys Branch Formation	Ocala Limestone	Ocala Limestone			Ocala Limestone (Lower part grades into Barnwell Formation up dip) Cooper Marl (lower part)	Barnwell Formation (up dip) Cooper Marl (lower part)	Absent	Chickahominy Formation[2]
	Middle Eocene	Claiborne Group	Cockfield Formation Cook Mountain Formation Sparta Sand Zilpha Clay Winona Sand Tallahatta Formation	Claiborne Group	Gosport Sand Lisbon Formation Tallahatta Formation			Avon Park Limestone Tallahassee Limestone[2] Lake City Limestone[2]	Claiborne Group[3]	Gosport (?) Sand Lisbon Formation (McBean Formation up dip) Tallahatta Formation	McBean Formation (up dip) Santee Limestone Warley Hill Marl (up dip) Congaree Formation (up dip)	Castle Hayne Limestone Absent	Absent
	Lower Eocene	Wilcox Group	Hatchetigbee Formation Tuscahoma Sand Nanafalia Formation	Wilcox Group	Hatchetigbee Formation Tuscahoma Sand Nanafalia Formation		Undifferentiated	Oldsmar Limestone[2]	Wilcox Group[5]	Hatchetigbee Formation Tuscahoma Sand Nanafalia Formation	Black Mingo Formation	Absent	Nanjemoy Formation
	Paleocene	Midway Group	Naheola Formation Porters Creek Clay Clayton Formation	Midway Group	Naheola Formation Porters Creek Clay Clayton Formation	Absent	Undifferentiated	Cedar Keys Limestone[2]		Clayton Formation	Undifferentiated	Beaufort Formation	Aquia Formation
Cretaceous	Upper Cretaceous	Selma Group	Prairie Bluff Chalk Ripley Formation Demopolis Chalk Coffee Sand[6] Mooreville Chalk	Selma Group	Prairie Bluff Chalk Ripley Formation Demopolis Chalk Mooreville Chalk	Providence Sand Ripley Formation Demopolis (?) chalk Mooreville (?) Chalk and Blufftown Formation	Undifferentiated[2]			(Much as in southeastern Alabama, northeastward the post-Tuscaloosa Cretaceous Formations do not crop out and are difficult to differntiate in the subsurface.)	Peedee Formation Black Creek Formation (Middendorf Formation up dip) Ellenton Formation[2]	Peedee Formation Black Creek Formation (Middendorf Formation up dip)	Mattaponi Formation[2]
			Eutaw Formation McShan Formation		Eutaw Formation McShan Formation	Eutaw Formation							
		Tuscaloosa Group	Gordo Formation Coker Formation[2]	Tuscaloosa Group	Gordo Formation Coker Formation	Undifferentiated[2]				Tuscaloosa Formation	Cape Fear Formation	Cape Fear Formation	
	Lower Cretaceous		Undifferentiated[2]		Undifferentiated[2]					Undifferentiated[2]	Undifferentiated[2]	Undifferentiated[2]	Potomac Group

▒ Fresh-water aquifers

▨ Tertiary limestone aquifer. Referred to in Florida as the Floridan aquifer; also has been referred to in Alabama, Florida, Georgia, and South Carolina as the principal artesian aquifer (Stringfield, 1966).

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[1] In southeastern Mississippi only.

[2] Does not crop out.

[3] In southeast Georgia only.

[4] The Meridian Sand Member of the Tallahatta Formation and the uppermost sand beds of the Wilcox Group form the Meridian-upper Wilcox aquifer.

[5] The basal sand beds of the Wilcox Group and sand beds in the Naheola Formation form the lower Wilcox aquifer.

[6] In northeastern Mississippi only.

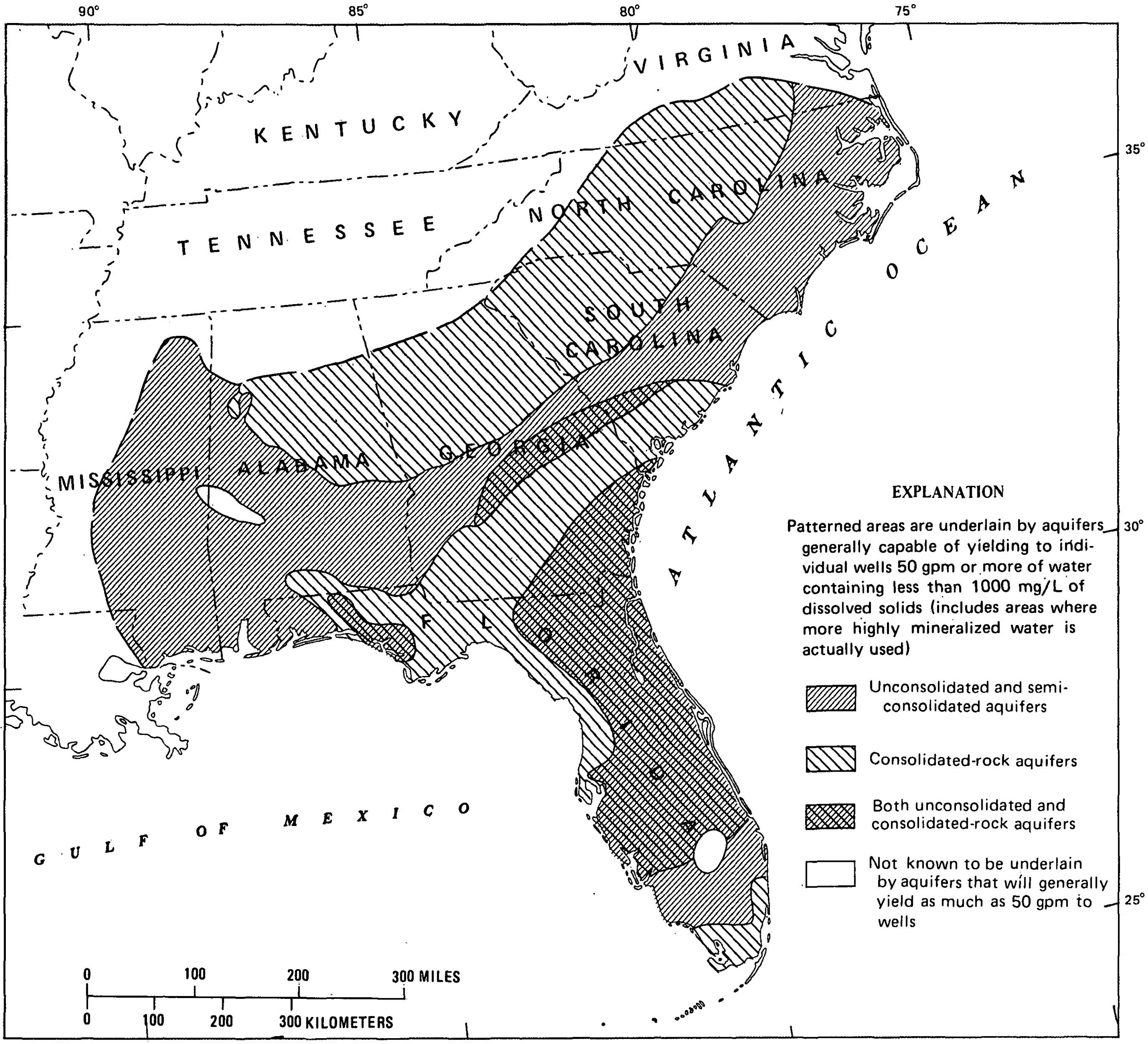

FIGURE 5.—Types of aquifers in the South Atlantic-Gulf Region.

Many investigators of the water resources in areas within the Mid-Atlantic Region have estimated the percentage of streamflow that is base flow, or ground-water discharge. In the Coastal Plain, base flow ranges from about 40 to 95 percent of the total streamflow; a conservative average would be about 55 percent. In that part of the region underlain by consolidated rocks, base flow ranges from about 25 to 90 percent of the streamflow, a conservative average being about 40 percent.

Wilson and Iseri (1967) show that the total annual streamflow from the South Atlantic-Gulf Region averages about 303,000 ft^3/s or 196,000 Mgal/d, 60 percent of which flows into the Gulf of Mexico. However, the proportion of this streamflow that originates in the Coastal Plain as opposed to the remainder of the region was not determined. Using only 40 percent (the conservation average percent of streamflow that is baseflow in the consolidated rocks part of the region) and applying this figure to the entire streamflow from the region, the average total yield of ground water from the South Atlantic-Gulf Region under present hydrologic conditions is at least 78,000 Mgal/d or about 286,000 $(gal/d)/mi^2$—the equivalent of about 6 inches of annual recharge. It is impractical and, in fact, environmentally undesirable to intercept all of this water before it is discharged into streams; however, the amount indicates the order of magnitude of ground water available as a potential resource.

There is also in storage in the ground-water reservoirs of the region about 600,000 billion cubic feet of water having a dissolved-solids concentration of less than 3,000 mg/L (M. I. Kaufman, oral commun., 1977). This volume of water is sufficient to cover the entire region to a depth of about 80 feet; however, much of this water cannot be withdrawn economically using present techniques. Moreover, the environmental effects of removing excessive amounts of ground water from storage may not be acceptable.

The hydrologic properties of an aquifer provide a means of measuring or predicting the aquifer's water-supply potential. In this regional appraisal of ground-water resources, data are not available covering the regional variation in physical properties and hydrologic characteristics, and instead ranges or averages for hydraulic properties are used. Terms used to describe hydraulic characteristics in this study include the following:

Transmissivity.—The rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient. Depends on the hydraulic conductivity and thickness of the aquifer. Expressed in units of square feet per day (ft^2/d).

Hydraulic conductivity.—The volume of water that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow. Expressed in units of feet per day (ft/d).

Storage coefficient.—The volume of water that an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head—dimensionless.

The values of transmissivity and hydraulic conductivity as defined above expressed in square feet per day and feet per day may be converted to units of transmissibility (gallons per day per foot) and permeability (gallons per day per square foot) by multiplying by 7.48. Explanations of the derivation and application of values for hydrologic properties are given by Lohman (1972).

PRESENT AND PROJECTED GROUND-WATER USE

The withdrawal of fresh and saline water for all uses from all sources in the South Atlantic-Gulf Region in 1975 was reported to be 43,000 Mgal/d. Surface water accounted for 38,000 Mgal/d or about 88 percent of the total, and ground water accounted for 12 percent. Consumptive use was 3,700 Mgal/d (Murray and Reeves, 1977, table 17).

Ground-water withdrawals in the region for all purposes in 1975 totaled about 5,500 Mgal/d (Murray and Reeves, 1977). The largest withdrawal, 1,953 Mgal/d, was for self-supplied industrial use. Public water supplies accounted for 1,500 Mgal/d, and rural and livestock, 660 Mgal/d. About 53 Mgal/d or 1 percent of the total was saline ground water used by self-supplied industries. Included in the total is 1,500,000 acre-ft of water withdrawn for irrigation (about 1,340 Mgal/d on an annual basis).

Ground water supplies about 48 percent of all water used for public supplies and 42 percent of all irrigation water in the region. The total of ground-water withdrawal is only about 7 percent of the estimated 78,000 Mgal/d available from the region.

Projections for future water needs made by the Water Resources Council (1968, table 1–2) are shown in the following table:

Projected water requirements, South Atlantic-Gulf Region

[Million gallons daily. From U.S. Water Resources Council, 1968]

Withdrawals, surface and ground water			*Consumptive use*		
1980	*2000*	*2020*	*1980*	*2000*	*2020*
53,180	87,440	130,190	3,395	5,655	8,265

Assuming that ground water continues to supply 14 percent of all water withdrawn in the region, projected ground-water use would be as shown in the following table:

Projected ground-water requirements based on the 1970 rate

[Million gallons daily]

Projected withdrawals			*Projected consumptive use*		
1980	*2000*	*2020*	*1980*	*2000*	*2020*
7,445	12,242	18,227	475	792	1,157

If one-fourth, or about 19,000 Mgal/d, of the estimated available ground-water supply can be withdrawn without serious environmental effects, the projected regional ground-water needs through 2020 can be met.

Large-capacity wells can be constructed in perhaps 40 percent of the region (fig. 5); hence, most of the ground-water development in the region will probably be in the most favorable area.

GROUND-WATER QUALITY

In the South Atlantic-Gulf Region good-quality ground water is generally taken for granted. In most of the region enough water of good quality is available for current requirements; however, simple treatment for excessive iron, corrosiveness, and hardness is common.

In this report the following classification is used for water hardness in terms of the amount of calcium carbonate (or its equivalent) that it contains:

[Values in milligrams per liter]

0–60	Soft.
61–120	Moderately hard.
121–180	Hard.
More than 180	Very hard.

In the sandy coastal plain formations there is normally a progressive increase in the mineral content of ground water downdip. Along the outcrop of the aquifers the water is low in mineral content but may be somewhat corrosive, and water from many wells is high in iron.

The high chloride concentrations in water in some Upper Cretaceous aquifers appear to be related to the permeability of the sediments. In places, saltwater has been replaced by freshwater that has moved farther downdip in high permeable sediments than in the shallower but less permeable sediments. The movement of water is slower in less permeable sediments.

Freshwater contains less than 1,000 mg/L of dissolved solids; however, some water supplies use water that has a dissolved-solids concentration higher than 1,000 mg/L, and some water containing up to 2,000 mg/L is suitable for irrigating some crops. In this report saline water is classified as follows according to the dissolved-solids concentration:

Description	*Dissolved solids mg/L)*
Fresh	Less than 1,000.
Slightly saline	1,000 to 3,000.
Moderately saline	3,000 to 10,000.
Very saline	10,000 to 35,000.
Brine	More than 35,000.

The younger Tertiary aquifers contain freshwater that extends to or even beyond the coast in most areas (Hathaway and others, 1976). In much of the coastal area the Tertiary limestone aquifer is protected from seawater intrusion by a cover of Miocene clays and marls of low permeability. However, deep saline water has migrated into the freshwater zone in a few places in response to sharp lowering of pressure.

The Pleistocene and Holocene unconsolidated sediments commonly yield slightly acidic water that is low in dissolved solids.

