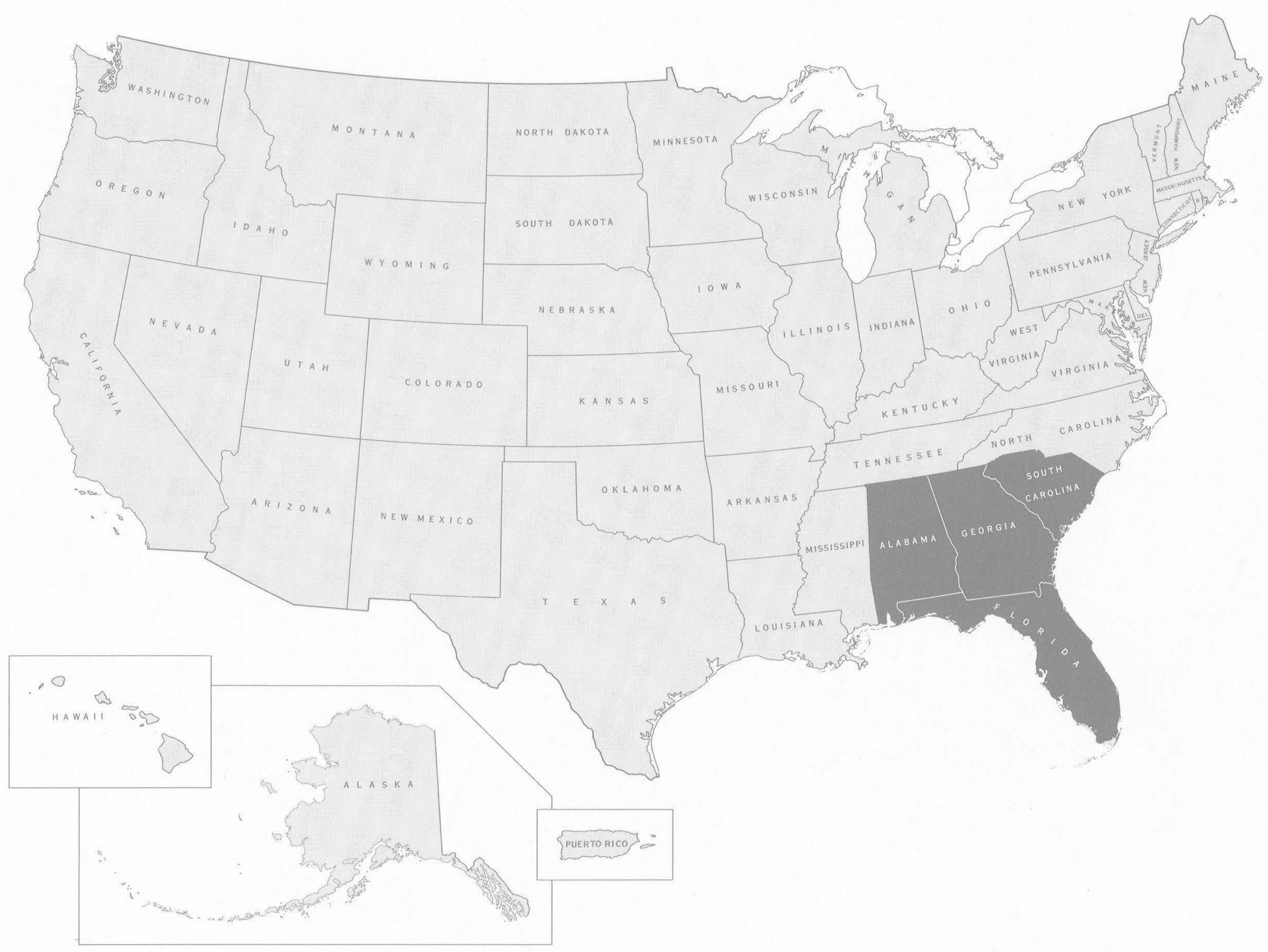
Ground Water Atlas of the United States

Segment 6

Alabama
Florida
Georgia
South Carolina



HYDROLOGIC INVESTIGATIONS ATLAS 730-G
U.S. Geological Survey

GROUND WATER ATLAS OF THE UNITED STATES
Hydrologic Investigations Atlas 730-G

FOREWORD

The Ground Water Atlas of the United States presents a comprehensive summary of the Nations's ground-water resources, and is a basic reference for the location, geography, geology, and hydrologic characteristics of the major aquifers in the Nation. The information was collected by the U.S. Geological Survey and other agencies during the course of many years of study. Results of the U.S. Geological Survey's Regional Aquifer-System Analysis Program, a systematic study of the Nation's major aquifers, were used as a major, but not exclusive, source of information for compilation of the Atlas.

The Atlas, which is designed in a graphical format that is supported by descriptive discussions, includes 13 chapters, each representing regional areas that collectively cover the 50 States and Puerto Rico. Each chapter of the Atlas presents and describes hydrogeologic and hydrologic conditions for the major aquifers in each regional area. The scale of the Atlas does not allow portrayal of minor features of the geology and hydrology of each aquifer presented, nor does it include discussion of minor aquifers. Those readers that seek detailed, local information for the aquifers will find extensive lists of references at the end of each chapter.

An introductory chapter presents an overview of ground-water conditions Nationwide and discusses the effects of human activities on water resources, including saltwater encroachment and land subsidence.

Dallas L. Peck

DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., *Secretary*

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, *Director*

CONVERSION FACTORS

For readers who prefer to use the International System (SI) units, rather than the inch-pound terms used in this report, the following conversion factors may be used:

Multiply inch-pound units	*By*	*To obtain metric units*
	Length	
inch (in)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon per minute (gal/min)	0.06309	liter per second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
billion gallons per day (Bgal/d)	3.785	million cubic meters per day (Mm^3/d)
	Temperature	
degree Celsius (°C)	9/5(°C)+32=°F	degree Fahrenheit (°F)

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

ATLAS ORGANIZATION

The Ground Water Atlas of the United States is divided into 14 chapters. Chapter A presents introductory material and nationwide summaries; chapters B through M describe all principal aquifers in a multistate segment of the conterminous United States; and chapter N describes all principal aquifers in Alaska, Hawaii, and Puerto Rico.

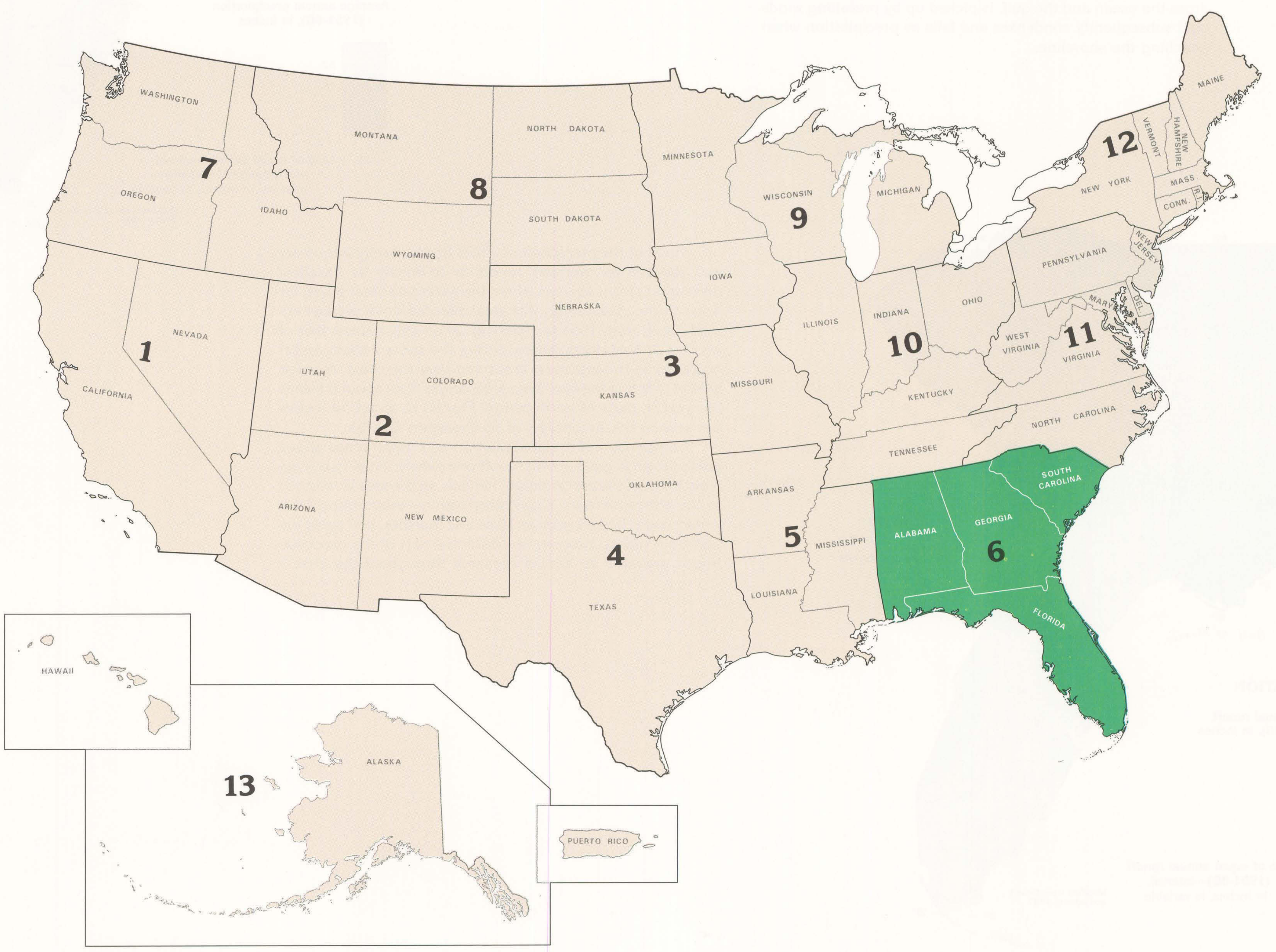
Segment Number	*Chapter content*	*Hydrologic Atlas Chapter*
–	Introductory material and nationwide summaries	730-A
1	California, Nevada	730-B
2	Arizona, Colorado, New Mexico, Utah	730-C
3	Kansas, Missouri, Nebraska	730-D
4	Oklahoma, Texas	730-E
5	Arkansas, Louisiana, Mississippi	730-F
6	Alabama, Florida, Georgia, South Carolina	730-G
7	Idaho, Oregon, Washington	730-H
8	Montana, North Dakota, South Dakota, Wyoming	730-I
9	Iowa, Michigan, Minnesota, Wisconsin	730-J
10	Illinois, Indiana, Kentucky, Ohio, Tennessee	730-K
11	Delaware, Maryland, New Jersey, North Carolina, Pennsylvania, Virginia, West Virginia	730-L
12	Connecticut, Maine, Massachusetts, New Hampshire, New York, Rhode Island, Vermont	730-M
13	Alaska, Hawaii, Puerto Rico	730-N

Ground Water Atlas of the United States

Segment 6

Alabama, Florida, Georgia, and South Carolina

By James A. Miller



CONTENTS

INTRODUCTION

The four States—Alabama, Florida, Georgia, and South Carolina—that comprise Segment 6 of this Atlas are located adjacent to the Atlantic Ocean or the Gulf of Mexico, or both. These States are drained by numerous rivers and streams, the largest being the Tombigbee, Alabama, Chattahoochee, Suwannee, St. Johns, Altamaha, and Savannah Rivers. These large rivers and their tributaries supply water to cities such as Columbia, S.C., Atlanta, Ga., and Birmingham, Ala. However, the majority of the population, particularly in the Coastal Plain which comprises more than one-half of the four-State area, depends on ground water as a source of water supply. The aquifers that contain the water are mostly composed of consolidated to unconsolidated sedimentary rocks, but also include hard, crystalline rocks in parts of three of the States. This chapter describes the geology and hydrology of each of the principal aquifers throughout the four-State area.

Precipitation is the source of all the water in the four States of Segment 6. Average annual precipitation (1951-80) ranges from about 48 inches per year over a large part of central South Carolina and Georgia to about 80 inches per year in mountainous areas of northeastern Georgia and western South Carolina. (**fig. 1**) In general, precipitation is greatest in the mountains (because of their orographic effect) and near the coast, where water vapor, which has been evaporated primarily from the ocean and the gulf, is picked up by prevailing winds and subsequently condenses and falls as precipitation when reaching the shoreline.

Figure 1. *Average annual precipitation (1951-80) ranges from about 48 to about 80 inches.*

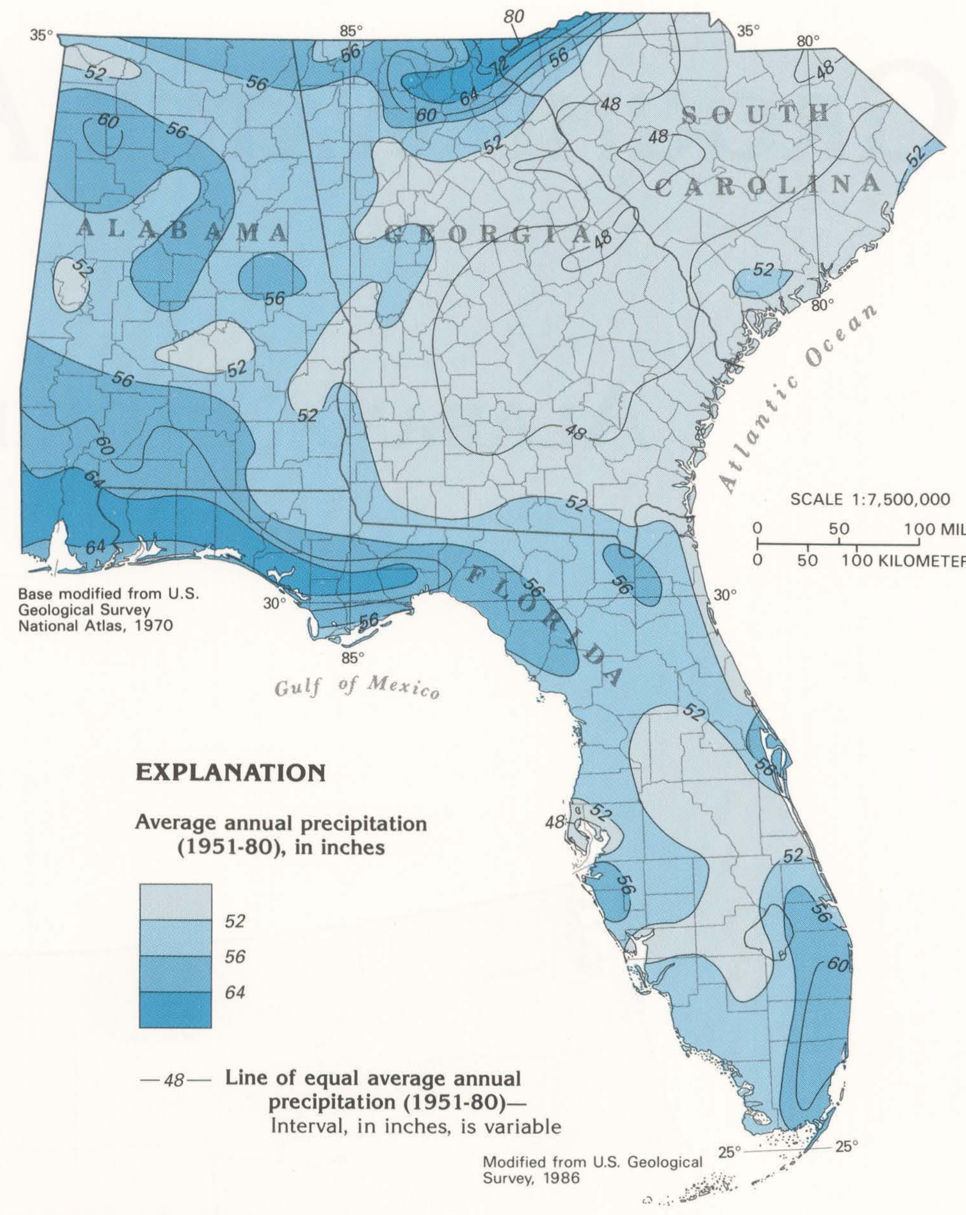
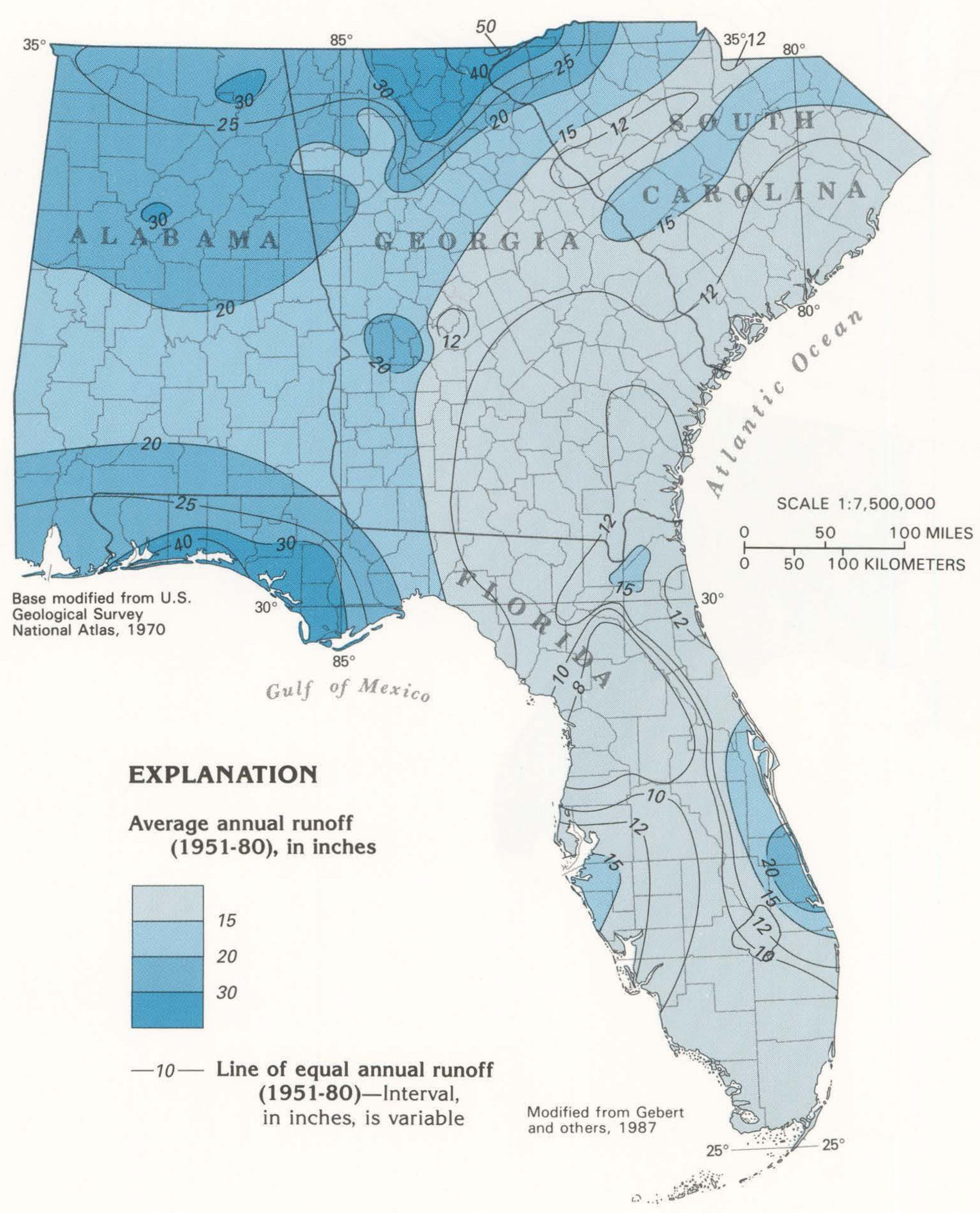


Figure 2. *Average annual runoff (1951-80) generally has the same areal distribution as precipitation; that is, runoff is greater where precipitation is greater.*



Much of the precipitation either flows directly into rivers and streams as overland runoff or indirectly as baseflow discharging from aquifers where the water has been stored for a short time. Accordingly, the areal distribution of average annual runoff from 1951 to 1980 (**fig. 2**) directly reflects that of average annual precipitation during the same period; runoff is greater in mountainous areas and near the coast. Average annual runoff in the four-State area ranges from about 8 inches per year in parts of north-central Florida to about 50 inches per year in the mountains of northeastern Georgia.

Comparison of the precipitation and runoff maps shows precipitation is greater than runoff everywhere in the four-State area. Much of the precipitation that falls on the area is returned to the atmosphere by evapotranspiration—evaporation from surface-water bodies, such as lakes and marshes, and transpiration from plants. However, a substantial part of the precipitation is available for aquifer recharge throughout the area.

MAJOR AQUIFERS

There are numerous aquifers in Segment 6, that range in composition from unconsolidated sand of the surficial aquifer system to hard, crystalline rocks of the Piedmont and Blue Ridge aquifers. These aquifers are grouped into nine major aquifers or aquifer systems on the basis of differences in their rock types and ground-water flow systems. An aquifer system consists of two or more aquifers that are hydraulically connected—that is, their flow systems function similarly, and a change in conditions in one aquifer affects the other aquifer(s).