Colored ground water occurs in a few places in Florida where turbid stream waters can move into the aquifers. In Mississippi, some Eocene aquifers yield colored water in their downdip extensions.

Outside the Coastal Plain, water is generally limited in quantity but of good quality. As the depth of groundwater occurrence commonly does not exceed a few hundred feet and the aquifers have long been free of seawater, the high salinity that is common in the deep zones of the Coastal Plain aquifers is not a problem. The aquifer materials with the exception of the carbonate rocks are relatively insoluble, and therefore the dissolved-solids concentration in the ground water is low.

In moving downdip, the slightly acidic water becomes neutralized, iron content decreases, and the hardness of water increases. Because of ion exchange at greater depth, the water becomes a soft sodium bicarbonate type (Cederstrom, 1957, p. 36). Still farther downdip the water becomes saline owing to the presence of seawater with which the formations were once saturated.

A similar progression is seen in water in some limestone aquifers. In those aquifers water may be initially harder than that in sandy formations, but hardness does not everywhere become excessive downdip owing to base-exchange action. Stringfield (1966) notes that although raw water for public supplies in Florida ranges up to 1,000 mg/L of hardness, only 9 percent of those supplies has a hardness greater than above 250 mg/L. Bicarbonate, however, may increase above 300 mg/L.

Low bicarbonate concentrations may be related to rapid recharge through sinkholes and solution openings by water having a low carbon dioxide concentration, whereas high bicarbonate concentrations may be expected where recharge water is high in carbon dioxide as a result of percolation through soil that is rich in organic matter (Trainer and Heath, 1976).

Although the quality of ground water in the Coastal Plain is generally good, contamination problems exist or may develop in certain areas. In most places ground water does not receive the amount of contamination that streams do. Surface contaminants tend to be degraded, diluted, and filtered before reaching the aquifer. Water moving miles downdip through sandy aquifers is almost everywhere free of organic contamination.

Ground water can be degraded, however. Heavy application of fertilizers, a concentration of septic tanks, sanitary landfills, or feed lots are sources of organic contaminants that may pollute both ground water and streams.

In some industrial areas, heavy metals or nondegradable contaminants may be present in waste water entering the ground-water reservoir. These are not filtered out by movement through sandy beds.

Limestone terranes that are not protected by a thick sandy or silty soil cover are particularly susceptible to contamination from the surface. Although such water may be diluted, no filtering action occurs, and contaminants may persist for miles.

GROUND WATER IN THE COASTAL PLAIN PROVINCE

Except in the Florida Peninsula, the Coastal Plain strata are generally present as a series of overlapping beds that dip gently seaward. The exposed inland outcrop areas absorb rainfall that moves downgradient, ordinarily seaward. Water accumulates in interfluve areas and moves slowly to the streams in response to gravity. In such areas, water occurs under unconfined (water-table) conditions.

Downdip the water is confined within the aquifer by permeable overlying material, such as clay, and is under pressure from the water filling the aquifer back to the outcrop area. Water will rise in wells drilled in such an aquifer, and the water occurs under confined (artesian) conditions.

This simple explanation suits the confined systems as a whole and is applicable without notable qualifications throughout the Coastal Plain. In much of the Florida Peninsula and in some smaller areas, recharge is local rather than at "inland" exposures of the formations.

A part of the potential recharge water in the outcrop area of the formations is rejected and becomes part of the sreamflows. Part of the water entering these strata, however, moves downdip into the confined parts of the aquifers. Some of the recharge that is not discharged as base flow to streams in the outcrop area leaks upward through confining beds downgradient from the outcrop area (Siple, 1967b).

Numerous aquifers are present in the Coastal Plain province of the South Atlantic-Gulf Region. They vary in areal distribution and extent, and some differ in name from one State to another even though they are lateral equivalents (table 1). Perhaps the most prolific aquifer is the Tertiary limestone aquifer which crops out or is near the surface in Florida, southern Alabama, central Georgia, and southeastern South Carolina and is made up of Paleocene to Miocene limy formations that function as one aquifer. The sand aquifers in the Tuscaloosa Group and correlative units of Cretaceous age crop out generally along the Fall Line and extend seaward beneath the younger formations from North Carolina to Mississippi. In the Western part of the region the thick permeable sand beds of the Miocene Series form an extensive aquifer system.

CRETACEOUS AQUIFERS

The Cretaceous deposits of the region have an outcrop area of about 40,000 mi^2 from Mississippi to Virginia (fig. 4) and extend seaward under a cover of younger sediments. Although the downdip limit of freshwater (water containing less than 1,000 mg/L dissolved solids) in the Cretaceous aquifers is not known in parts of the region, the areal extent of freshwater in these aquifers probably exceeds 70,000 square miles.

Except in North Carolina and Virginia, the Lower Cretaceous sedimentary rocks (including the aquifers) are overlapped in the subsurface and do not crop out. These rocks contain salty water in the region except in North Carolina and Virginia and in a limited area in Mississippi (where the quality of water is inferred from geophysical logs). At Franklin, Isle of Wright County, Va., industrial and municipal pumpage from Lower Cretaceous deposits has caused water-level declines over a 1,300 square-mile area that extends into North Carolina (Brown and Cosner, 1974). Yields of individual wells are as high as 2,500 gal/min in Virginia, and the aquifer is a source of large ground-water supplies in North Carolina.

Upper Cretaceous formations crop out along the inner edge of the Coastal Plain from Mississippi to North Carolina. The Tuscaloosa aquifers, which extend over 500 miles from Mississippi to North Carolina, form one of the more extensive ground-water reservoirs in the region (fig. 6). In Mississippi and southwestern Alabama the Tuscaloosa Group consists of the Coker and Gordo Formations. In Georgia, units within the Tuscaloosa are not differentiated. The correlative units of the Tuscaloosa in North and South Carolina are the Cape Fear Formation and, in the updip areas, the overlying Middendorf Formation. Yields of 1,000 gal/min from the Tuscaloosa aquifers are common, and, where the full thickness is developed, yields of 3,000 gal/min may be possible.

In Mississippi and northwestern Alabama, the McShan and Eutaw Formations overlie the Tuscaloosa Group. Sand beds in these formations are fair aquifers in some areas.

Above the Eutaw Formation, except in east-central Mississippi, are sand beds in the Selma Group. In northern Mississippi, these beds are in the Coffee Sand and the Ripley Formation. In eastern Alabama and western Georgia, the Selma includes in ascending order the Blufftown Formation, Ripley Formation, including the Cusseta Sand Member, and Providence Sand. These units are only fair aquifers near their outcrop, but downdip in Alabama high yields are available from combinations of these strata. In eastern Georgia, South Carolina, and North Carolina, the aquifers correlative with Selma sequences are the Black Creek and Peedee Formations.

The yields from wells in the Cretaceous aquifers will vary from place to place in each aquifer and from aquifer to aquifer. Table 2 shows the maximum reported yield from each aquifer in several counties in each State. These values do not imply that such yields can be obtained everywhere in the aquifer or that such yields are the maximum possible yields.

The highest average transmissivities for Cretaceous aquifers are those for the Tuscaloosa Group (Formation). The Coker Formation is an extremely productive aquifer in eastern Mississippi where the highest transmissivity, 80,200 ft^2/d, was reported for a well 1,857 feet deep in Noxubee County, Miss. (Newcome, 1971, p. 36). Results

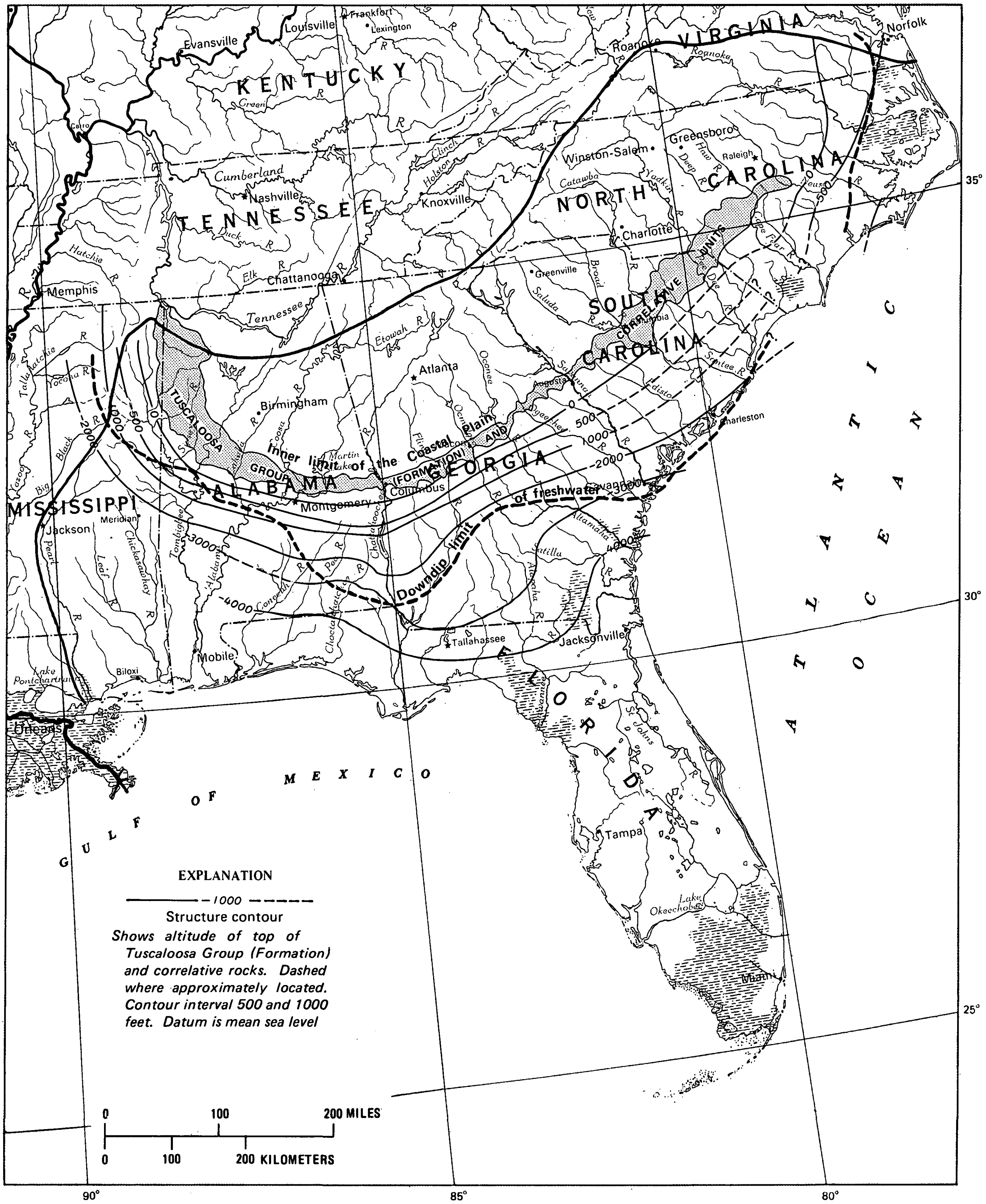

FIGURE 6.—Outcrop area, depth below sea level to the top, and downdip limit of freshwater in the Tuscaloosa Group (Formation) and correlative rocks.

TABLE 2.—*Maximum reported yields of wells in Upper Cretaceous aquifers, Mississippi to North Carolina*

State and county	Yield (gal/min)	Drawdown (ft)	Aquifer
Alabama:			
Autauqa	500	—	Coker.
Barbour	350	—	Blufftown-Providence Sand.
Bullock	515	212	Gordo.
Dale	[1]1,400	—	Ripley.
Greene	11,000	—	Coker.
	11,000	—	Gordo.
	460	32	McShan.
Houston	700	—	Providence Sand.
Montgomery	1,000	—	Coker.
	200	—	Gordo.
Pickens	640	55	Gordo.
	600	38	McShan.
Tuscaloosa	500	—	Coker.
Georgia:			
Bibb	500	40	Blufftown-Providence Sand.
Houston	1,850	—	Do.
Macon	1,230	70	Do.
Peach	656	23	Do.
Screven	870	flow	Providence Sand-Clayton.
Sumpter	800	—	Blufftown-Providence Sand.
Terrell	1,000	—	Providence Sand-Clayton.
Mississippi:			
Chickasaw	600	—	Eutaw-McShan.
Clay	900	75	Gordo.
Lee	770	43	Eutaw-McShan.
Lowndes	600	—	Gordo.
	2,300	flow	Coker.
Monroe	1,600	—	Gordo.
Noxubee	1,200	57	Coker.
Oktibbeha	1,000	42	Gordo.
North Carolina:			
Bertie	550	—	Tuscaloosa (?).
Bladen	650	—	Black Creek.
	700	—	Peedee.
Colombus	500	—	Do.
Craven	2,000	57	Tuscaloosa(?)-Black Creek.
Duplin	700	71	Black Creek-Peedee.
	750	90	Black Creek.
Greene	550	122	Tuscaloosa(?).
Hertford	1,000	67	Do.
Hoke	900	—	Do.
Johnston	300	—	Do.
Lenoir	1,300	—	Black Creek.
	1,000	52(?)	Tuscaloosa(?)-Black Creek.
Martin	700	—	Black Creek-Peedee.
Onslow	500	80	Black Creek-Peedee(?).
Pender	600	40	Black Creek.
Pitt	380	—	Peedee.
	1,100	—	Tuscaloosa(?). Black Creek(?).
	800	—	Lower Cretaceous. Tuscaloosa(?)-Black Creek.
Robeson	775	—	Tuscaloosa(?).
	800–1,000		Do.
Sampson	650	—	Black Creek.
Wayne	720		Do.
South Carolina:			
Aiken	3,300	122	Upper Cretaceous (Tuscaloosa?).
Beaufort	100	flow	Lower Black Creek-Tuscaloosa.
Colleton	1,200	flow	Black Creek(?)-Tuscaloosa.
Hampton	500	flow	Upper Cretaceous-Peedee-Black Creek(?).
Horry	1,200	120	Black Creek.
Sumter	1,690	—	Upper Cretaceous (Tuscaloosa?).
Williamsburg	1,100	—	Peedee-Black Creek.

[1] Estimated.

of about 30 tests in Cretaceous aquifers in Mississippi indicate an average transmissivity of 1,200 ft^2/d for the Eutaw and McShan Formations and 6,500 ft^2/d for the Gordo Formation (Newcome, 1971). Similar conditions can be expected in adjoining parts of Alabama. Siple (1960, p. 165) reported a transmissivity of 26,700 ft^2/d for a well developed in his "Tuscaloosa Formation" (Cape Fear Formation) in South Carolina, a value accepted by Callahan (1964, p. 10) for use in evaluating the Tuscaloosa aquifer in Georgia and adjoining states.

In northeastern North Carolina transmissivities in Cretaceous aquifers range from 190 to 27,000 ft^2/d (Lindskov, 1972, table 4). A reasonable value for the average transmissivity is 10,000 ft^2/d. In the opinion of R. C. Heath (written commun., 1977), most of the water withdrawn from the Cretaceous aquifers in North Carolina is derived from compression of the aquifer, expansion of the water, and drainage of the confining beds. In northeastern South Carolina, the hydraulic conductivity averages about 30 ft/d (A. L. Zack, oral commun., 1977).

Water in and near the outcrops and in the updip parts of the Cretaceous aquifers is generally low in dissolved solids, high in iron, and slightly acid (corrosive). Although much higher concentrations of iron have been reported in places in Mississippi and Alabama, 2 or 3 mg/L is common in most areas. Downdip the water becomes neutral or slightly alkaline, and the iron content decreases sharply.

Water from some wells in North Carolina is hard, presumably because recharge is by seepage down through overlying limy Miocene sediments. Samples high in bicarbonate and low in hardness from deeper wells in the same area have presumably traveled for some distance downdip from their point of origin. In South Carolina, water from the Black Creek aquifer is characterized by low iron and high fluoride.

At varying distances downdip and at depth, water in the Cretaceous aquifers is highly mineralized owing to the fact that the sediments were once saturated with saline waters.

LOWER TERTIARY AQUIFERS

TERTIARY LIMESTONE AQUIFER

The Tertiary limestone aquifer, the most extensive and widely used aquifer in the South Atlantic-Gulf Region, underlies an area of about 90,000 square miles which includes Florida (where it is referred to as the Floridan aquifer), southern and coastal Georgia, and adjacent parts of Alabama and South Carolina (fig. 7). Local names for this aquifer are given in table 1. The aquifer is the source of some of the largest ground-water supplies in the United States (Stringfield, 1966, p. 1). It has been commonly referred to as the "principal artesian aquifer," although in many areas it is an unconfined aquifer. The aquifer includes parts of several geologic units (table 1) that are principally Tertiary limestone but contain intercalated beds and lenses of dolomite, sand, silt, marl, and clay in which porosity and permeability differ greatly from place to place. The aquifer thickness increases in a seaward direction from about 50 feet in its

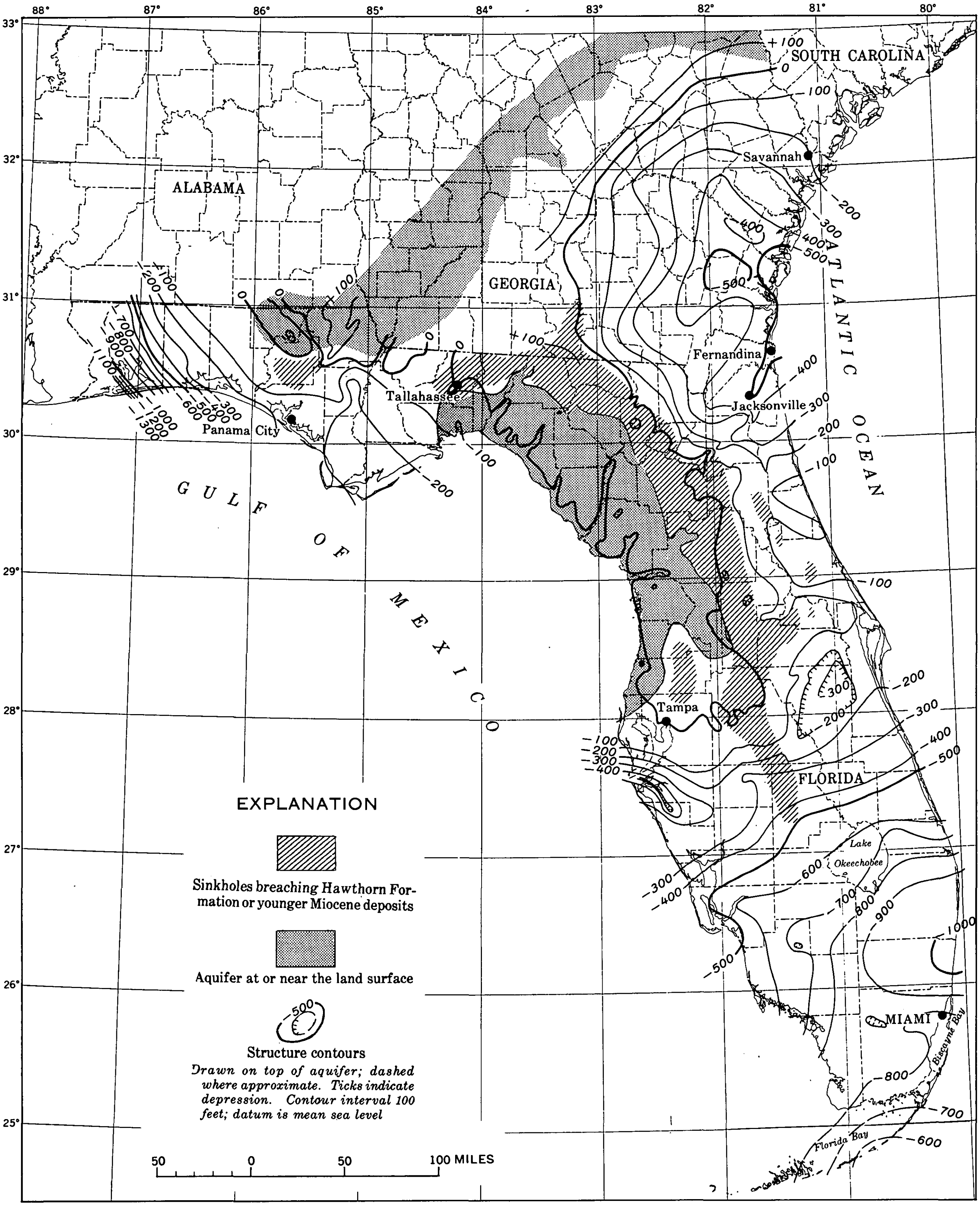

FIGURE 7.—Distribution and structure contour map of the top of the Tertiary limestone aquifer. (From Stringfield, 1966, fig. 23).

updip areas in Georgia to more than 2,500 feet in parts of Florida (Klein, 1971).

Most of the massive limestone of Tertiary age has been removed by erosion from the Cap Fear Arch. Nevertheless, the Tertiary limestone of North Carolina is considered a hydrologic equivalent of this aquifer.

The several limestone units constituting the aquifer (table 1) are principally of marine origin and generally grade into or interfinger with clastic deposits toward the continental landmass to the north from which the clastics were derived. These peripheral clastic facies are not considered part of the aquifer. The aquifer is near the surface and in hydraulic continuity with the unconfined shallow aquifers over an extensive area where overlying rocks of lesser permeability are perforated by innumerable sinkholes, particularly around the Ocala Uplift (fig. 3). Elsewhere the impermeable clays of the Hawthorn Formation overlie the aquifer; however, this formation is breached in a few places, as near Parris Island and Brickyard Point, Beaufort County, South Carolina.

Ground-water development is extensive, including withdrawal of hundreds of millions of gallons per day to meet the water-supply needs of numerous major cities, such as Savannah, Jacksonville, and St. Petersburg; the phosphate, pulp, paper, and allied chemical and other industries; and for citrus and other crop irrigation. Throughout the area, the aquifer yields water to tens of thousands of domestic, industrial, and irrigation wells, but most of the large industrial supplies are developed in coastal areas.

The wide range in hydraulic characteristics in the Tertiary limestone aquifer reported by Stringfield (1966, p. 101–109) is representative of an aquifer composed of sediments that range from interbedded sand and clay to cavernous limestone. The reported transmissivities range from 3,700 to 134,000 ft^2/d, hydraulic conductivities from 35 to 334 ft/d, and storage coefficients from 0.00019 to 0.021. These values do not indicate the true potential; for example, Callahan (1964, table 4) estimated transmissivity values in Georgia as high as 268,000 ft^2/d for his determinations of ground-water flow through the aquifer.

Large springs having yields ranging up to hundreds of millions of gallons per day from the Tertiary limestone aquifer are numerous in Florida and Georgia. Silver Springs and Rainbow Springs in central Florida are the largest, their combined flow averaging about 1,000 Mgal/d (Rosenau and Faulkner, 1974). Well yields of 2,000 gal/min are common. Locally, yields up to 11,000 gal/min are known, and a natural flow of 20,000 gal/min is reported for a well in central Florida (Pascale, 1975). The base flow of streams is well sustained as a result of ground-water discharge through springs.

Under natural conditions, the aquifer contains potable water as defined by Klein (1971) to depths of more than 2,000 feet in parts of the area (fig. 8). The extent and thickness of the freshwater body is dependent upon the rainfall and the geologic and hydrologic properties of the rocks.

Since the last emergence of the land from the sea, the aquifer has been flushed of seawater in most areas. In southern Florida and in places along the eastern seaboard where the potentiometric head is low, the aquifer has not been completely flushed, and the water is saline. Increases in salinity with depth are commonly abrupt immediately below an impermeable stratum underlying a freshwater zone.

In the Georgia and South Carolina coastal plains, water at depth inland is fresh through the full thickness of the aquifer. At Savannah, Ga., the section is about 600 feet thick, but 70 percent of the water produced in that area comes from two upper zones that have a combined thickness of about 100 feet (McCollum and Counts, 1964). Saline water occurs in the lower part of the aquifer at Hilton Head Island, S. C., and the entire aquifer is saline in most of Beaufort County, S. C. (L. R. Hayes, oral commun., 1977). At Brunswick, Ga., the 500- to 1,000-foot zone is fresh; saline water is present from 1,000 to 1,400 feet and low chloride water occurs from 1,400 to 1,700 feet (R. L. Wait, 1965, p. 67).

The freshwater in the aquifer is generally hard. In the recharge area, the water may contain less than 20 mg/L hardness as calcium and magnesium bicarbonate, but almost everywhere downdip the hardness is generally in excess of 100 mg/L.

At centers of heavy pumping, lowered head tends to induce upward flow of deeper, possibly saline, water. Many wells have been drilled through several zones of the aquifer, thereby providing direct flow paths for deeper more highly mineralized water to migrate upward (or laterally) and contaminate the freshwater reservoir. Upward movement may occur in a short time and is, therefore, the greater hazard.

In southwestern Florida, the mineral content of ground water along the Peace River is high. Kaufman and Dion (1967) suggested that here deep ground water rises "along a linear zone (fault?) of greater vertical permeability." In eastern Florida, "upward leakage of highly mineralized water from deep artesian zones" is in part "along fault zones" (Klein, 1971).

Saline water is moving laterally from points of vertical leakage into well fields at Brunswick, Ga. (Wait and Gregg, 1967). At Jacksonville, Fla., saline water has migrated into the lowermost zone of the Tertiary limestone aquifer, thus eliminating it as a source of potable water.

Contamination by seawater is possible in coastal areas where the overlying confining bed is breached. Seawater is presently migrating toward the Savannah wells from the Hilton Head Island, S.C., area (Counts and Donsky, 1963, p. 72); however, under existing hydraulic conditions, salt water will require many years to reach the center of heaving pumping.

LOWER TERTIARY AQUIFERS OTHER THAN THE TERTIARY LIMESTONE AQUIFER

The Paleocene, Eocene, and Oligocene sediments that make up the lower Tertiary aquifers (exclusive of the Tertiary limestone aquifer) in the region have an outcrop area of 45,000 square miles from Mississippi to Virginia (fig. 4). They dip seaward under a cover of younger sed-