The areas where eight major aquifers are exposed at land surface are shown in **figure 3** (see opposite page). Many of these aquifers extend underground far beyond the limits of outcrop, and, accordingly, may be used for water supply in much larger areas than the size of their outcrop may indicate. In places, deeper aquifers that contain freshwater underlie the major aquifers mapped here. For example, in southeastern South Carolina, the surficial aquifer system shown on the map is underlain by the Floridan aquifer system, which in turn is underlain by the Southeastern Coastal Plain aquifer system, all of which contain mostly freshwater. In other places, such as the areas where aquifers of the Piedmont, Blue Ridge, Valley and Ridge, and Appalachian Plateaus physiographic provinces are mapped, deeper aquifers are nonexistent. In places in Alabama, Georgia, and Florida, a clayey confining unit that overlies the Floridan aquifer system is exposed at land surface, and wells need to be drilled through this clayey confining unit to penetrate the underlying aquifer.

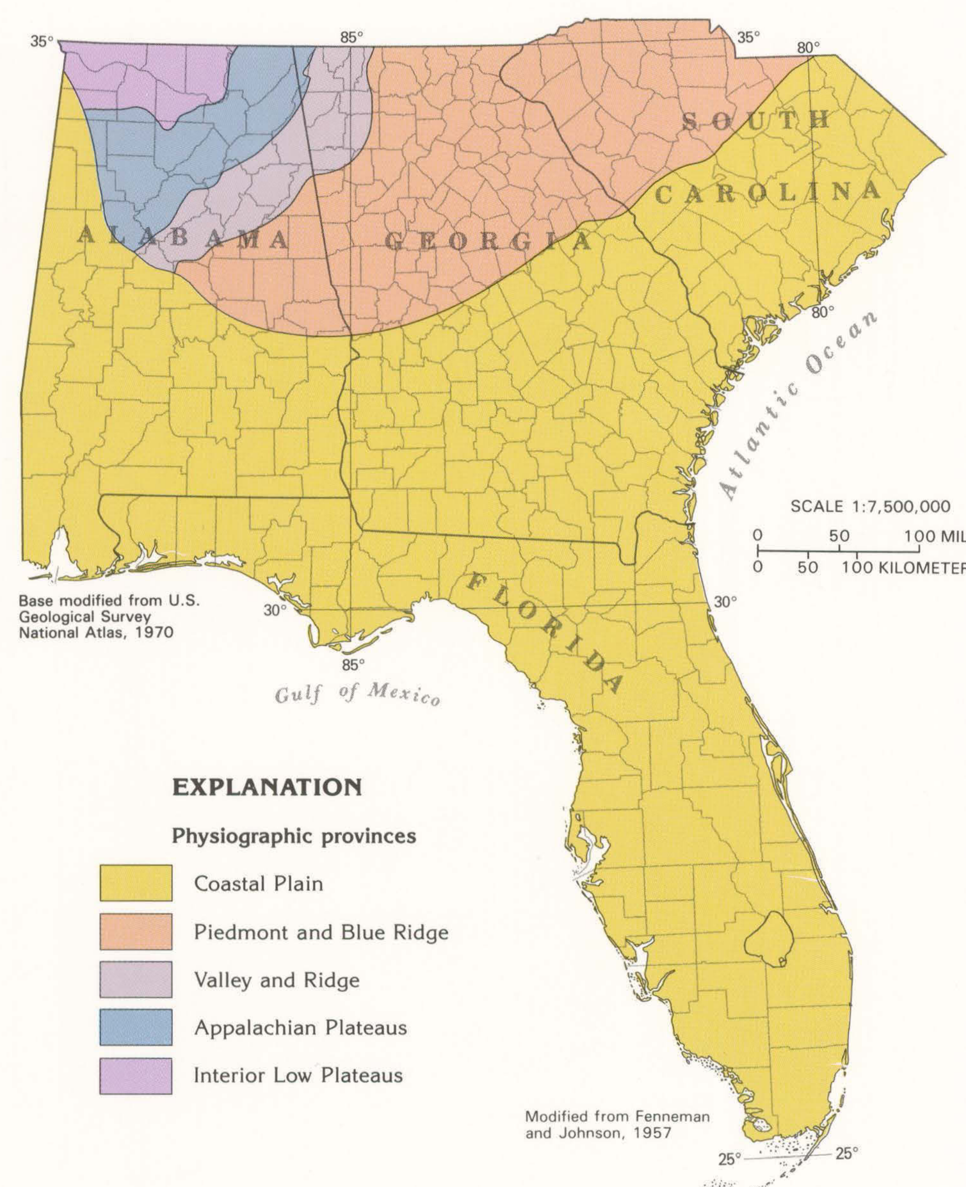
The surficial aquifer system consists mostly of unconsolidated sand, but also contains a few beds of shell and limestone. The sand and gravel and Biscayne aquifers are separately recognized parts of the surficial aquifer system that consist of distinctive rock types. The sand and gravel aquifer consists of complexly interbedded lenses and layers of coarse sand and gravel, and the Biscayne aquifer consists predominantly of limestone. The intermediate aquifer system consists of sand and limestone and lies between the surficial aquifer system and the Floridan aquifer system. The intermediate aquifer system does not crop out, and, accordingly, is not shown on the map.

The Floridan aquifer system consists of limestone and dolomite, and is the most productive of the aquifers in the mapped area, in terms of total water yield. The Southeastern Coastal Plain aquifer system consists of four regional aquifers that are predominately sand, but these aquifers also contain some beds of gravel and limestone. All the aquifers from the surficial aquifer system down through the Southeastern Coastal Plain aquifer system are present in the Coastal Plain physiographic province (**fig. 4**). Water in all of the Coastal Plain aquifers is present primarily in intergranular pore spaces. However, solution openings in carbonate rocks of the Biscayne aquifer and Floridan aquifer system yield large volumes of water.

Piedmont and Blue Ridge aquifers consist of indurated metamorphic rocks, such as gneiss and schist, and igneous rocks, such as granite, that underlie the rolling hills of the Piedmont physiographic province and the mountains of the Blue Ridge physiographic province. Water is present in these rocks in fractures, but locally a large volume of water is stored in the regolith, or blanket of weathered material that overlies the rock.

Folded Paleozoic rocks underlie the Valley and Ridge physiographic province, and flatlying Paleozoic rocks underlie the combined Appalachian Plateaus and Interior Low Plateaus physiographic provinces. In these three provinces, the Paleozoic rocks consist of indurated sedimentary rocks; the major aquifers consist of limestone. However, the ground-water flow system is different where these rocks are folded and where they are not.

Figure 4. *Six physiographic provinces are present in Segment 6. Two of these provinces—Piedmont and Blue Ridge—have been combined in this chapter because of similarity in geology and hydrology.*



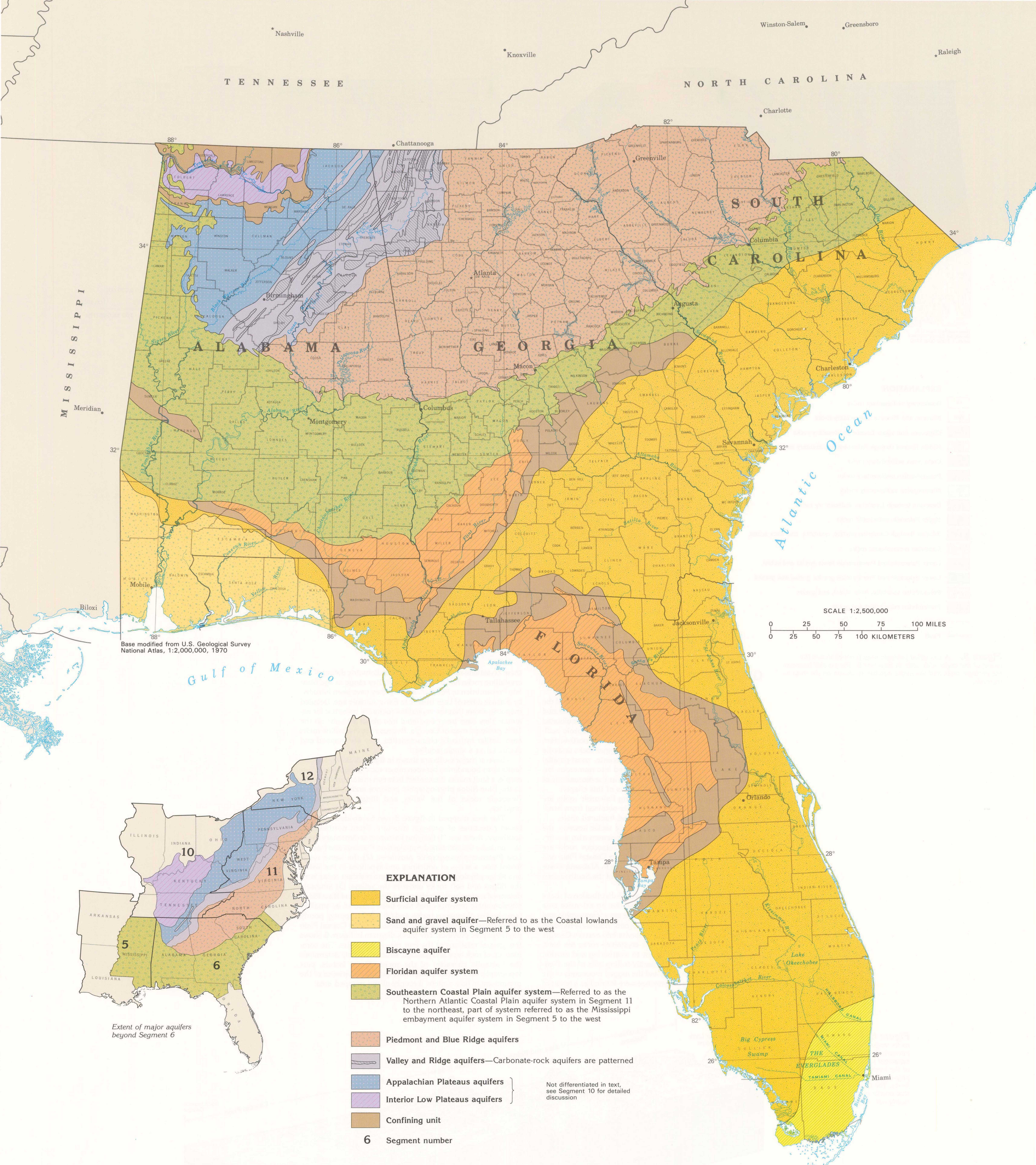


Figure 3. *The numerous aquifers in Segment 6 can be grouped into nine major aquifers or aquifer systems. The extent of eight of these major aquifers or aquifer systems at the land surface is mapped here. One aquifer, the intermediate aquifer system, is not exposed at the land surface.*