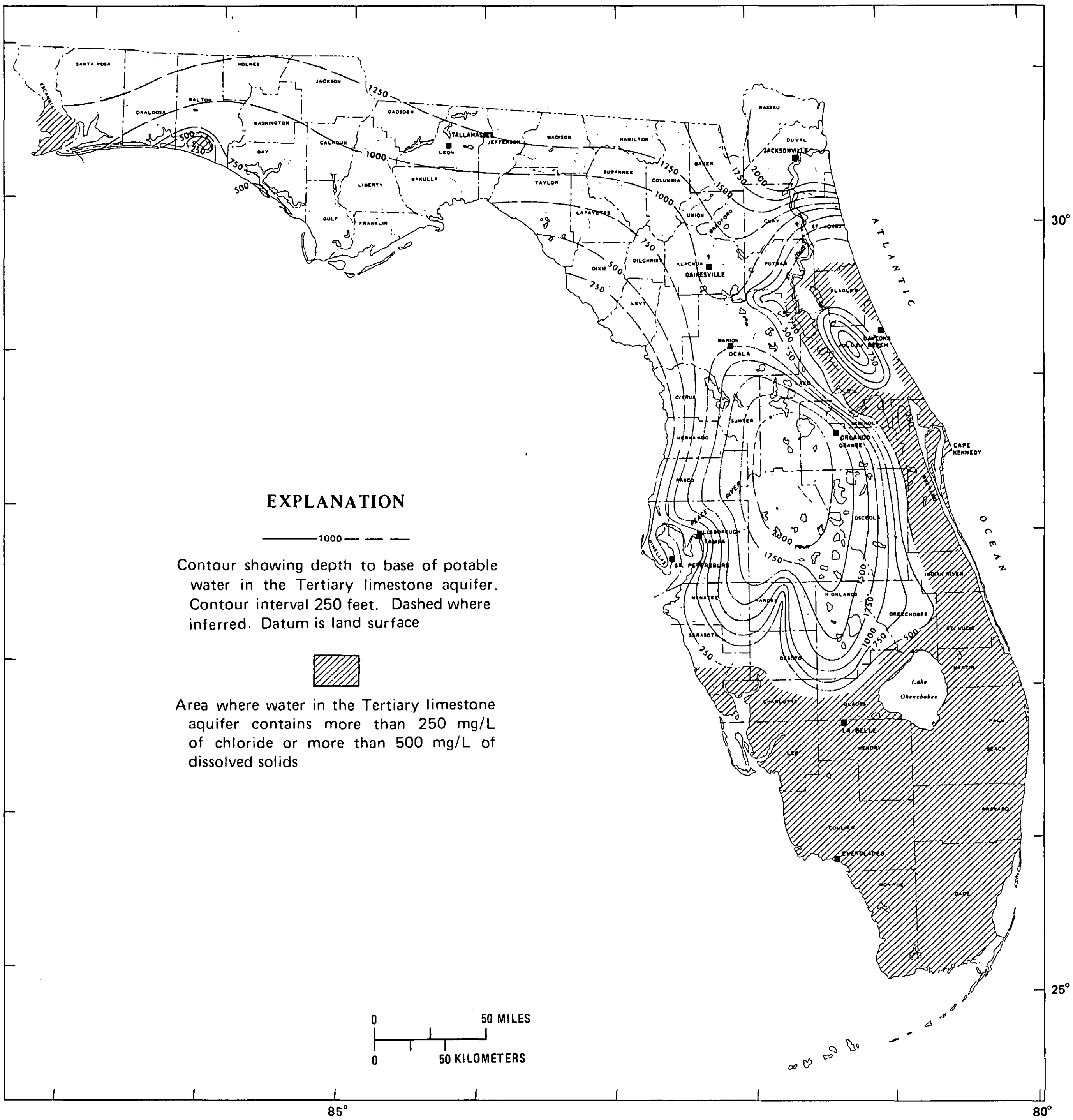

FIGURE 8.—Depth to the base of potable water in the Tertiary limestone aquifer (Floridan aquifer) in Florida.

iments. Although the individual lower Tertiary aquifers are not as extensive areally as the Cretaceous aquifers, they are major sources of ground water where they occur in the region (table 1).

The lower Tertiary aquifers include limestone beds that grade laterally into the Tertiary limestone aquifer (table 1). These strata have poor hydraulic connection with one another, and development of maximum supplies in any one place would require either several wells ending in different aquifers or a well screened at various levels.

Without exception, water in the lower Tertiary aquifers is fresh in the area of outcrop and for a few tens of miles downdip, beyond which the water is saline. Maximum development at present is ordinarily confined to whatever productive stratum lies nearest the surface. Additional supplies are available at greater depths in many places, but in other places the deeper beds yield only saline water.

The lower Tertiary aquifers in Mississippi, Alabama, and western Georgia (table 1) are highly productive. Yields ranging up to 2,000 gal/min to individual wells are common. A well field in Tertiary limestone yielded as much as 15 Mgal/d at Ft. Gaines, Ga. (Callahan, 1964, p. 19). Well yields of 2,000 gal/min or more could be reasonably expected from efficiently constructed wells at many places in the Pascagoula River basin in Mississippi (Newcome, 1967b, p. 1). Deeper parts of some of the Tertiary aquifers in Mississippi, in areas where freshwater extends to depths of 3,000 feet (fig. 9), remain virtually untapped and are potential sources of future water supplies.

The Castle Hayne Limestone, separated from the Tertiary limestone aquifer by erosion across the Cape Fear Arch, is the principal source of water supplies in the coastal plain area of North Carolina. Withdrawals of water from the Castle Hayne in Beaufort County, N. C., for mining exceeded 60 Mgal/d in 1974 (North Carolina Department of Natural Resources, 1974).

The lower Tertiary aquifers exhibit a very wide range in hydraulic properties. The estimated average transmissivity for the Castle Hayne Limestone in North Carolina is about 25,000 ft^2/d (R. C. Heath, written commun., 1977), and the range for the lower Tertiary aquifers in South Carolina is from 350 to 13,400 ft^2/d (C. A. Spiers, oral commun., 1977). Callahan (1964, p. 19) reported that transmissivities ranged from 940 to 20,000 ft^2/d in Georgia.

A compilation of about 110 aquifer tests made in lower Tertiary aquifers in Mississippi (Newcome, 1971) shows a range in hydraulic conductivity from near 1 to about 240 ft/d. Corresponding values for transmissivity in an aquifer 100 feet thick would be as much as 24,000 ft^2/d. The average transmissivity for a 100-foot aquifer would be about 6,400 ft^2/d. Values for lower Tertiary aquifers in Alabama are estimated to be about the same.

UPPER TERTIARY AQUIFERS

Miocene and Pliocene sediments make up the upper Tertiary aquifers in the South Atlantic-Gulf Region. These sediments crop out over an area of about 70,000 square miles from Mississippi to Virginia (fig. 4).

Miocene beds are widely distributed in the region and extend from Mississippi to Virginia, although absent over the Cape Fear Arch. From Georgia to central South Carolina, Miocene limestones are significant parts of the upper Tertiary limestone aquifer.

In the Florida panhandle, Alabama, and Mississippi, the Miocene beds dip toward the south and southwest and thicken rapidly. The total Miocene section is as much as 5,000 feet thick in southwestern Mississippi, but only the higher beds contain freshwater. The depth to base of freshwater in the area (fig. 9) ranges from 500 feet near the northern limit of those formations to as much as 3,000 feet near the coast and near the mouth of Pearl River in Mississippi.

Units of Pliocene age overlie the Miocene deposits and are part of the freshwater hydrologic system of the Gulf Coastal area. The Citronelle Formation of Pliocene age is the source of water for many domestic and public-supply wells, but most large yield wells have been drilled into the underlying Miocene aquifers where water is under higher artesian pressure.

Practially all domestic and municipal water supplies and most industrial supplies along the Gulf Coast in western Florida, Alabama, and Mississippi are obtained from Miocene to Pliocene aquifers. Well yields commonly exceed 1,000 gal/min. At Pensacola, in western Florida, municipal wells yield 1,500 to 2,000 gal/min, and pumpage exceeded 17 Mgal/d in 1970. In the Pascagoula River basin in Mississippi, with careful programs of exploration and development, individual well yields of 2,000 gal/min could become commonplace, and yields of 5,000 gal/min are not unreasonable to expect in some places (Newcome, 1967b, p. 35).

The upper Tertiary aquifers are characterized by high hydraulic conductivity and transmissivity values. Lindskov (1972, table 4) reported transmissivity values ranging from 44 to 2,710 ft^2/d for aquifers in the Yorktown Formation in North Carolina. Callahan (1964, p. 47) refers to transmissivities ranging from 4,540 to 66,800 ft^2/d in northwestern Florida and southern Alabama and indicates that conditions are similar in the Atlantic Coastal area of Georgia in the Pliocene to Holocene aquifers (Callahan, 1964, p. 50). In southern Mississippi the upper Tertiary aquifers, mostly of Miocene age, are among the most productive in the State. Newcome (1971) summarized about 130 aquifer tests that indicated hydraulic conductivities ranging from 5 to 334 ft/d. The average hydraulic conductivity for all tests was 94 ft/d. Assuming that the average aquifer is 100 feet thick, the average transmissivity would be 9,400 ft²/d. The largest transmissivity value for the Miocene aquifer system in Mississippi was 84,000 ft²/d at a site in Harrison County (Newcome, 1971, p. 25).

There appears to be little contamination of deep aqui-

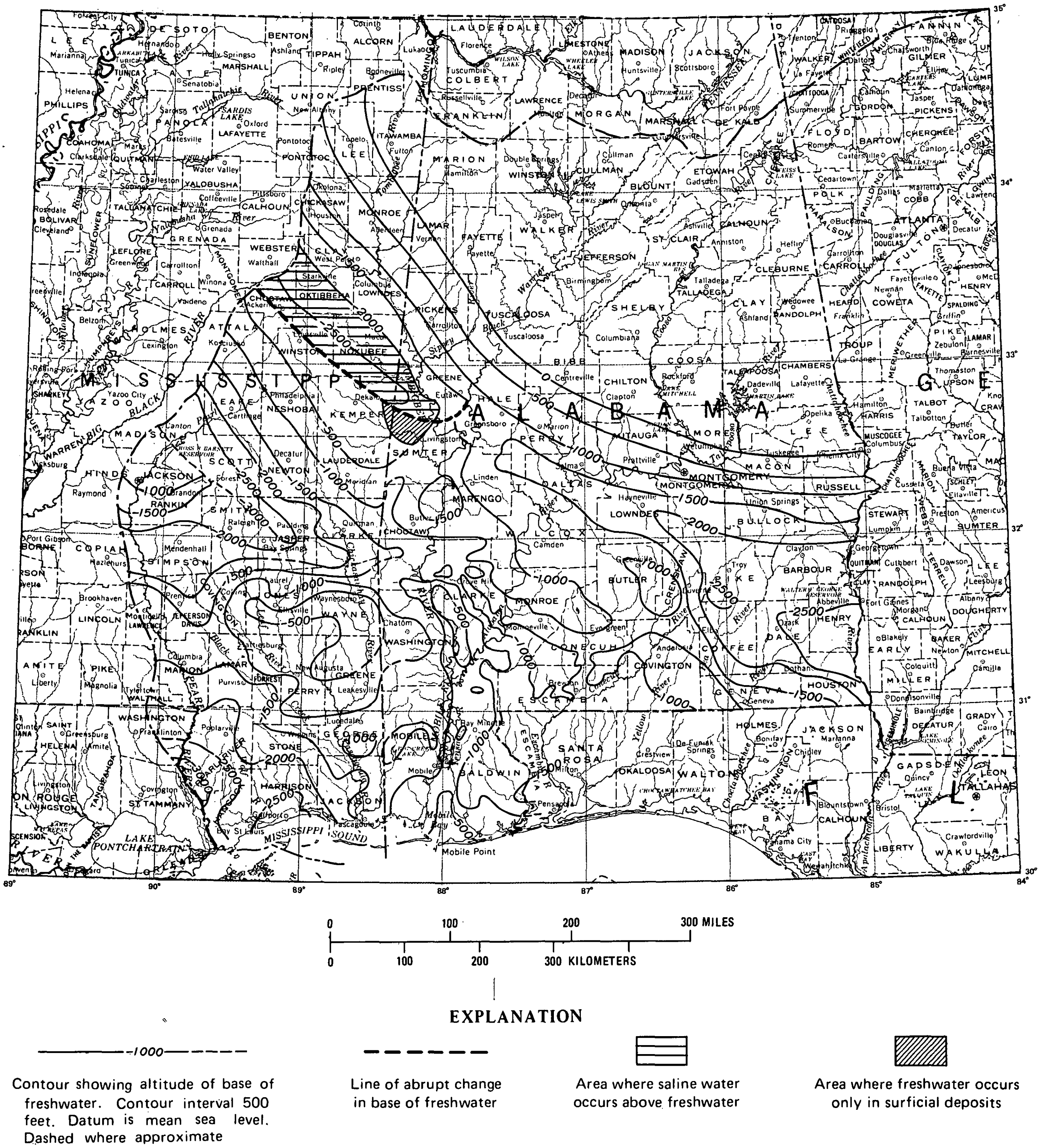

FIGURE 9.—Altitude of the base of freshwater in Alabama and Mississippi.

fers by seawater, but contamination of the shallower aquifers that are hydraulically connected to estuarine streams probably occurs in a few places (Newcome, 1967b, p. 29).

QUATERNARY AQUIFERS

Pleistocene and Holocene sediments make up the Quaternary aquifers in the South Atlantic-Gulf Region. The sediments crop out over an area of about 40,000 square miles, primarily in the coastal area from Mississippi to Virginia (fig. 4).

In the western Florida panhandle, the upper Tertiary and Quaternary units (Miocene to Holocene) constitute a large unconfined (water table) aquifer. The sand and gravel deposits are thickest to the south and west and thin to the north and east. Wells 200 to 400 feet deep, capable of producing 1,000 to 2,000 gal/min, are common. The quality of the water is excellent except for the erratic occurrence of excessive iron. The aquifer is susceptible to saltwater encroachment near estuaries.

During the drought of 1954 to 1956, the minimum discharge or ground-water outflow at 10 of 15 gaging stations in the Florida panhandle was 0.308 (Mgal/d)/mi^2 (Pride and Crooks, 1962, table 2, p. 34–35), equal to about 6.5 inches of precipitation. Thus, in the 6,500 square mile panhandle area, a minimum of about 2,000 Mgal/d would be available for development if the environmental effects of the withdrawals were acceptable.

Deposits of Miocene to Holocene age also make up an important freshwater aquifer in southwestern Florida. The aquifer is about 130 ft thick in western Collier County, but thins eastward and wedges out toward Dade and Broward Counties. Most of the wells near the Gulf are generally less than 100 feet deep, and the municipal water-supply wells are properly spaced and discharged at low rates to prevent saltwater encroachment (McCoy, 1962). Wells inland yield up to 1,300 gal/min. The quality of the water is good except for a high iron content.

The highly productive Biscayne aquifer, predominantly highly permeable limestone of Quaternary age, is the most important source of freshwater for populous southeastern Florida, including the Miami area (Parker and others, 1955). The aquifer underlies about 3,000 square miles of Dade, Broward, and parts of Palm Beach Counties. It is as much as 400 feet thick along the shoreline, but is more commonly less than 200 feet thick and thins to a featheredge 40 miles to the west. It is estimated that about two-thirds of the 60 inches annual rainfall infiltrates the zone of saturation in Dade County (Parker and others, 1955, p. 221).

Well yields commonly exceed 2,000 gal/min (Pascale, 1975). An estimated 120 billion gallons of water was pumped from a 600 mi^2 area in the coastal ridge in 1965, of which 22 billion gallons was consumptive use. Although copious supplies are available, one of the factors limiting withdrawals is the susceptibility of the aquifer to saltwater encroachment from the ocean and from tidal canals.

Prior to the 1930's, little attention was paid to the detrimental effects of the tidal canals; however, water management practices initiated in 1945 have effectively stabilized the saltwater instrusion. These are (1) the importation of freshwater through canals to maintain higher water levels, (2) the construction of salinity-barrier dams in tidal canals to prevent the intrusion of salty water and furnish additional water to infiltrate into the aquifer, and (3) the shifting of pumping to new well fields to the west.

North of Palm Beach County, a shallow sand aquifer extends along most of the coastal area. In Duval County, more than 40,000 wells produce 10 to 25 Mgal/d (Fairchild, 1972) from a shallow aquifer system consisting of Miocene to Holocene deposits.

The coastal aquifers in the Quaternary deposits (fig. 4) generally yield only small supplies to wells. They are relatively low in permeability, and the storage capacity at any one place usually is small; however, these aquifers absorb rainfall readily, and in many areas they are a perennial source of small water supplies and recharge to streams and underlying aquifers.

Where Quaternary aquifers are extensive in humid areas, both storage and recharge potential are favorable. At Elizabeth City, N. C., for instance, 14 shallow wells yield a total of 450 gal/min—more than half the city supply (R. C. Heath, oral commun. Nov. 30, 1972). The greater cost in such developments may be the cost of land and pipelines rather than that of the wells. Along some of the larger rivers in the region, alluvium as much as 75 feet thick may yield up to 1,000 gal/min. Sustained yields of this magnitude should not be expected except where wells are properly spaced and recharge conditions are favorable.

Data on hydraulic characteristics of the Quaternary deposits are limited because few aquifer tests have been made. Large wells in Quaternary aquifers are not common because of limited available drawdown, and in many localities, the water requires treatment for most uses. A noteworthy exception is the Biscayne aquifer, the major source of water supplies in southeastern Florida. Parker and others (1955, p. 2) reported that the Biscayne is among the most permeable aquifers investigated by the Geological Survey. Transmissivities for the aquifer range from 400,000 to 2,670,000 ft^2/d, and the average is 670,000 ft^2/d. The average storage coefficient is 0.20. A reasonable value for transmissivity of Quaternary deposits in North Carolina is about 750 ft^2/d (R. C. Heath, written commun., 1977). Transmissivity values for Quaternary aquifers in South Carolina range from

850 to 2,000 ft^2/d (C. A. Spiers, oral commun., 1977), and Callahan (1964, p. 50) estimated that values could be as large as 66,800 ft^2/d in the Pliocene to Holocene section in Georgia.

The chief value of the Quaternary deposits in the hydrologic system is their function of absorbing and storing large volumes of precipitation for gradual release to underlying aquifers and to streams.

GROUND WATER IN THE PIEDMONT PROVINCE

In describing the occurrence of ground water in the Piedmont and Blue Ridge provinces, LeGrand (1967, p. 8) states

> The water table, representing the top of the reservoir, generally lies in the clay, or disintegrated rock materials. In the lower part of the reservoir, water occurs in interconnecting fractures in bedrock; the fractures diminish in number and size with increasing depth. Water enters the fractures by seeping through the overlying clay, and drilled wells draw water from these fractures. The source of this water is precipitation in the general area of a well and not in some remote place.

Minor valleys generally mark zones of fracture and, in places, fault zones, and yields are significantly higher there than elsewhere (Baker, 1957). The majority of wells in the Piedmont, however, are located for convenience on high ground, commonly under the community water tank. These wells nearly always are low yielding; consequently, the Piedmont is considered an area where well yields are low (fig. 5).

LeGrand (1967, p. 9) stated that 90 percent of all ground water in the area occurs in the first 100 feet below the water table and that generally two wells 200 feet deep each will yield more water than one well 400 feet deep. Yields of up to 500 gal/min have been reported from wells in crystalline rocks (Johnson and others, 1968), but many deep wells yield less than 75 gal/min.

The source of recharge in the Piedmont is the precipitation that saturates the saprolite (weathered rock) that overlies unweathered rock. Where the saprolite cover is thick or sandy, wells will have the better yields. A well in crystalline rocks ordinarily draws water from a limited area in the general vicinity of the well, and fissure zones supplying water to the well are commonly limited in extent. Wells must be widely spaced in order to avoid mutual interference, and successive wells located along the same rock lineament will create more mutual interference than if successive wells are located at right angles to the "grain" of a rock mass. Wells near a stream may have significantly higher yields than wells distant from such a source of recharge.

The 7-day, 2-year low flow in Pickens County, S.C., ranges from 0.3 to 0.7 $(Mgal/d)/mi^2$ (Johnson and others, 1968). This measurement of ground-water discharge to the stream, at the time of low hydraulic gradients, indicates that the average annual recharge is at least 6.3 to 17.5 inches.

An example of ground-water development in the Piedmont province is at Tega Cay, S. C., where 22 wells averaging 580 feet in depth were drilled to provide water for a resort (McCall, 1972). The well sites were located on the basis of a careful evaluation of geology and hydrology. Yields ranged from less than 10 gal/min to 370 gal/min and averaged 109 gal/min. From this group, 14 wells yielding an average of 160 gal/min were selected as supply wells. Most of the water is obtained from below a depth of 450 feet. This well field is on a peninsula jutting into Lake Wylie, a possible source of recharge that may have been a factor in the high yields obtained even though the path to the wells was circuitous and the source of recharge somewhat distant. Tests for coliform bacteria in the well waters were negative, suggesting that if the lake is a source of much of the recharge, slow filtration through the fine-grained saprolite has been highly effective in removing the bacteria. However, in areas where the saprolite cover is thin, filtration of surface-water seepage would not be very effective.

GROUND WATER IN THE VALLEY AND RIDGE PROVINCE AND CUMBERLAND PLATEAU SECTION

A small part of the study area lies within the folded Appalachians, largely that area in Alabama and Georgia drained by the headwaters of the Coosa River. The underlying rocks are Paleozoic limestone, dolomite, sandstone, and shale, mostly overlain by a mantle of residual material. In the Valley and Ridge province (fig. 1), the rocks are not only crumpled by compressive stresses but are broken into several huge segments, some of which have slid over the more stable masses. Lesser displacements occur along high-angle faults. The Paleozoic rocks of the Cumberland Plateau section, adjacent to the Valley and Ridge province on the northwest, are gently warped.

Synclines (downwarps of rock strata) may be thought of as favorable locations for ground-water development in the sense that water funnels into troughs, but circulation is poor due to the compression of fractures in deep synclinal troughs and the water may be of inferior quality. Anticlines (upwarps), on the other hand, tend to crack the rock into open fractures along their crests during folding and are favorable recharge areas.

In this area of large-scale deformation, the more brittle rocks were shattered and sheared; subsequently, dissolution by percolating water enlarged the fractures in limestone and dolomite (the carbonate rocks). Fractures in sandstone, unless calcareous, are not enlarged by later solution. True (noncalcareous) shales, initially poor aquifers, scarcely improve in water-bearing character as a result of deformation and later dissolution.

The hydrology of shattered consolidated rocks is greatly different from that of the unconsolidated sandy formations. In shattered limestone, water can move nearly as fast as through a pipe, and in both fractured limestone and sandstone filtering action is lacking. The cone of depression around a well in a highly fractured rock mass enlarges quickly, and water may move rapidly to a well from long distances. Stored water in the carbonate rocks may be that filling an open cavern, an interconnected series of smaller openings, or in the unconsolidated materials overlying the limestone that is hydraulically connected to water in the caverns. Although the rate of recharge in a carbonate rock terrane overlain by a clay mantle may be low, water can flow rapidly to a well from a large surrounding area and high yields with small drawdowns are possible.

In Talladega County, Ala., the Cambrian dolomites are highly productive (Causey, 1965). One well yields 1,100 gal/min with 27 feet of drawdown and has been pumped at 1,600 gal/min. A well in Precambrian(?) marble yields 900 gal/min with 72 feet of drawdown.

Cressler (1970) notes that in northwestern Georgia, 1,000 gal/min should be available in many places from properly located wells. Near Huntsville, Ala., just north of this report area in the Cumberland Plateau section, a recently completed well 160 feet deep yielded 2,900 gal/min with 20 feet of drawdown (W. J. Powell, oral commun., March 1, 1972).

In Calhoun County, Ala., a 95-foot well in Cambrian dolomite yielded 257 gal/min with only 1.6 ft of drawdown; whereas, a 550-foot well yielded about as much with 15 feet of drawdown (Warman and Causey, 1962). It is entirely possible that drilling to 400 or 500 feet in strongly deformed areas may intersect a low-or high-angle fault from which large quantities of water may be obtained; therefore, it seems likely that deep drilling is desirable where maximum production is sought. Drilling in the most convenient locations relative to points of use can easily result in failure; whereas, sites a mile or a few miles distant that are selected on the basis of structural control may provide ample water at very low cost.

It is probable that the ground-water potential of the Valley and Ridge province is generally underrated, although many examples are known of failures to develop productive wells.

GROUND WATER IN THE BLUE RIDGE PROVINCE

In the rugged Blue Ridge province weathered rock cover (residuum) is commonly thin or absent except in valleys. Ground water generally occurs in residuum or alluvium and in fractures in the underlying igneous and metamorphic rocks. Small water supplies are available from the springs that drain the fracture systems and residuum. Well yields depend on the number and degree of interconnection of fractures penetrated by the well but commonly are only a few gallons per minute. Where all the available water is stored in fractures, the yield diminishes as stored water is pumped and the water level declines. LeGrand (1967) determined that wells are more productive and have a more stable yield where there is a thick mantle of residuum and that most interconnected fractures occur no deeper than 150 feet below the surface. Few wells produce significant quantities of water from depths greater than 300 feet.

Ground water in the province is generally of good quality. The dissolved-solids concentration is very low, and the principal quality problems are excessive iron and acidity (low pH). Aquifers in rock fractures are subject to contamination, however, in areas where the residuum is too thin to be an effective filter.

SALINE-WATER RESOURCES

Vast quantities of saline water are available in the South Atlantic-Gulf Region. This saline-water resource is mostly in aquifers in the unconsolidated rocks that underlie the Coastal Plain above the Paloezoic "basement" rocks to depths that approach 20,000 feet in southern Florida and southwestern Mississippi. All permeable deposits below the deepest freshwater (fig. 9) are saturated with saline water, some of which has a much higher dissolved-solids concentration than seawater.

Some of the dissolved minerals are of economic value; however, the most likely reason for immediate development will be utilization of slightly saline and moderately saline water. Some water containing up to about 2,000 mg/L of dissolved solids can be used for irrigation. Slightly saline water can be blended with freshwater to augment ground-water supplies for public and industrial uses. Desalting operations for public water supplies and other uses are more economical where the raw water has a low concentration of dissolved solids.

Saline aquifers offer reservoir space for injection and temporary storage of freshwater. The Norfolk, Va., injection project demonstrated that only 15 percent of the injected water was not potable upon recovery (Brown and Silvey, 1977, p. 51). Injection and storage could be used to provide a supplemental source of water to meet peak demands or as an emergency source.

DEVELOPMENT AND MANAGEMENT OF GROUND-WATER RESOURCES

OBJECTIVES

The manager has the responsibility of examining the alternatives for developing sources of supply; that is, a ground-water supply based on conventional development and management procedures as against supplies based on unconventional technologies. The planner is necessarily responsive to public expression regarding acceptable types of development and to the economic and social aims and interests of the particular States concerned. One of the major considerations confronting both manager and planner is the effect of ground-water development on the environment, particularly if a drastic lowering of water levels or large reduction in streamflow is involved. Where these constraints take precedence, dollar costs will be of minor significance in reaching final decisions.

In dealing with total available supply, ground water is not an entity separate from surface water. Much of the ground water that is not lost by evapotranspiration becomes the base flow of streams. Capture by wells of ground water moving toward a stream or induced infiltration of streamflow is highly desirable in many places but does not increase the total water supply. The increase in the ground-water supply is balanced by decrease in streamflow.

Where there is salvage of evapotranspiration loss, that salvage is an addition to the total water supply available for man's use; however, the effects on the environment must be considered. Reuse of water, the use of treated sewage effluent, or the use of poor-quality water for cooling or other purposes will conserve the total available supply. Use of ground water that would otherwise discharge into saline estuaries is an addition to the total supply in most situations.

The above mentioned management techniques are intended to show that the total available supply can be increased by utilizing aquifer storage during the low streamflow months and making up the resultant underground reservoir deficiency by capture of streamflow during the high-flow period.

Although the value of conventional approaches to many problems is granted (wider spacing of wells, for instance), emphasis here is placed on procedures that are not generally in use in the region but which have been demonstrated to be effective in other areas. Objections to any of the suggested management procedures may be based on costs; however, alternate sources would also be expensive.

NATURAL RECHARGE

The overland and ground-water runoff in the southeastern Coastal Plain is about one-third the total rainfall, roughly 15 inches, and the remainder is assigned to evapotranspiration loss and ground-water recharge (Pierce, 1966). Estimates of ground-water recharge have ranged from 1 to 11 inches (Callahan, 1964). Recharge of 6 inches would amount to about 0.29 (Mgal/d)/mi^2.

Some extreme exceptions to this generalization are highly permeable localities in areas underlain by the sandy Cretaceous formations. Callahan (1964, p. 12) states that in places the Cretaceous sand aquifers may discharge to streams the equivalent of 40 inches per year. Thomson and others (1956) showed that in one place the 7-day, 2-year flow (1937–55) of streams fed by Cretaceous aquifers was about 1.04 (Mgal/d)/mi^2—equivalent to about 22 inches of recharge.

DEVELOPMENT OF UNCONFINED SANDY AQUIFERS

Unconfined aquifers are similar to surface reservoirs in that water pumped from storage can be replenished by natural or artifical recharge. Recharge may be seasonal precipitation or it may be from another natural source (streams, lakes, or leakage from deeper aquifers). Overdraft, within limits, during dry periods leaves storage space for the surplus water available for recharge during wet periods—a condition that can be planned. During the period of high recharge, the intercepted ground-water outflow to the stream, although much greater in volume, is insignificant in relation to the total flow of moderate sized or large streams. The amount of intercepted ground-water flow to streams during low-flow periods is small because the normal ground-water contribution to the stream at that time is small. Planning the development of unconfined aquifers can involve many combinations of numbers and locations of wells and well fields relative to streams or other sources of recharge. Additional flexibility is provided by various methods of artifical recharge.