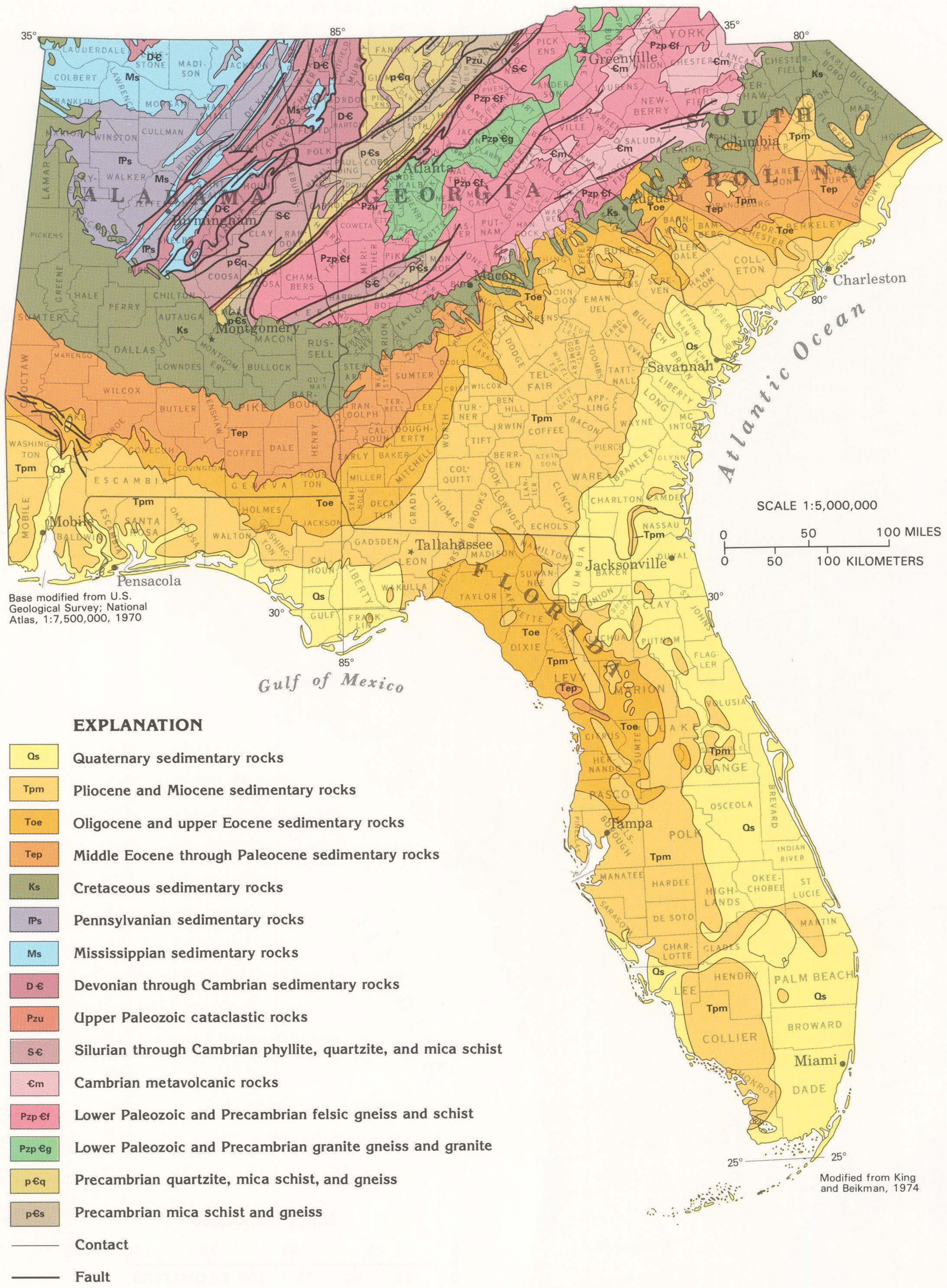


Figure 5. A simplified geologic map (above) shows the extent of the major rock units in Segment 6. The parallel between the geologic units and the major aquifers is shown on the map to the right.

GEOLOGY

Two categories of sedimentary rocks comprise most of the rocks underlying the four States of Segment 6: well-indurated rocks of Paleozoic age and poorly indurated to unconsolidated rocks of Cretaceous age and younger. The Paleozoic sedimentary rocks crop out in northern Alabama and northwestern Georgia; whereas, the Cretaceous and younger rocks underlie the Coastal Plain and form a broad, arcuate, coast-parallel band. Both categories have been divided into numerous formations, as shown on correlation charts in the discussions of the major aquifers in following sections of this chapter.

The majority of the water-yielding Paleozoic rocks are limestone; however, some water also is obtained from sandstone and, locally, from chert beds and fractured shale.

Most Coastal Plain strata are clastic rocks; however, the carbonate rocks of the Floridan aquifer system also are important. Triassic, Jurassic, and Lower Cretaceous rocks are present only in the deep subsurface of the Coastal Plain and do not form aquifers except in a local area in Alabama where Lower Cretaceous rocks form a small part of the Southeastern Coastal Plain aquifer system.

The geologic map (**fig. 5**) shows the distribution of rocks by major age category and also shows that an extensive area is underlain by crystalline rocks. These are metamorphic and igneous rocks that crop out in a broad, northeast-trending band that widens from eastern Alabama into eastern Georgia and western South Carolina. The crystalline rocks are hard, and generally are more resistant to weathering and erosion than sedimentary rocks. The gently rolling hills of the Piedmont physiographic province and the rugged mountains of the Blue Ridge physiographic province were formed as a result of these crystalline-rock characteristics. Radiometric dating of the crystalline rocks has determined that they range in age from late Precambrian to Permian. Locally, they have been intruded by diabase dikes of Late Triassic to Early Jurassic age. Detailed mapping shows that the crystalline rocks are complex; for example, they have been separated into about 90 units on the 1976 geologic map of Georgia. Because the crystalline rocks have similar hydraulic characteristics, they are mapped and discussed as a single aquifer.

Several major faults are shown in **figure 5**. Some of these faults form boundaries between major rock categories; for example, a fault marks the contact between metamorphic rocks of the Blue Ridge physiographic province and tightly folded Paleozoic rocks of the Valley and Ridge physiographic province.

The area mapped in **figure 5** can be divided into four broad categories of geologic structure. From northwest to southeast, these are: (1) flatlying Paleozoic sedimentary rocks that underlie the combined Appalachian Plateaus and Interior Low Plateaus physiographic provinces; (2) the same rocks folded into a series of anticlines and synclines in the Valley and Ridge physiographic province, where resistant rocks form the ridges and soft rocks underlie the valleys; (3) intensely deformed metamorphic rocks of the Piedmont and Blue Ridge physiographic provinces that have been intruded by small to large bodies of igneous rocks; and (4) gently dipping, poorly consolidated to unconsolidated sediments of the Coastal Plain physiographic province. The block diagram in **figure 6** shows the general relations of the four major categories. The combination of rock type and geologic structure largely determines the hydraulic character of the rocks. These factors, plus topography and climate, determine the characteristics of the ground-water flow system throughout the mapped area.

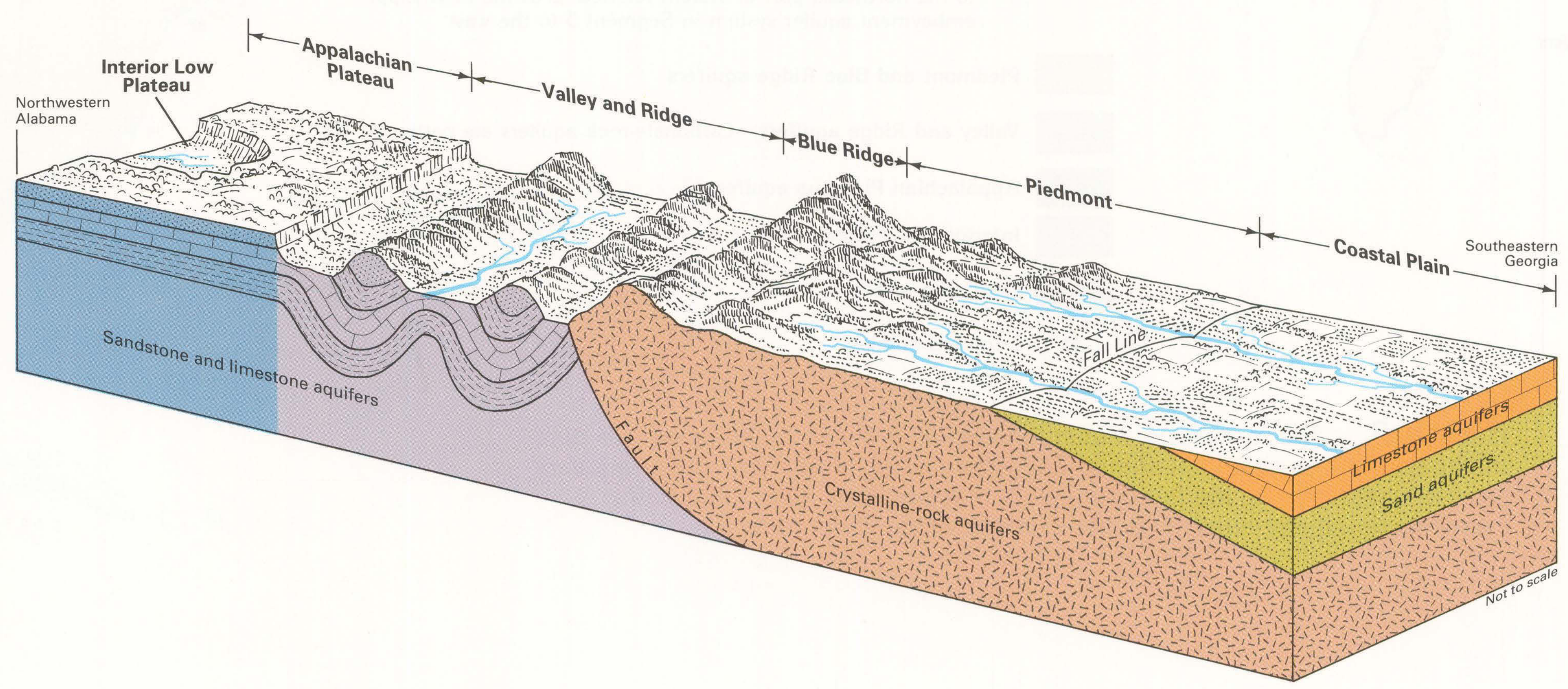


Figure 6. The Paleozoic rocks range from flatlying to intensely folded. They are separated from crystalline rocks of the Piedmont and Blue Ridge physiographic provinces by faults. The Coastal Plain strata that overlie older rocks are nearly flat.