In widely separated well fields the recharge that falls upon a well field in an unconfined aquifer is not the only water available to those wells. Water flows to the pumping wells from all directions; thus the wells draw in water replenished by recharge over many square miles.

Removing water from storage in unconfined aquifers lowers the water level, thereby reducing the losses to evapotranspiration.

DEVELOPMENT OF CONFINED SANDY AQUIFERS

Only part of the recharge water in the outcrop area is removed by evapotranspiration, discharged as streamflow, or intercepted by withdrawals. Some moves downdip into the confined part of the aquifer.

Applying Darcy's Law and assuming a transmissivity of 27,000 ft^2/d and an average hydraulic gradient of 2.5 ft/mi, 0.5 Mgal/d will move downdip in a typical aquifer across each mile of the section. Increasing the hydraulic gradient in the confined aquifer (by establishing a cone of depression or by raising the head in the recharge area) would increase the downdip flow proportionately. Further application of Darcy's Law indicates that a 5-mile width of aquifer would transmit 10 Mgal/d if the hydraulic gradient were increased to 10 ft/mi.

The transmissivity of the aquifer establishes the first constraint on ground-water development. Acceptable pumping lifts in deepening cones of depression establishes the second constraint. Larger volumes of water would be made available by increasing the drawdown and the eventual extent of the cone of depression. Leakage from aquifers above and below might occur, providing additional water to that which moves laterally and diminishing the supply in the other aquifers. A temporary bonus is water released from storage as a result of lowering the pressure during the water-level decline. Artificial recharge in either the unconfined or confined zones of the aquifer will increase the available water supply. Where enough data are available, and through the use of analog and digital modeling, the optimum combination of recharge, hydraulic gradient, and pumping lift can be planned and problems can be minimized.

Certain effects on the environment, such as the potential for land subsidence, should be considered when large withdrawals from confined aquifers are planned.

DEVELOPMENT OF THE TERTIARY LIMESTONE AQUIFER

Callahan (1964, p. 26) points out that in the Valdosta, Ga., area the base flow of streams was relatively low in the fall of 1954, 0.014 to 0.054 ft^3/s/mi^2 or 0.009 to 0.035 (Mgal/d)/mi^2, but that much of the infiltrating rainfall of 1.25 ft^3/s/mi^2 (0.81 (Mgal/d)/mi^2) may have moved downdip in the principal artesian aquifer rather than emerging as base flows of streams. According to H. B. Counts (oral commun., Feb. 18, 1977), in November 1972 the total flow of the Withlacoochee River, an estimated 12 Mgal/d, drained into two sinkholes and much more could have been accepted.

Estimates of rates of recharge to the Tertiary limestone aquifer have been made by determining outflow through the aquifer (table 3) according to various published values or estimates of transmissivity and hydraulic gradients. These are given below for the several large areas.

In the Alachua-Bradford-Clay-Union County, Fla., area the recharge computation of 0.08 (Mgal/d)/mi^2 (table 3) is based on a transmissivity value derived from development of the upper 200 feet of the aquifer (Clark and others, 1964) in an area where the aquifer is about 1,000 feet thick.

In the Green Swamp (Florida) recharge area the outflow is limited by the cross-sectional area through which water must flow (Pride and others, 1966). Hence, although the transmissivity is higher in the western basin, the cross-sectional area through which discharge takes place is smaller, and the apparent recharge is smaller.

TABLE 3.—*Recharge rates to the Tertiary limestone aquifer based on estimates of flow through the aquifer*

	Area (mi^2)	Aquifer flow (Mgal/d)	Recharge rate per square mile		Equivalent precipitation (in/yr)
			(ft^3/s)	(Mgal/d)	
Florida:					
Alachua-Bradford Clay-Union Counties above the 75-ft contour.	525	45	0.132	0.085	1.8
Orange County	950	210	.34	.22	4.62
Polk County:					
Alfia and Peace Rivers	640	163	.395	.255	5.36
Kissimmee River	415	151	.536	.364	7.65
Green Swamp area	870	114.8	.204	.132	2.7 min.
		121.8	.217	.140	2.9 avg.
		166.2	.28	.191	4.0 max.
Western basin	160	22.1	.214	.138	2.9
Eastern basin	208	67.4	.501	.324	6.8
Hillsborough County:					
Local	1,040	450	.67	.432	9.1
Inflow	566	100	.274	.177	3.72

It was estimated that in Hillsborough County, Fla., in the late 1950's about 100 Mgal/d entered the county from the north and east through the aquifer, but there was additional local recharge of about 0.43 (Mgal/d/mi^2, equivalent to 9.1 inches of precipitation per year (Menke and others, 1961, p. 15). Results of other determinations are given in the table.

Although only 0.2 to 0.5 Mgal/d of water per square mile of recharge area moves downdip at present, potential production from the artesian beds in the aquifer is much greater. When gradients are increased, the flow is increased proportionally, and additional ground water that is now discharged to streams or springs would be captured. For instance, there are large springs northwest of where the Miocene deposits overlap older strata (fig. 10). These springs may represent potential recharge to the Tertiary limestone aquifer that cannot pass southeastward under the Miocene cover and through fault zones under existing hydraulic gradients.

Some or much recharge through the top of the aquifer will also be available if gradients are increased, and in some areas water from deeper sources may rise along faults. In some instances additional water would be available through capture of evapotranspiration loss and from inflow from streams originating outside the area.

Florida's two largest springs, Silver Springs and Rainbow Springs, each have a ground-water drainage area of about 625 square miles underlain by a thin or broken clay cover. The average combined flow for the two springs was almost 1,000 Mgal/d in 1968 (Faulkner, 1970). Discharge ranged from 0.5 to 1.3 (Mgal/d)/mi^2 (table 4). An annual recharge rate of 10.6 to 28 inches of rainfall is thus indicated. Additional water was probably lost by evapotranspiration from the water table.

Freshwater is discharged through springs from the Tertiary limestone aquifer in more than one-half (30,000 square miles) of the Florida land area. Estimated flow of springs cataloged by Callahan (1964) and

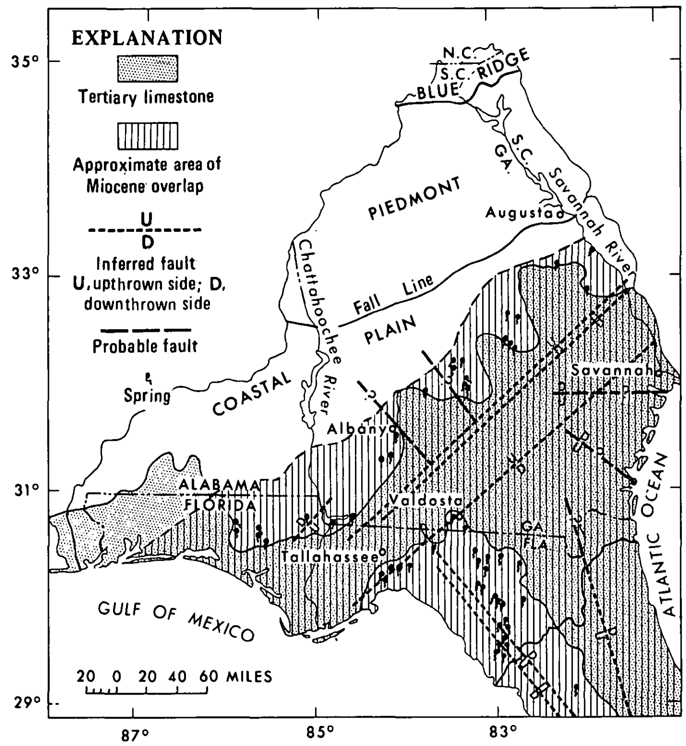

FIGURE 10.—Location of large springs in Georgia and northern Florida. (Modified from Callahan, 1964, figs. 5 and 7.)

TABLE 4.—*Recharge rates to the Tertiary limestone aquifer based on spring discharge*

	Area (mi²)	Total flow (Mgal/d)	Flow per square mile (ft³/s)	Flow per square mile (Mgal/d)	Precipitation (in./yr)
Florida Springs area	30,000	2,456 9,824	0.127 .5	0.082 .328	1.72 min. 6.88 max.
Silver Springs	625	348 531 833	.862 1.314 2.06	.557 .849 1.333	11.7 min. 17.8 avg. 28 max.
Rainbow Springs	625	315 468 684	.780 1.16 1.67	.504 .748 1.094	10.6 min. 15.7 avg. 22.9 max.
Northwestern Peninsular Florida above the 30–40-ft contours	1,950	95	.0754	.0487	1.0
North Central-Peninsular Florida above the 50–60-ft contours	3,770	181	.0743	.048	1.0
South Central Lake District above the 70-ft contour	6,000	544	.139	.09	1.9

Stringfield (1966) probably represents less than half the total discharge of all springs. With all cataloged springs considered at maximum flow, recharge is estimated to be about 0.32 (Mgal/d)/mi² or about 7 inches of rainfall.

The minimum flow of cataloged springs (half the total) is equal to 82 percent of the 3,000 Mgal/d of ground water pumped in all of Florida during 1970 (Murray and Reeves, 1977).

Spring discharge, like base-flow measurements, does not take into account water "lost" by underground flow downdip or by evapotranspiration. Hence, the value of 0.32 (Mgal/d)/mi² noted above is only an indication of the volumes available.

Recharge to the Tertiary limestone aquifer may occur through the Miocene cover at a very low rate. The rate is dependent on the thickness, the hydraulic conductivity of the overlying stratum, and the gradients involved. For instance, a highly conservative estimate of recharge through the thick Miocene cover in the Okefenokee Swamp area is about 0.035 (Mgal/d)/mi² under maximum development (Callahan, 1964, p. 27). An extremely large volume of water is in storage in the Tertiary limestone aquifer in Florida and Georgia. Seventy thousand square miles of Florida and Georgia are underlain by water-bearing strata with thicknesses ranging from several hundred feet to a maximum of about 2,000 feet (fig. 8). In northwestern Florida a part of the aquifer thickness shown includes aquifers below the Tertiary limestone aquifer. In the other States the volume of water stored in the Tertiary limestone aquifer is much less but is significant. Withdrawing much of this water in storage cannot be considered today in view of undesirable environmental effects that would occur.

Recharge to the Tertiary limestone aquifer would increase if water levels were lowered. About 70 percent of the 48 to more than 55 inches of rainfall in the area is lost by evapotranspiration. Where the area is riddled with sinkholes (fig. 7), it must be assumed that a high percentage of the rainfall will enter the ground and that much of it will be available to wells, either in the area of recharge or downdip in the confined part of the aquifer.

The volume of water that would move downdip through the upper 500 feet of a mile-wide section of the aquifer assuming a transmissivity of 60,000 ft²/d and a hydraulic gradient of 2 ft/mi is estimated to be 0.9 Mgal/d.

If gradients were increased to 4 ft/mi and if 1,000 feet of the aquifer were penetrated, 3.6 Mgal/d would flow through each linear mile of the aquifer (taken along the strike). In any one well field of limited areal extent, however, water will be drawn into that center of discharge laterally and from downdip, and "leakage" will take place through the roof and the floor. On the basis of calculations of maximum recharge as derived from the flow of springs (table 4), maintaining a discharge of 3.6 Mgal/d might require as little as 3 square miles of recharge area. With lowering of the water table and capture of some evapotranspiration loss, the recharge area required would be even smaller.

Maximum production of water supplies from wells will necessarily take into account the tendency to induce a lateral flow of saline water into the well field from the sea. Also, in certain areas there is a tendency for sinkholes to occur as a result of lowering water levels. In any event, monitor wells and mathematical models of the aquifer would be beneficial in understanding the behavior of the hydrologic system where maximum stress is approached.

The Tertiary limestone aquifer is exceedingly complex and differs greatly in its physical makeup from place to place. The generalizations given here can only bring out several of the pertinent factors that must be considered.

DEVELOPMENT OF AQUIFERS IN THE APPALACHIAN MOUNTAINS AND THE PIEDMONT

Success in developing ground-water supplies in the part of the region outside the Coastal Plain can be enhanced by applying scientific principles and modern techniques. Although many unsuccessful or low-yielding water wells are known, the ground-water potential of the upland area has probably been underrated. Numerous reports of high-yielding wells in this part of the region indicate that well-site selection based on various geologic and hydrologic criteria and exploratory techniques can result in very productive wells.

It is now know that remote-sensing techniques can identify the lines of structural deformation with which many highly productive wells are associated. Remote sensing may be useful in identifying soil or vegetation types that may be useful in locating ground water. Geophysical techniques may help in identifying and delineating solution openings in carbonate rocks.

Ground reconnaissance by trained personnel will improve the chances for locating satisfactory well sites. In a study of the occurrence of ground water in the Piedmont and Blue Ridge provinces, LeGrand (1967) found that topography and soil thickness are good indices for siting high-yielding wells. The most favorable locations are in valleys or draws that have a thick cover of alluvium, residuum, or weathered rock.

Except in cavernous carbonate-rock aquifers, the volume of ground water that is available is directly related to (1) the number, size, and depth of fracture openings and (2) the thickness and permeability of the soil cover. The soil cover, where present, is the source of recharge to the underlying fractures and also serves as a storage reservoir when saturated. Experience has shown that in many areas most interconnecting fractures occur within 150 feet of the land surface, and drilling deeper than about 300 feet is generally not justified (LeGrand, 1967, p. 5).

OTHER MANAGEMENT PROCEDURES

Management procedures other than those already discussed may be employed where the supply of potable ground water appears to be limited. Briefly they fall under these major headings: (1) use of multiple sources of water, (2) use of saline water for special purposes, (3) artificial recharge, and (4) conjunctive use of ground water and surface water.

MULTIPLE SOURCES OF FRESH GROUND WATER

Where fairly thick sand terraces border large losing streams, an inexpensive source of ground water can be developed (Paulson and others, 1962). Assuming that the river terrace is rather wide, maximum advantage might be taken of such a shallow aquifer by pumping naturally filtered river water from wells near the river during periods of high flow and by pumping from wells as far back from the river as practicable in the low-flow period.

In a situation where a supply from a confined aquifer is declining, wells in the terrace deposits might be relied upon to a maximum extent in the higher rainfall months during which time the deep aquifer would be drawn upon less. In the following rather brief low-flow river period, the confined aquifer might then supply much or all of the water needed.

Where wells in confined aquifers yield a reliable supply of highly mineralized water, river terrace water might be used for blending, and furthermore at times of maximum availability, excess freshwater from the shallow aquifer might be used to recharge the confined aquifer.

In most places where higher or inland terrace deposits are present, it is questionable whether those deposits would yield supplies large enough to function economically in a combination system; however, there is a possibility that higher inland terrace deposits may be as thick as 150 feet in some areas. The use of shallow well water as a source of municipal supply at Elizabeth City, N. C., has been noted above. In Norfolk, Va., as much as 60 gal/min has been developed from wells in terrace sands (Cederstrom, 1945).

USE AND MANAGEMENT OF SALINE WATER

In most places freshwater occurs in near-surface formations, whereas at greater depths the water is saline. Use of saline water after desalinization may relieve the draft on a freshwater aquifer.

In most aquifers, particularly those that are confined, pressure head increases with depth; therefore, where the shallow freshwater stratum is drawn upon heavily, the poor-quality water at greater depth may migrate upward. Where the beds underlying the freshwater aquifer are silts, lenticular clays, or massive rocks riddled with solution channels or broken by faults, contamination may become a real concern. Utilization of the deeper water for special purposes, therefore, would tend to reduce the head in the lower aquifer and minimize that concern as well as add to the total supply.

One problem of using deep poor-quality water is that hydraulic connection may be established in the borehole between the deep and shallow aquifers. Saline-water wells should, therefore, be grouted through the freshwater strata.

In special cases where contamination of the upper stratum has taken place, pressure-relief wells may be drilled to diminish head in the deeper stratum. This technique was attempted in Brunswick, Ga., to minimize the upward movement of saline water in the Tertiary limestone aquifer. However, sufficient reduction of pressure head to completely halt the upward flow of saltwater could not be effected owing to the high transmissivity of the saltwater aquifer (Harlan Counts, oral commun., Nov. 30, 1972).

In many downdip localities in Alabama, Mississippi, and the Carolinas, the deeper Cretaceous aquifers yield water that is fresh, whereas the overlying formations are saline. In such places the water developer—farmer, municipality, or industrialist—must bear the cost of a well 1,000 feet or more in depth or use shallower water of inferior quality. Additionally, an obvious disadvantage is the danger of contamination of freshwater aquifer by movement of saline water from above as heavy pumping from the deeper aquifer continues. To guard against degradation of water in the deeper aquifer, water users should be encouraged to use the more cheaply developed inferior shallow water to the fullest extent possible in order to maintain a low-pressure head in the formation.

In some areas where relatively shallow water is of inferior quality and freshwater is available only at considerable depth, nearly all users initially will develop the shallower source of inferior water. In these areas, taking advantage of normal pressure differentials (where deeper aquifers have higher heads), connector wells which would allow freshwater to move upward to dilute the saline water aquifer might be desirable.

In an ideal situation a connector well would be centrally located with reference to several heavily pumped shallower wells or to a local supply consisting of many private wells. With maintenance of lower head in the upper formation through heavy withdrawals for air conditioning or other purposes not requiring the highest quality water, normal upward flow of freshwater through the connector well would be accelerated, and in time all wells in the general area might benefit from an improvement in the quality of water. Owing to normal head differences, even during periods of no pumping, flow would continue upward and outward into the shallower stratum, although the flow would be less than when pumps are operating.

Where the deep aquifers contain saline water and there is surplus water under higher pressure in shallow aquifers, the system could be reversed, thereby storing freshwater in a saline-water reservoir.

In most confined aquifers there is a downdip transition from freshwater to saline water. Planners may consider measures to forestall lateral or updip movement of saline water into centers of freshwater withdrawal. An example is the situation at Montgomery, Ala., where water from both the Eutaw and Gordo Formations is of good quality (Knowles and others, 1963). West of Montgomery, the chloride content of water in the Eutaw Formation increases rapidly. Flowing wells tapping the Eutaw Formation west of Montgomery along the Alabama River lower the head of water in the Eutaw Formation and bleed off highly saline water, thereby affording a measure of long-term protection to the Montgomery supply. The flowing wells discharge highly saline water (1,150, 1,330, and 1,600 mg/L chloride).

Where a well field is threatened by lateral intrusion of poor-quality water, including the intrusion of seawater, artificial recharge by injection wells, connector wells, or a combination of water spreading and connector wells, might be employed to create freshwater barriers between the well field and the source of contamination.

ARTIFICIAL RECHARGE OF GROUND WATER

Ground-water discharge accounts for a large part of streamflow; hence, development of ground-water supplies may not add greatly to the total available supply of water. Additional water can be made available to the system, however, by reducing losses due to evapotranspiration, by recycling of water, and by interception of high-flow components of streamflow. Interception of high streamflow in the past has been almost entirely accomplished by the construction of surface reservoirs. However, in recent years in California the recharging of underground reservoirs with water pumped from distant streams is widely practiced. The practice is less common in the mid-western States and unusual in the eastern States.

Methods range from collecting storm runoff in pits to constructing canals and pipelines that bring water to the recharge basins or injection wells. Difficulties attend these efforts in places, depending on type of water used, hydraulic characteristics, climatological conditions, and the methodology employed. Nevertheless, the practicality of artificial recharge is well established, and we may expect that, generally, technology will provide satisfactory answers to most problems.

In the arid West, ground-water levels generally occur well below the level of ephemeral streams, and there is storage space for whatever recharge water can be made available. In the humid Southeast, however, ground-water levels generally are fairly close to the surface. Addition of water to the unconfined aquifers will be limited by space requirements and may only promote more rapid lateral migration of that water to the streams.

Storage space can be provided by pumping during the dry periods, which are times of maximum demand and low streamflow. Water levels will decline, and space will then be provided for receiving and storing the excess water that becomes available during wet periods.

The most likely sites in the region for artificial recharge are those places where large cones of depression or significant water-level declines have been caused by ground-water withdrawals.

The techniques of water spreading by flooding, or by ditches, furrows, and pits, are outlined generally by Muckel and Schiff (1955). The effectiveness of recharge by spreading water on the surface, as opposed to pits or injection wells, depends upon the soil type, the type of cover material, and of course, the permeability of the formation beneath the soil cover. Bare soils tend to need treatment, but soil covered with undisturbed vegetation is highly receptive to infiltration. Intermittent flooding and drying and chemical treatment of the soil are beneficial in some areas.

Losing streams are uncommon in the East except in limestone terrain. Where streams lose water naturally or as a result of pumping from connected aquifers, small low-head dams would facilitate infiltration.

From Mississippi to southern North Carolina the sandy sediments store a tremendous volume of water. The amount of water that will drain from a sandy column upon lowering of the water table (specific yield) ranges from 15 to 20 percent in medium- to coarse-grained sediments. Assuming a value of 20 percent, a square mile of unconfined sandy reservoir in which the water level could be lowered 10 feet would have a capacity of 418 million gallons—equal to 24 inches of water or a pumping rate of 1.14 Mgal/d for 12 months. In this situation, assuming an annual recharge rate of 6 inches, there is an annual recharge deficit of 18 inches of water or 0.86 Mgal/d that can be provided by artificial recharge during a high rainfall season.

The thick weathered rock mantle (saprolite) that lies above consolidated rocks in the southern Piedmont has a high storage capacity (Stewart, 1962), but depending on the clay content, vertical drainage may be slow. Repeated flooding of the saprolite surface may be highly effective and preferable to trying to increase storage by injection wells that penetrate fresh rock at some depth. Flooding might be accomplished by constructing distributaries from large streams and rivers that would divert part of the high flows. In some instances, abandoned quarries in the Piedmont may lose water through fissures in the walls and floor and thus function as large recharge pits.

Where confined aquifers are intensively developed, the potentiometric surface may be greatly depressed. An eventual natural limitation on ground-water development in some areas may be forestalled by employing artificial recharge. Recharge by injection of water through wells built for the purpose is an alternate method to spreading water. Injection through wells is the only method for immediately recharging confined aquifers. The method is especially attractive if accomplished by gravity rather than under pressure, thereby conserving energy. The injection-well method of storing water or recharging aquifers is feasible where surplus water that is chemically and physically suitable for the operation is available. The characteristics of the available water must be such that clogging of the well screen and the aquifer are minimal.

Where rivers are bordered by sandy terrace deposits or other thin shallow aquifers, gravity recharge connector wells might be constructed to conduct naturally filtered water to deep confined aquifers in which the head is depressed. The operation might be restricted to periods when river stage rises above some predetermined point. Such recharge wells would be particularly suited to areas underlain by the highly permeable limestone aquifers.

This method might be considered for parts of Florida and along the Atlantic coast into South Carolina. Heavy draft is imposed upon the limestone aquifer in those areas, and additional draft may be expected in the future. Hence, maintaining a relatively high head upgradient from major well fields might do much to forestall potential saltwater intrusion and in any event would help minimize pumping costs.

Cool water is necessary in the development of water supplies for some industrial uses. In Hopewell, Va., cold surface water has been recharged during the winter months through wells that are ordinarily pumped to supply a chemical plant. Cold water stored temporarily in the ground and pumped out during the hot summer season is particularly advantageous in processing operations (Cederstrom, 1945).

Injection wells ending in sandy sediments might need to introduce water under pressure in order to achieve a significant (economically practical) rate of acceptance. High efficiencies might be achieved if the injection and formation waters are compatible and if the water injected is free of gases and particulate matter. However, chemical or biochemical actions that form slimes may occur, which would reduce the efficiency. Where hard waters are injected into aquifers, carbonate precipitates would be likely to form unless the waters were pretreated. Turbidity would also have to be reduced to insignificant amounts. Where the aquifer to be injected is a cavernous or highly shattered limestone or dolomite, as in the Appalachian Highlands and in some Coastal Plain formations, there may be little or no difficulty with clogging. In all instances, treatment to remove pollutants would be desirable.

RECHARGE USING EFFLUENT FROM TREATED SEWAGE

About 1,300 sewage-disposal systems in the United States in 1967 disposed of 19.8 billion gallons of treated sewage effluent by land-disposal methods (Wilson and Beckett, 1968). About two-thirds of these systems were used specifically for waste-water treatment as such, and one-third for crop benefits gained.

This practice may be considered as a method of continuous artificial recharge. The controlled spreading or spraying of treated sewage effluent on a soil surface allows oxidation and plant and biochemical action to take place, which upgrades the character of that water. After percolation down to the unconfined aquifer, the purified effluent may move into the confined aquifers or laterally to springs and streams. The aquifers are recharged or streamflow is augmented, presumably without deleterious ecological and health effects.

Disposal of effluent proceeds more slowly than other methods of recharge, allowing ample time for purification by plants and soils. Ground-water recharge should take place, however, even when only light applications of effluent are available, because the soil is kept near the saturation point and summer rains will tend to percolate through to the water table instead of being retained to satisfy soil-moisture requirements.

The sandy beds in the outcrop areas of the post-Paleozoic aquifers seem ideal for land disposal of effluent from treated sewage. The climate is favorable for functioning of digestion lagoons all year, the permeability of the surficial materials is high, the sands are thick, and in many places the water level is low enough to favor the process. Tremendous areas covered by the coastal sandy terrace formations likewise offer ideal sites for land disposal of effluent.

In some instances, as a result of the land disposal of treated sewage effluent, the quality of stream water might be upgraded to the extent that less treatment would be required by some of the downstream consumers. More water would be available for downstream consumers or, conversely, less water from upstream would have to be provided to maintain flow at a standard required for dilution of contaminants.

Land disposal of treated sewage effluent in relatively impermeable terrain may be feasible even though the geologic setting is quite different from that in the sandy areas. Here the objective would be to provide water for dry-weather irrigation and augmentation of flow of small streams.

Briefly, on the presumption that there are no adverse environmental effects, the process of land disposal of treated sewage offers a constant source of water for ground-water recharge or low-flow augmentation of streams, provides a solution to the problem of finding space for disposal of solid sewage waste, eliminates gross pollution of surface streams, and may upgrade the quality of soil in disposal areas.

FRESHWATER STORAGE IN SALINE AQUIFERS

Artificial recharge offers some significant advantages in those parts of the Coastal Plain where sandy confined strata are now saturated with saline water, as in northeastern North Carolina. Freshwater can be injected through wells and stored in the saline-water confined beds and pumped back for later use. The feasibility of storage under such conditions has been demonstrated (Cederstrom, 1957, p. 45–52), and further work to determine quantitative and other factors involved is now underway (Brown and Silvey, 1977; Kimbler and others, 1973).

Some coastal areas where there is a short but fairly high summer demand may find this method of increasing their supply advantageous as an alternative to piping in freshwater from inland wells or surface reservoirs. The large volume of water available from shallow wells in a high-rainfall winter season may suffice for recharge operations to the confined saline-water beds.

LOW-FLOW AUGMENTATION OF STREAMS

Low-flow augmentation is a technique for increasing the volume of streamflow by releasing stored water from reservoirs or by discharging water from wells into streams or reservoirs. This method is commonly practiced to increase streamflow during dry periods, thereby increasing the water supply for downstream users. It is also a technique for improving the capacity of the stream to accept and dilute wastes or to provide a better recreational environment.

Within the belt of Upper Cretaceous formations in Mississippi and Alabama, the chalk beds of the Selma Group are an extreme example of low-permeability formations. Streams originating within the chalk belt or impermeable clay belts are intermittent, flowing during and shortly after heavy rains. In dry weather the stream bed becomes dry, and in wet weather surface runoff is almost the equivalent of rainfall (Pierce, 1966). Chalk and clay offer a minimum of storage and thus increase the effect of floods. Streams originating in these areas cannot be sources of water supply during the dry seasons without storage.