VERTICAL SEQUENCE OF AQUIFERS

Some of the major aquifers and aquifer systems in Segment 6 lie atop others. For example, the Biscayne aquifer in southern Florida overlies the Floridan aquifer system, but the two are separated by a thick, clayey confining unit (**fig. 7**). Water is able to move vertically between some of these aquifers. Movement is in the direction of decreasing hydraulic head, and occurs most easily where the confining units separating the aquifers are absent, thin, or leaky.

The sequence of maps on this page shows the extent of each aquifer or aquifer system. Comparison of the maps shows the places where aquifers are stacked upon each other. The three uppermost aquifers in the Coastal Plain are shown in **figure 8**. These aquifers, the surficial aquifer system, sand and gravel aquifer, and Biscayne aquifer are all the same geologic age (primarily Pleistocene and younger), and all contain water mostly under unconfined (water table) conditions. However, even though these aquifers are lateral equivalents, the lithology and permeability of each are different. The surficial aquifer system is a thin, widespread layer of unconsolidated sand beds that commonly contains a few beds of shell and limestone. This aquifer system generally yields small volumes of water, and primarily is used for domestic supplies. The sand and gravel aquifer consists largely of interbedded layers of coarse sand and gravel that were deposited by streams. Thin clay beds in this aquifer locally create semiconfined conditions. The sand and gravel aquifer yields moderate volumes of water, and is an important source of supply for several counties in westernmost panhandle Florida and southwestern Alabama. Westward, in Mississippi, the sand and gravel aquifer grades into the Coastal lowlands aquifer system. The Biscayne aquifer, the source of water supply for several large cities along the southeastern coast of Florida, is a highly permeable sequence of mostly carbonate rocks that were deposited in marine waters.

The intermediate aquifer system (**fig. 9**) underlies the surficial aquifer system and overlies the Floridan aquifer system. The intermediate aquifer system is bounded above and below by clayey confining units. The system is not exposed at land surface and is recharged primarily by downward leakage from overlying aquifers. Sand beds and limestone lenses comprise the permeable parts of the system. The intermediate aquifer system is an important source of municipal supply in Sarasota, Charlotte, and Glades Counties, Fla.; elsewhere, it primarily is used for domestic supplies.

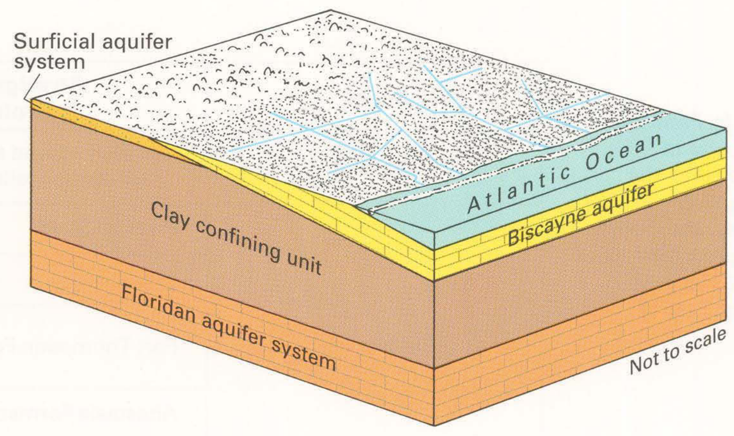


Figure 7. In places, some major aquifers overlie others. In south Florida, for example, the freshwater-yielding Biscayne aquifer is separated from the underlying Floridan aquifer system, which contains saltwater, by a thick, clayey confining unit.

The Floridan aquifer system (**fig. 10**) consists of a thick sequence of carbonate rocks and is the most productive aquifer in Segment 6. The Floridan underlies the intermediate aquifer system where the latter is present; it also underlies the surficial aquifer system, the sand and gravel aquifer, and the Biscayne aquifer, but is separated from them practically everywhere by a thick, clayey confining unit. Where the surficial aquifer system overlies the Floridan, the clayey confining unit between the systems is thick in some places and thin or absent in other places. The Floridan supplied more than 3 billion gallons of water per day during 1985, primarily for municipal and agricultural purposes.

The Southeastern Coastal Plain aquifer system (**fig. 11**) underlies the Floridan aquifer system in some places (mostly in western Georgia and westward) and grades laterally into the Floridan in other places (mostly in southeastern Georgia and southwestern South Carolina). The upper part of the Southeastern Coastal Plain aquifer system grades laterally into the Mississippi embayment aquifer system in western Alabama (**fig. 3**). The Southeastern Coastal Plain aquifer system consists of four regional aquifers that are primarily sand beds, but which contain some gravel and limestone. The four regional aquifers generally yield large volumes of water in updip areas, where they are mostly sand, but the aquifers are less permeable in a coastward direction due to increasing clay content toward the coast. The system is an important source of water supply for all purposes throughout the inner part of the Coastal Plain.

Although rocks of the Piedmont, Blue Ridge, Valley and Ridge, and the combined Appalachian Plateaus and Interior Low Plateaus physiographic provinces (**fig. 12**) extend under the Southeastern Coastal Plain aquifer system, these rocks generally are not used as aquifers there because water can be more readily obtained from the shallower, unconsolidated Coastal Plain sediments. Piedmont and Blue Ridge aquifers consist of a complex sequence of metamorphic and igneous rocks, and primarily supply domestic or agricultural wells. Well yields generally are small; the water is obtained from fractures in the unweathered crystalline rock and from the mantle of regolith (weathered materials, soil, and alluvium) that overlies it. Major fault systems separate the Piedmont and Blue Ridge aquifers from the Valley and Ridge aquifers to the northwest.

The Valley and Ridge and the combined Appalachian Plateaus and Interior Low Plateaus aquifers consist of indurated sedimentary rocks of Paleozoic age. Water is obtained primarily from limestone in these provinces and secondarily from sandstone, chert beds, or fractured shale. In the Valley and Ridge province, these sedimentary rocks have been tightly folded into a sequence of northeast-trending anticlines and synclines that have been displaced by thrust faults in many places. Ground-water circulation extends to greater depths in these folded rocks than in the Appalachian Plateaus and Interior Low Plateaus provinces to the northwest where the same rocks are almost flatlying. In the Appalachian Plateaus province, the flatlying beds are topped with a resistant cap of sandstone; in the Interior Low Plateaus province, the sandstone has been dissected by erosion, and underlying limestone beds are exposed. The contact between the Valley and Ridge and Appalachian Plateaus provinces is distinct in some places where it follows faults and is gradational from nearly horizontal strata to folds in other places.

Figure 8. The uppermost Coastal Plain rocks are divided into three aquifers, all consisting of strata of the same age. The surficial aquifer system is a thin blanket of sand and shell beds that yields small volumes of water, the sand and gravel aquifer is a thick sequence of coarse clastic rocks that yields moderate volumes of water, and the Biscayne is a carbonate-rock aquifer that yields large volumes of water.

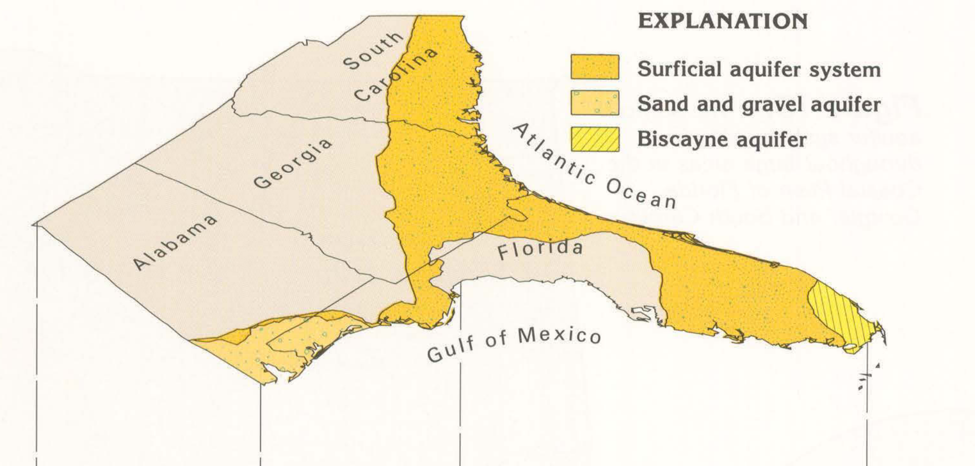


Figure 9. The intermediate aquifer system underlies the surficial aquifer system in southwestern Florida and consists mostly of sand, which yields small volumes of water, with some limestone beds, which yield large volumes of water.

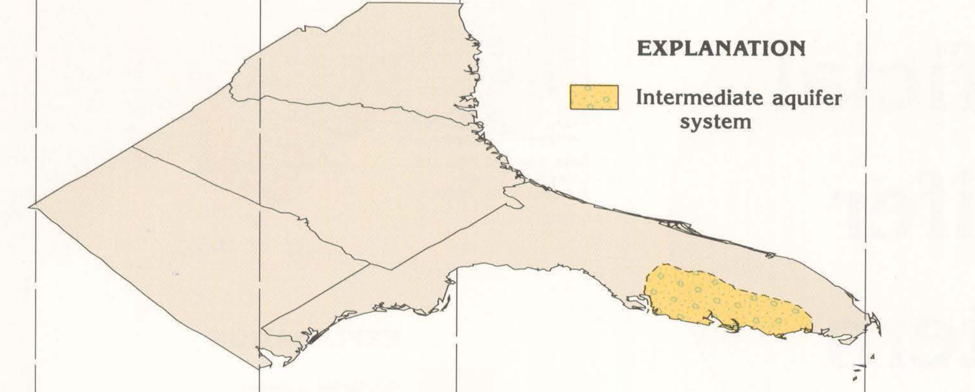


Figure 10. The Floridan aquifer system consists of carbonate rocks and is the most productive water-yielding unit in Segment 6. The Floridan is overlain by the intermediate aquifer system and also by the three younger aquifers shown in figure 8. In most places, the Floridan is separated from these overlying aquifers by a clayey confining unit.

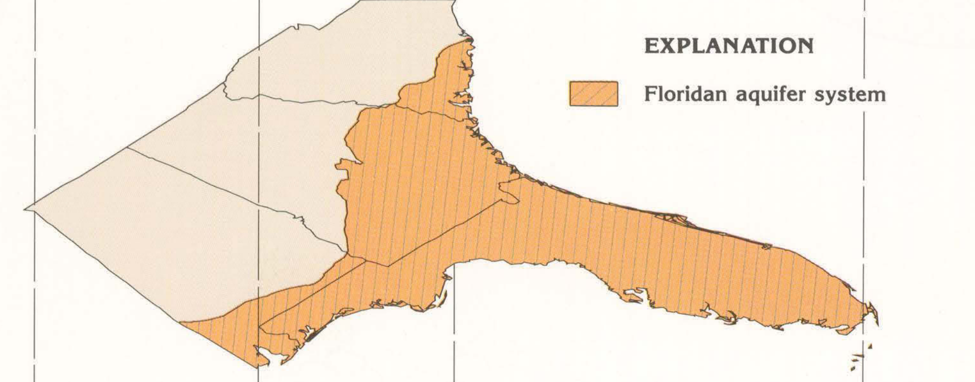


Figure 11. The clastic rocks of the Southeastern Coastal Plain aquifer system yield moderate volumes of water. The clastic rocks underlie the Floridan aquifer system in places, and grade laterally into the Floridan in other places. A clayey confining unit separates the two systems in Alabama and western Georgia.

Figure 12. Crystalline rocks, such as granite, gneiss, and schist, comprise aquifers in the Piedmont and Blue Ridge provinces; indurated sedimentary rocks comprise aquifers in the Valley and Ridge province and in the combined Appalachian and Interior Low Plateaus provinces. All of the aquifers shown on this figure generally yield small volumes of water, and extend under the Southeastern Coastal Plain aquifer system, but are little used where the greater yielding Coastal Plain rocks cover them.

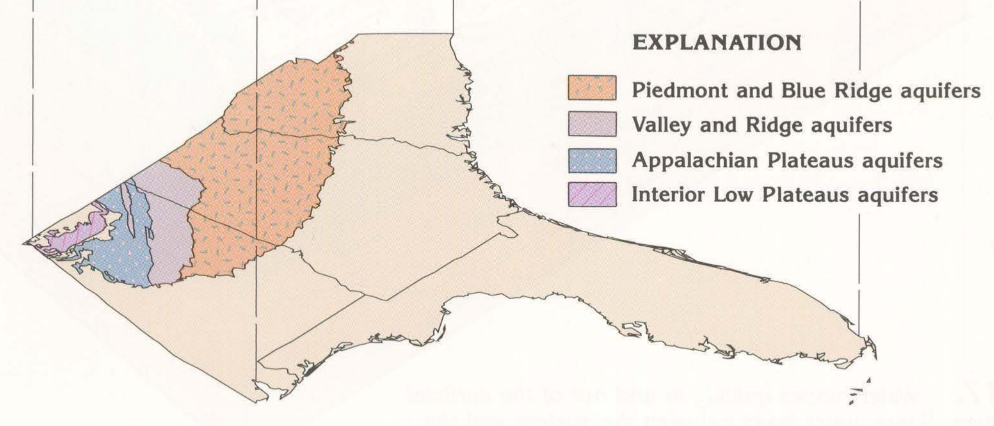
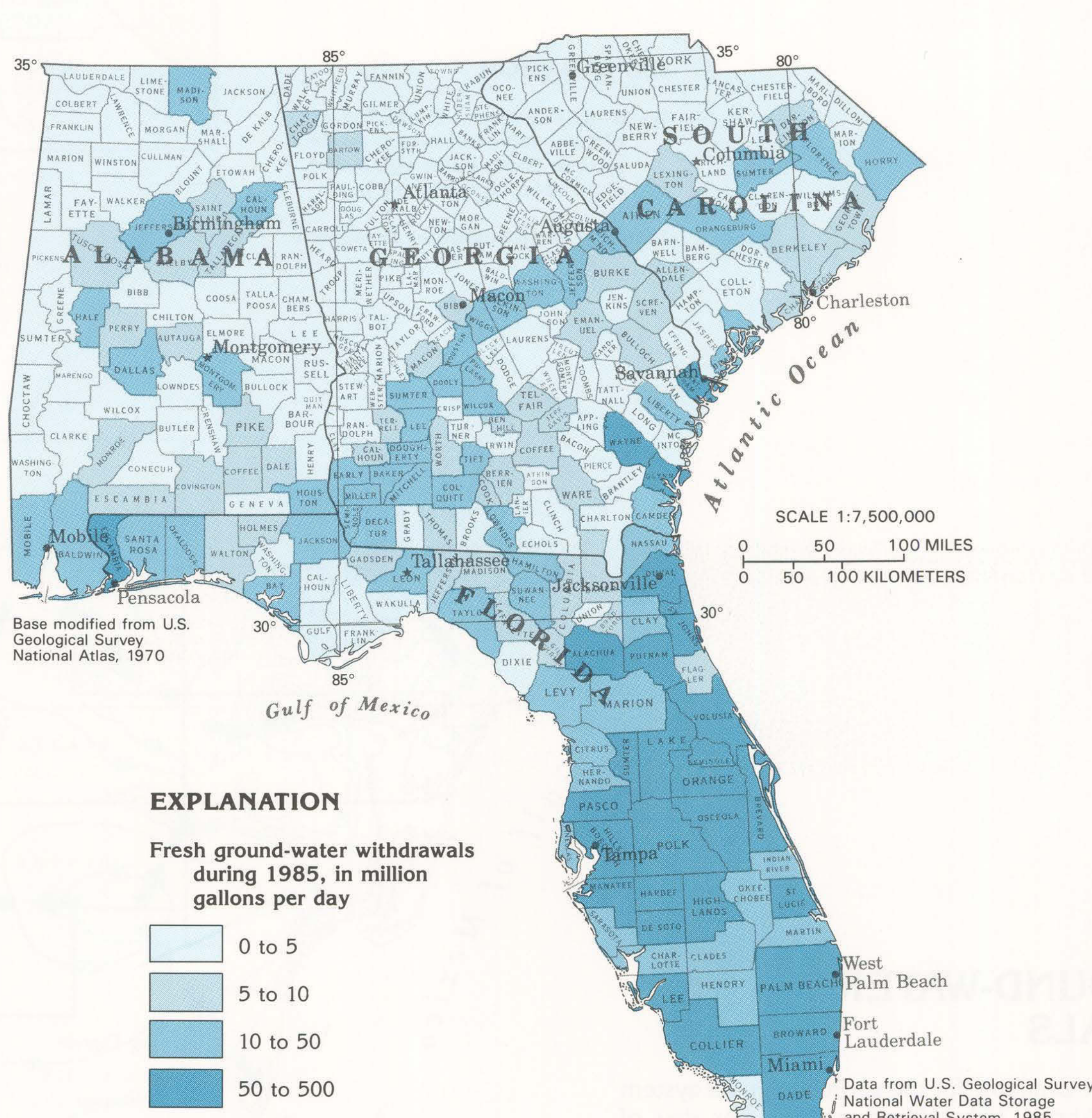


Figure 13. Fresh ground-water withdrawals were greatest in Florida during 1985 because the large population centers and extensive areas of agricultural water use in the State rely primarily on ground water for their water supplies.



FRESH GROUND-WATER WITHDRAWALS

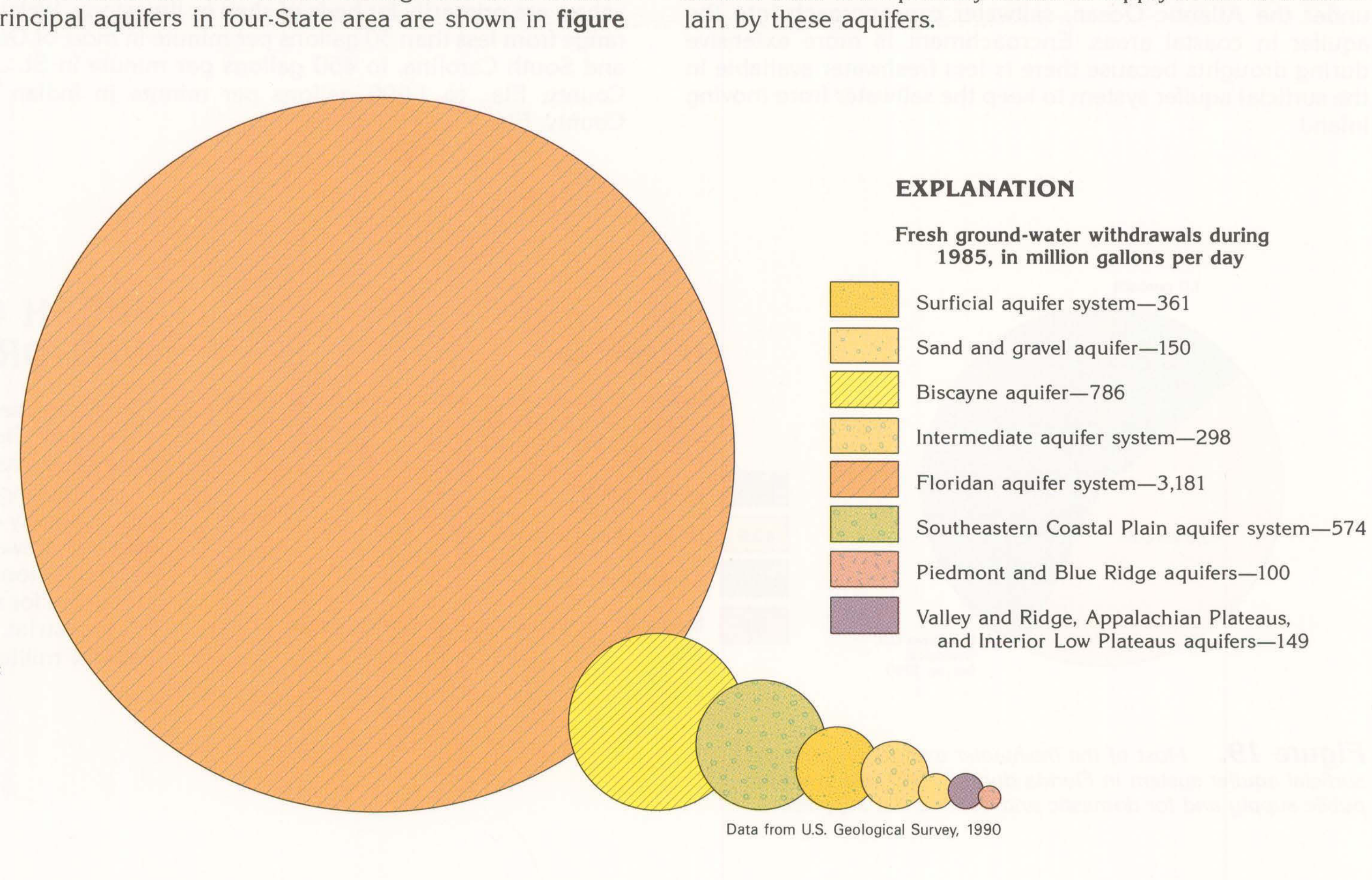
Ground water is the source of water supply for almost 11 million people, or about 73 percent of the population in the four-State area.

About 5,600 million gallons per day was withdrawn from all the principal aquifers during 1985; 46 percent was used in rural areas for domestic and commercial supplies and for agricultural supplies. Withdrawals for public supply were somewhat less, accounting for 35 percent of the total water withdrawn.

Total withdrawals of fresh ground water, by county, are shown in **figure 13**. Counties with the largest withdrawals are those that have large population centers except for south-central Florida, where combined agricultural and mining uses account for most of the withdrawals. Fresh ground-water withdrawals for most water use categories are increasing, according to a recent (1990) nationwide compilation of water-use data by the U.S. Geological Survey.