Where justified by economic, environmental, or general esthetic considerations, this situation could be ameliorated by development of the aquifers underlying the streams. Widely spaced wells might be located along the streams and discharge directly into the streams or into minor tributaries. Examples of aquifers that might be used in this way are the Eutaw Formation and the Tuscaloosa Group.

Ground water from some aquifers would make a particularly desirable dilutant for highly contaminated streams; also, because ground water is somewhat oxygenated it would act positively in reducing biochemical-oxygen demands.

In downdip locations deep wells yielding mineralized water might be constructed where such water is considered acceptable for augmenting the flow of streams with a low discharge. If the discharge of the receiving stream is low, addition of high-chloride water may not be tolerable, but in a stream with a higher discharge the increase in chloride concentration may be acceptable. Although esthetics would be served, the extent to which the ecosystem (if aquatic life is present) would be affected by dilution of a highly contaminated stream with saline ground water would have to be considered.

Areas that have desirable locations for users requiring moderate volumes of water for cooling purposes might benefit from low-flow augmentation. A rise of stream-water temperature might be acceptable in areas where the streams would otherwise be dry during low-rainfall seasons and where aquatic life is absent. Another effect of augmenting low flow with ground water that might be desirable is the dilution of small polluted flows.

Ground water may also be used in conjunction with surface-water reservoirs intended for low-flow augmentation. Depending on the geological setting and environmental considerations, ground water may be available to augment impounded surface water.

One advantage of the use of supplemental wells is that their yield is not dependent upon rainfall in any particular year; thus even a relatively small amount of water pumped over a period of many months may furnish a very desirable increment to a surface-water supply. Furthermore, where wells are used for brief periods of time, ground-water withdrawals may be at rates greater than the aquifer can support continuously. Thus a well field might be pumped at two or three times the sustained yield of the aquifer if there is ample recharge during intervening periods of no pumping.

GROUND WATER FOR PUMPED STORAGE

In some areas there are extensive aquifers that are readily recharged. Transfer of water from these aquifers to pumped-storage reservoir sites might help alleviate peak power shortages if the combination of aquifers and storage sites can be found. In localities where power is generated, the power excess generated in off-peak hours could be used for pumped storage of water. In water-short areas diversion of streamflow for storage may not be desirable where that flow is needed for dilution or where the flow is allocated to downstream users.

In the Piedmont, pumped storage of ground water is generally not practicable. In the Valley and Ridge Province, pumped storage might be practicable if high-yield wells can be constructed tapping major fractures of fault zones.

CONJUNCTIVE USE OF GROUND WATER AND SURFACE WATER

Conjunctive use is the technique for integrating withdrawals of surface water and ground water in order to provide maximum utilization of these resources. In many areas an economical and satisfactory water supply might be developed by taking advantage of both ground- and surface-water sources where neither source is sufficient to supply the total demand at all times.

With both sources developed, surface reservoirs may be drawn upon heavily in the high rainfall season. In the dry season, a ground-water reservoir not subject to short-term vagaries of precipitation might provide all or nearly all the supply and preclude possible expensive additions to the surface-supply system. Most aquifers may be overpumped for a period of weeks or a few months, discharging much more water than if they were in continuous use and at the same time providing more storage space for recharge.

Recharging aquifers by injecting excess water available from surface sources may be an economical operation where a water- treatment plant is already in operation for treatment of the surface water and if the cost of the treatment and well maintenance are not prohibitive.

Where surface supplies carry a heavy waste load, the cost of treatment of that water may be excessively high at times of low flow. At such times maximum reliance may be placed upon a well supply, granting the presence of suitable aquifers. Conversely, surface water of good quality may be mixed with poor-quality ground water to increase the total supply.

GROUND-WATER PROBLEMS

One of the most critical ground-water problems in the South Atlantic-Gulf Region is the regional lowering of potentiometric surfaces and the development of extensive cones of depression in areas where large ground-water withdrawals have been made. In some areas of northeastern Mississippi withdrawals of water from the Eutaw Formation are exceeding the volume of water that the aquifer can transmit. At Mobile, Ala., and in some areas in Florida, concentrated withdrawals have caused intrusion of seawater. Contamination of the Tertiary limestone aquifer by saline water at Brunswick, Ga., is attributed to incomplete flushing of connate saline water (Gregg and Zimmerman, 1974, p. 36). In other areas, the lowered heads in cones of depression have induced the upward migration of saline water from underlying aquifers—a potential threat where confining beds are leaky or where there is faulting.

Notable ground-water declines have occurred outside the region in the Franklin, Va., area, where water levels have declined about 185 feet since 1937–39 (Brown and Cosner, 1974) and the cone of depression extends into northern North Carolina. At Brunswick, Ga., pumpage of over 100 Mgal/d has induced upward migration of saline water (Krause and Gregg, 1972). In central Florida large industrial and agricultural withdrawals have lowered water levels in confined aquifers more than 50 feet since 1934 (Kaufman, 1967). In North Carolina dewatering for open-pit mining has lowered the potentiometric surface below sea level in an area of about 800 square miles (Peek, 1969, p. 12).

There is potential for saltwater encroachment along much of the Atlantic Coast and in some areas on the Gulf Coast where shallow aquifers are hydraulically connected to the sea or to estuaries. Withdrawals can cause lateral movement of saline water, and natural factors such as inundation by hurricane flooding can change the position of the freshwater-saltwater interface in estuaries.

Head differentials permit the movement of water through boreholes or damaged casing from one aquifer to another. Generally, the direction of movement is upward, and where the deeper confined aquifers contain water of undesirable quality, the shallower aquifers become contaminated. Deep water wells and oil-test wells are the common potential sources of this type of contamination.

Lowered water levels result in correspondingly lower pumping levels. Obviously, there is a direct cost relation between total pumping head and energy consumption. Excessive pumping lift can be attributed either to inefficient well construction or to water-level declines. Many water wells in the region have excessive pumping lifts due to poor well design or improper completion and development methods.

Land subsidence is a potential threat where large volumes of ground water are pumped from aquifers in uncompacted sediments. The areas in the South Atlantic-Gulf Region that have the highest subsidence potential are Late Eocene and Quaternary deposits near the coastline where the effects would be most noticeable. Subsidence of as much as 4 inches was reported at Savannah, Ga. (Davis and others, 1963). More spectacular are sinkhole collapses related to ground-water withdrawals. Examples of this activity, some of which were catastrophic, have been reported by Newton and Hyde (1971, p. 1) and Kaufman (1967, p. 30). Sinkholes are restricted to those areas underlain by carbonate rocks.

Mining at some places causes problems of ground-water quantity and quality. Most public attention today is directed toward strip and pit mining. These operations may result in actual destruction of parts of shallow aquifers, and water-soluble mining products and byproducts can contaminate ground-water supplies. The need for low-grade coal and lignite to help meet energy requirements will intensify the problem caused by mining.

Landfills, considered an economical method for disposing of solid wastes for many years, commonly have been operated without consideration of the character and movement of leachate and without regard for the potential effect on water supplies. Improperly located or managed landfills can be expected to be a major source of ground-water contamination.

The technology of deep-well injection is now quite advanced but not without problems. Most of the injection operations are for waste disposal, and some wastes are highly toxic. The U.S. Geological Survey and other agencies and industries are conducting research to evaluate techniques and potential effects of injection. Current studies in the region, involving the Geological Survey, include ascertaining the feasibility of storing materials, liquids, and gases in artificial cavities in salt domes and in the extensive impermeable clay and chalk strata. The protection of ground-water resources is a primary consideration in planning injection for disposal or storage.

Problems with natural ground-water quality in the region are generally the result of excessive concentrations of iron, chloride, hydrogen sulfide, fluoride, or color. Acidic (low pH) and hard waters are common. Some of these objectional constituents and properties are amenable to simple water treatment; however, the cost of treatment for excessive color, chloride, or fluoride may be prohibitive.

The unequal distribution of the ground-water resources in the South Atlantic-Gulf Region is a significant factor in future economic development. Generally, the largest undeveloped ground-water supplies are in the Coastal Plain. Generally, the available supply increases as aquifers thicken and become more numerous seaward. Because water-resources development engenders water problems, most of the major problems in the future can be expected in coastal areas.

DATA NEEDS

This description of the round-water resources of the South Atlantic-Gulf Region is based on data and interpretations resulting from geologic and water-resources studies. The volume of data available and the complexity of evaluating, planning, and managing water-resources development dictate the use of computer analysis and modeling for optimum utilization of these resources. A basic need is for additional data in areas where coverage is sparse and for studies that will point out areas where water problems may be-anticipated.

An immediate need is for management of the ground-water system in areas that have problems related to concentrated withdrawals. Digital and electric-analog models are useful tools for approximating solutions to hydrologic and related problems. Almost as urgent is the need for modeling entire aquifers or aquifer systems. Models are capable of simulating effects of past, present, and projected ground-water withdrawals—basic needs in planning and managing water-resources development; however, model projections should be used with caution.

More data are needed about the magnitude of and the potential for saltwater encroachment in the Coastal Plain aquifers. Modeling can be an effective tool in studies related to this problem.

Artificial recharge, subsurface storage of liquids and gases, and subsurface disposal of wastes employ similar methodologies. Studies are needed to develop more satisfactory methods of operation and management in these fields. Many more data are needed on the properties of potential reservoir materials below the freshwater zone and on the alternation, diffusion, and dispersion of injected substances.

Research is underway to ascertain the offshore extent of freshwater aquifers along the Atlantic coast. There is a need to intensify these studies and to expand the work to the Gulf Coast. The importance of these potential sources of water in the development of the coastal areas cannot be overemphasized.

Saline water as an economic resource has received little attention. Highly mineralized water and brines may contain minerals of economic value.

Further studies of land subsidence and sinkhole collapse, particularly with reference to prediction and prevention of catastrophic occurrences, are needed.

Use of reclaimed water will become more significant in total development of the resource. Studies are needed to find methods of reclaiming economic products from waste water. Also, the increasing cost of energy suggests the need for methods of recovering heat from cooling water.

Surface water and ground water are closely related in the highly permeable formations in the Coastal Plain. Special studies are needed to evaluate and predict the effects of changes in either regimen.

SUMMARY AND CONCLUSIONS

The rapid population increase and industrial growth now underway in the South Atlantic-Gulf Region will accelerate as the energy situation becomes more critical. The reason is that economic development will favor areas in the Nation that have moderate climate, access to ample energy, abundant labor, and adequate water supplies.

With planning and management, the ground-water supply in the South Atlantic-Gulf Region is adequate to meet needs through 2020 if one-forth of the estimated ground-water yield of 78,000 Mgal/d in the region can be withdrawn. In 1970, 4,500 Mgal/d, about 14 percent of all water pumped in the region, was obtained from ground-water sources. If the same use ratio for ground water and surface water continues, projections indicate that about 12,200 Mgal/d would be needed in 2000 and about 18,200 Mgal/d in 2020. The projections indicate that consumptive use will account for only about 6 percent of the total, so most of the water will be available for reuse.

Although virtually the entire region is underlain by aquifers that will yield more than 50 gal/min to wells, the most prolific sources of ground water are (1) the Tertiary limestone aquifer, (2) the Miocene, Pliocene, and Quaternary sand and gravel aquifers that are more or less interconnected, and (3) the Tuscaloosa sand and gravel aquifers. The Tertiary limestone aquifer and the Miocene-through-Quaternary aquifers are the most prolific sources of water owing to extremely high transmissivities and favorable conditions for direct recharge from precipitation and streams. The Tuscaloosa aquifers, although capable of large yields, have a more limited potential owing to the relatively small recharge areas and the generally restricted interconnection with other aquifers.

Rapid advances in computer science and in mathematical and electronic modeling will provide useful tools for planners and managers; however, these tools will be only as accurate as the data on which their output is based. The collection, assimilation, and analysis of dependable ground-water data are prerequisites for successful planning and management.

Management of the major and minor aquifers will require establishing the optimum sustained yield of the aquifers. The optimum sustained yield of the aquifer is the condition whereby the maximum long-term withdrawal is accomplished with a minimum of undesirable effects. Undesirable effects include excessive diversion of streamflow either by capture of ground-water discharge to streams or by increasing ground-water recharge from streams; water-level declines that result in uneconomical pumping lifts or land subsidence; and intrusion of poor-quality water from the sea, estuaries, surface sources, other aquifers, or other parts of the same aquifer.

Conjunctive use of surface and ground water and the optimum sustained development of aquifers, or any controlled development of water resources, are administered by water-management agencies. The most efficient utilization of the resource may require transferring water from one management area (for example, a basin) to another, suggesting the need for coordination among agencies.

Among the first problems confronting water managers will be the redistribution of withdrawals to minimize or terminate saltwater encroachment, reduce the extent of extremely deep cones of depression, and control pollution. Extraordinary coordination of water-management agencies may be required in the instances where cones of depression extend over hundreds of square miles.

Efficient use of ground water by the primary users is a means of conserving water resources by reducing the draft on the aquifer. One of the major considerations in water-deficient areas is the reuse of the waste water. Some waste water requires minimal treatment for many uses, and there are some uses for waste water containing a large load of suspended and dissolved materials. Beneficial use for water discharged from heat-exchange applications is highly probably.

Widespread artificial recharge of aquifers with surplus surface water and treated waste water (or in special instances, untreated waste water) is a inevitable, and high priority should be given to developing and applying this technique. Artificial recharge by wells is especially attrative if accomplished by gravity rather than under pressure, thereby conserving energy. Artificial recharge by spreading can be environmentally acceptable.

Less than 10 percent of the region's mean annual runoff (197,000 Mgal/d), if used for artificial recharge, could meet the entire projected requirement for ground water without significantly affecting streamflow. Systematic recharge of major aquifers during wet seasons would offset the effects of the removal of large quantities of ground water from storage, limiting the spread of cones of depression and avoiding undesirable effects such as large pumping lifts and saltwater intrusion.

One of the basic considerations in developing groundwater sources is the effect on the low flow of streams and on vegetation. These environmental considerations are among the constraints that should be considered in the optimum development of aquifers.

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GPO 689-035