Total withdrawals of freshwater during 1985 from each of the principal aquifers in four-State area are shown in **figure 14**. About 3,181 million gallons per day was withdrawn from the Floridan aquifer system, almost four times as much water as was withdrawn from the second most used aquifer, the Biscayne aquifer (786 million gallons per day), and almost twice as much water as was withdrawn from all the other principal aquifers combined. More water was withdrawn from the Biscayne aquifer, although it only extends throughout a small area in the southeastern tip of Florida, than from either the Southeastern Coastal Plain aquifer system (574 million gallons per day) or the surficial aquifer system (361 million gallons per day), even though both have a much larger areal extent. This is because the Biscayne is the source of supply for several large cities, including Miami, West Palm Beach, and Fort Lauderdale, along the southeast coast of Florida. About 298 million gallons per day was withdrawn from the intermediate aquifer system, about 150 million gallons per day from the sand and gravel aquifer, and about 149 million gallons per day from the combined Valley and Ridge, Appalachian Plateaus, and Interior Low Plateaus aquifers. Only about 100 million gallons per day, or about 2 percent of the total freshwater withdrawn, was obtained from the Piedmont and Blue Ridge aquifers because surface water is the primary source of supply in the area underlain by these aquifers.

Figure 14. The Floridan aquifer system was the source of about 57 percent of the fresh ground-water withdrawals in the four-State area during 1985; about 14 percent of the fresh water was withdrawn from the Biscayne aquifer, the second most used aquifer.



Surficial aquifer system

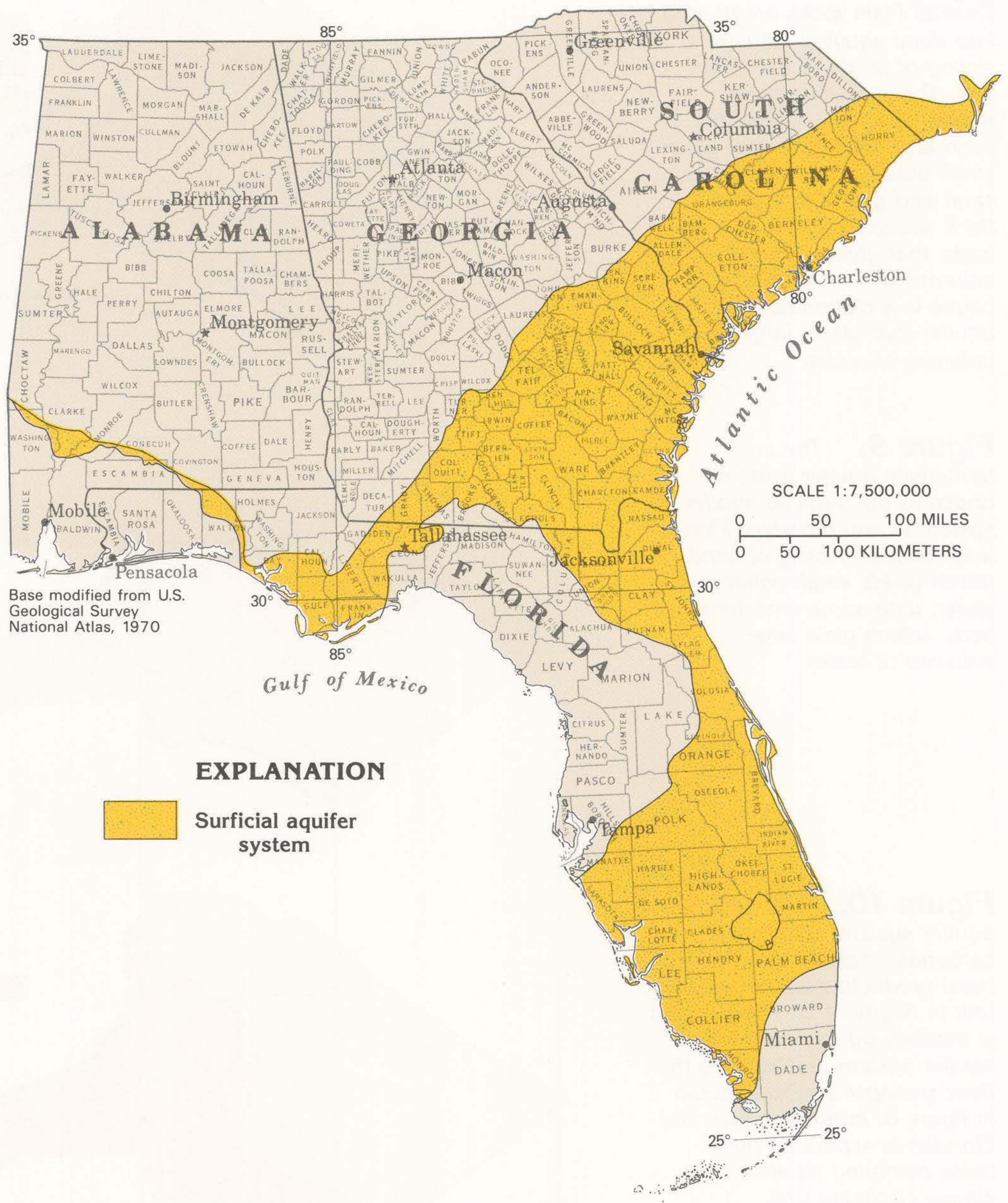


Figure 15. The surficial aquifer system extends throughout large areas in the Coastal Plain of Florida, Georgia, and South Carolina.

INTRODUCTION

The surficial aquifer system (**fig. 15**) in the southeastern United States includes any otherwise undefined aquifers that are present at the land surface. Even though the sand and gravel aquifer of Florida and southwestern Alabama, and the Biscayne aquifer of southern Florida are present at the land surface and are the lateral equivalents of the surficial aquifer system, they are treated separately in this Atlas because of their importance as water sources. The sand and gravel, and the Biscayne aquifers supply large municipalities; the surficial aquifer system, although used by a large number of people, principally is used only for domestic, commercial, or small municipal supplies.

The thickness of the surficial aquifer system is typically less than 50 feet, but its thickness in Florida is as much as 400 feet in Indian River and St. Lucie Counties; 250 feet in Martin and Palm Beach Counties; and 150 feet in eastern St. Johns County. In southeastern Georgia, thicknesses of about 60 feet have been mapped for the system. The system generally thickens coastward.

HYDROGEOLOGIC UNITS

The surficial aquifer system consists mostly of beds of unconsolidated sand, shelly sand, and shell. Locally, in southwestern Florida, limestone beds form an important and highly permeable part of the system. In places, clay beds are sufficiently thick and continuous to divide the system into two or three aquifers; mostly, however, the system is undivided. Complex interbedding of fine- and coarse-textured rocks is typical of the system.

The rocks that comprise the surficial aquifer system range from late Miocene to Holocene in age. Although **figure 16** shows that nine geologic formations are part of the system at different places in Florida, the entire sequence of formations is not present at any one location. The formations are thin and mostly lens-like, and it is unusual for more than three or four of them to comprise the aquifer system at any place. Many of the geologic formations shown interfinger with each other, and some of them, such as the Caloosahatchee Marl, are not particularly productive aquifers. In Georgia and South Carolina, unnamed, sandy, marine terrace deposits of Pleistocene age and sand of Holocene age comprise the system. These sandy beds commonly contain clay and silt. In Alabama, a thin, unnamed sand of Holocene age comprises the system.

Limestone beds of the Tamiami and Fort Thompson Formations, mostly restricted to southern and southwestern Florida, are the most productive parts of the surficial aquifer system. Yields from these formations are especially large where large-scale openings have been developed by dissolution of part of the limestone. In places where the combined Pamlico Sand and overlying sand deposits of Holocene age are 40 feet or more thick, moderate yields are obtained; elsewhere, the system generally does not yield much water.

Figure 16. In Florida, rocks of late Miocene to Holocene age comprise the surficial aquifer system. In Alabama, Georgia, and South Carolina, a thin, unnamed sand sequence of Pleistocene and younger age comprises the system.

Series	Stratigraphic and hydrologic units		Lithology
Holocene	Undifferentiated alluvium and terrace deposits	Surficial aquifer system	Sand with local shell beds
Pleistocene[1]	Pamlico Sand		Fine to medium sand
	Miami Oolite		Oolitic limestone
	Fort Thompson Formation		Interbedded sand, shell, and limestone
	Anastasia Formation		Sandy limestone and marl
	Caloosahatchee Marl		Marl with minor sand and silt
Pliocene	Tamiami Formation		Marl with beds of fossiliferous limestone
	Bone Valley Formation		Phosphatic sand and clay
Miocene	Choctawhatchee Formation		Sand and limestone

[1]Stratigraphic units are equivalent in part. Order does not necessarily reflect relative age)

Modified from Healy, 1982

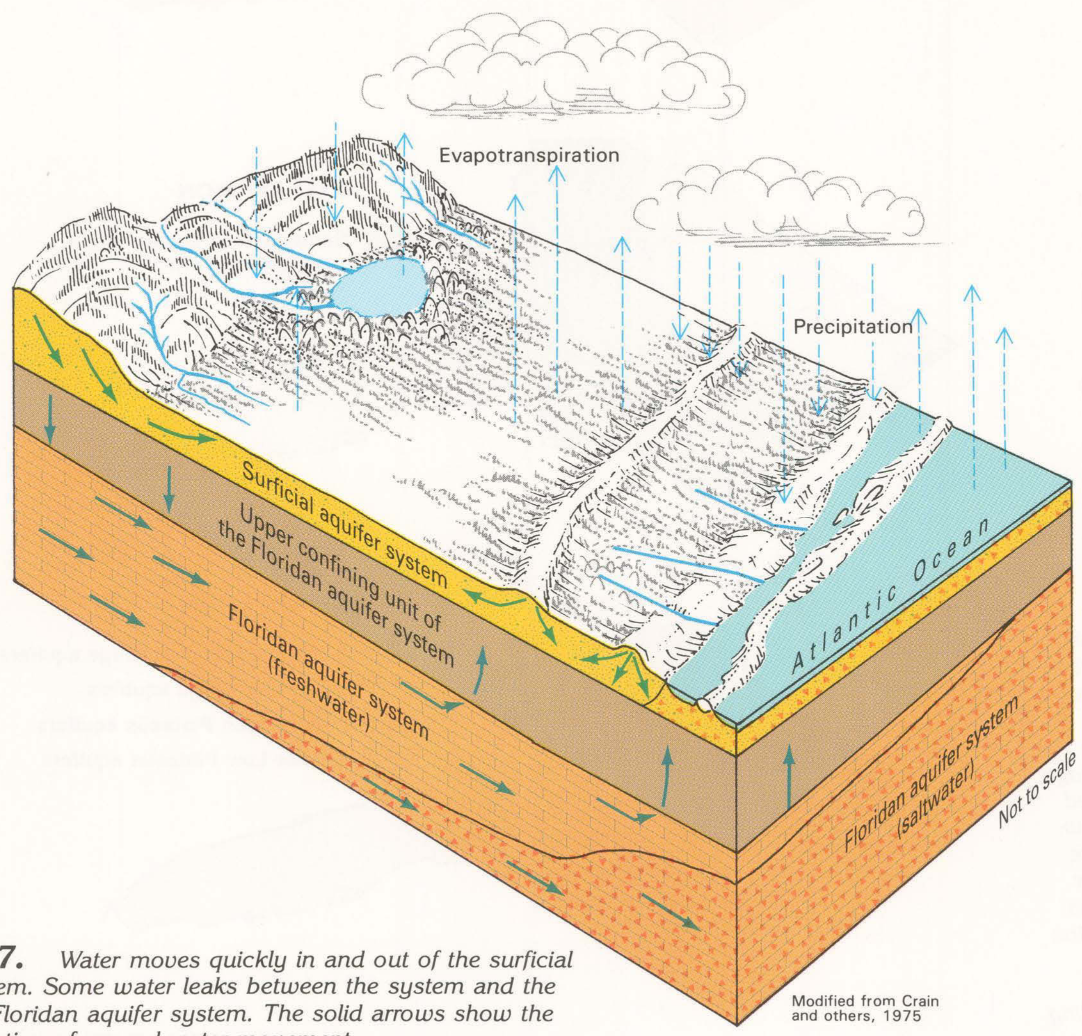


Figure 17. Water moves quickly in and out of the surficial aquifer system. Some water leaks between the system and the underlying Floridan aquifer system. The solid arrows show the general direction of ground-water movement.

GROUND-WATER FLOW

Ground water in the surficial aquifer system is under unconfined, or water-table, conditions practically everywhere. Locally, thin clay beds create confined or semiconfined conditions within the system. Most of the water that enters the system moves quickly along short flowpaths and discharges as baseflow to streams.

The general movement of water within the system is illustrated in **figure 17**, which is an idealized diagram representing hydrologic conditions in Indian River County, Fla. Water enters the system as precipitation. A large percentage of this water is returned to the atmosphere by evapotranspiration. Water that is not returned to the atmosphere by evapotranspiration, or that does not directly run off into surface-water bodies, percolates downward into the surficial aquifer system and then moves laterally through the system until it discharges to a surface-water body or to the ocean.

In places, some water leaks upward from the underlying Floridan aquifer system through the clayey confining unit separating the Floridan and surficial systems (**fig. 17**). In other places, where the hydraulic head of the Floridan is lower than the water table of the surficial aquifer, leakage can occur in the opposite direction.

Because the surficial aquifer system extends seaward under the Atlantic Ocean, saltwater can encroach into the aquifer in coastal areas. Encroachment is more extensive during droughts because there is less freshwater available in the surficial aquifer system to keep the saltwater from moving inland.

The configuration of the long-term, average water table of the surficial aquifer system, where it has been mapped in the eastern and southern part of the Florida peninsula, is shown in **figure 18**. The water-table configuration is generally a subdued reflection of the topography of land surface. Steep gradients occur between streams and ridges or hills, and gentle gradients occur in broad, flat interstream areas and under broad topographic highs.

The arrows in **figure 18** show that the general direction of ground-water movement is toward the Atlantic Ocean, the Gulf of Mexico, or toward major rivers. The water-table surface is complex, reflecting the fact that water in the surficial aquifer system moves quickly toward the nearest surface-water body. Accordingly, local directions of ground-water movement change markedly within short distances.

The wide spacing of the contours in Collier County and adjacent areas reflects two conditions: (1) the Big Cypress Swamp, which is virtually flat, is present throughout much of this area; and (2) the surficial aquifer system largely consists of highly permeable limestone in this area. Steeper gradients elsewhere are more typical of a sand aquifer in an area of gentle topography.

The transmissivity of the surficial aquifer system is extremely variable. Most reported values range from 1,000 to 10,000 feet squared per day; in places, values of 25,000 to 50,000 feet squared per day have been reported. The larger values are primarily for beds of shell or limestone. Well yields range from less than 50 gallons per minute in most of Georgia and South Carolina, to 450 gallons per minute in St. Johns County, Fla., to 1,000 gallons per minute in Indian River County, Fla.

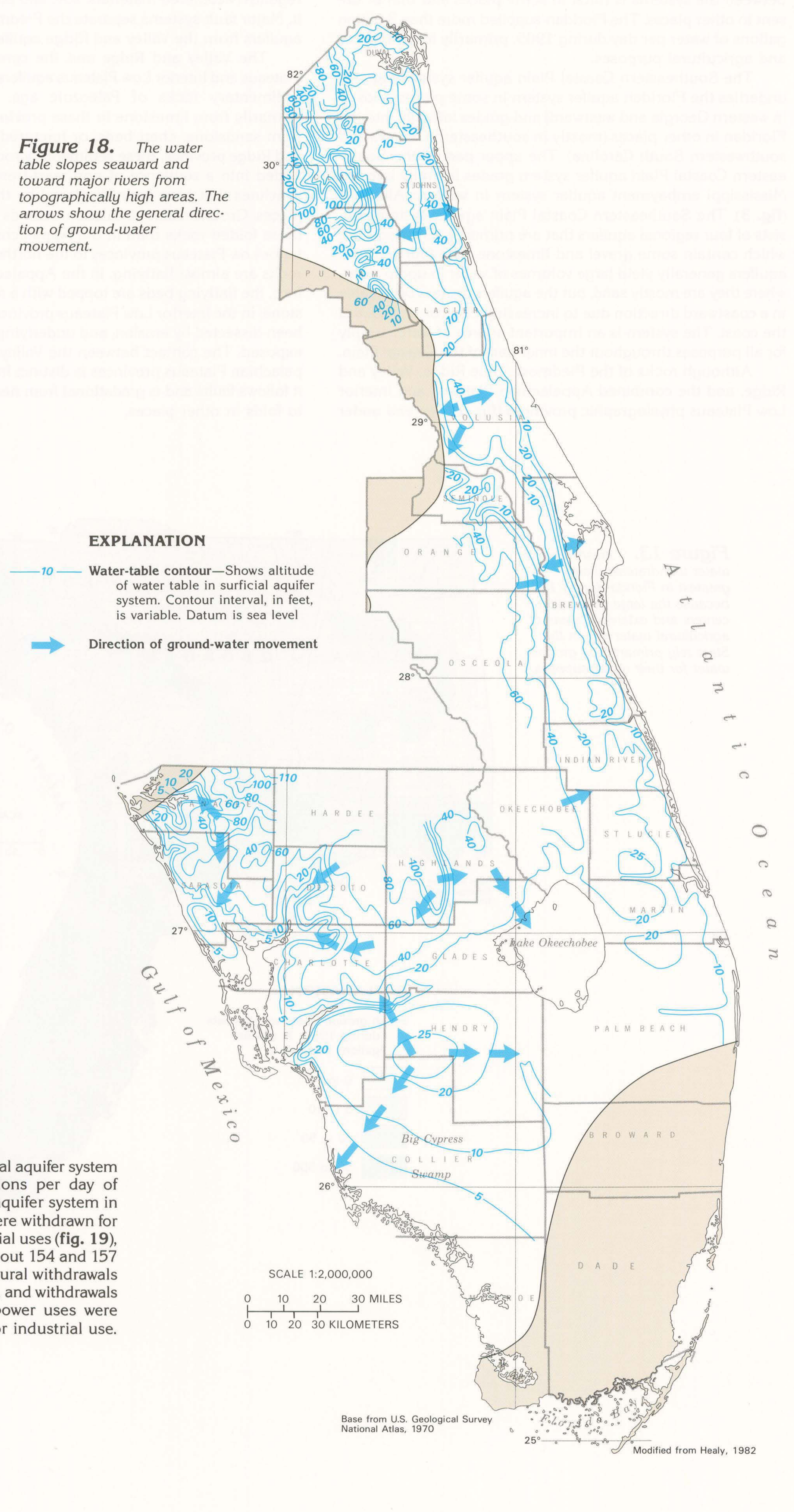


Figure 18. The water table slopes seaward and toward major rivers from topographically high areas. The arrows show the general direction of ground-water movement.

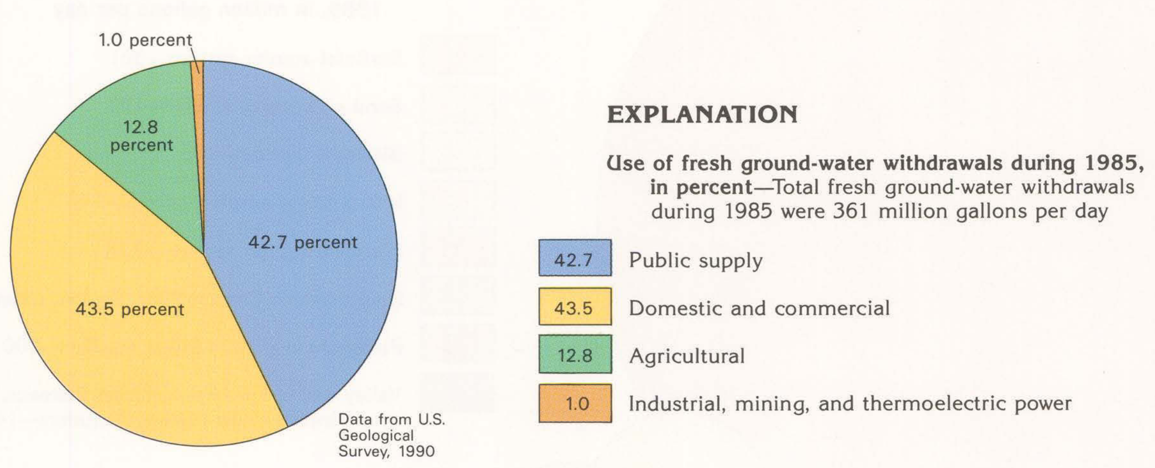


Figure 19. Most of the freshwater withdrawn from the surficial aquifer system in Florida during 1985 was used for public supply and for domestic and commercial supplies.

FRESH GROUND-WATER WITHDRAWALS

Water-use data are available for the surficial aquifer system only from Florida. About 361 million gallons per day of freshwater was withdrawn from the surficial aquifer system in Florida during 1985. Nearly equal volumes were withdrawn for public supply and for domestic and commercial uses (**fig. 19**), with withdrawals for these categories being about 154 and 157 million gallons per day, respectively. Agricultural withdrawals accounted for about 13 million gallons per day, and withdrawals for industrial, mining, and thermoelectric-power uses were about 4 million gallons per day, primarily for industrial use.

Sand and gravel aquifer

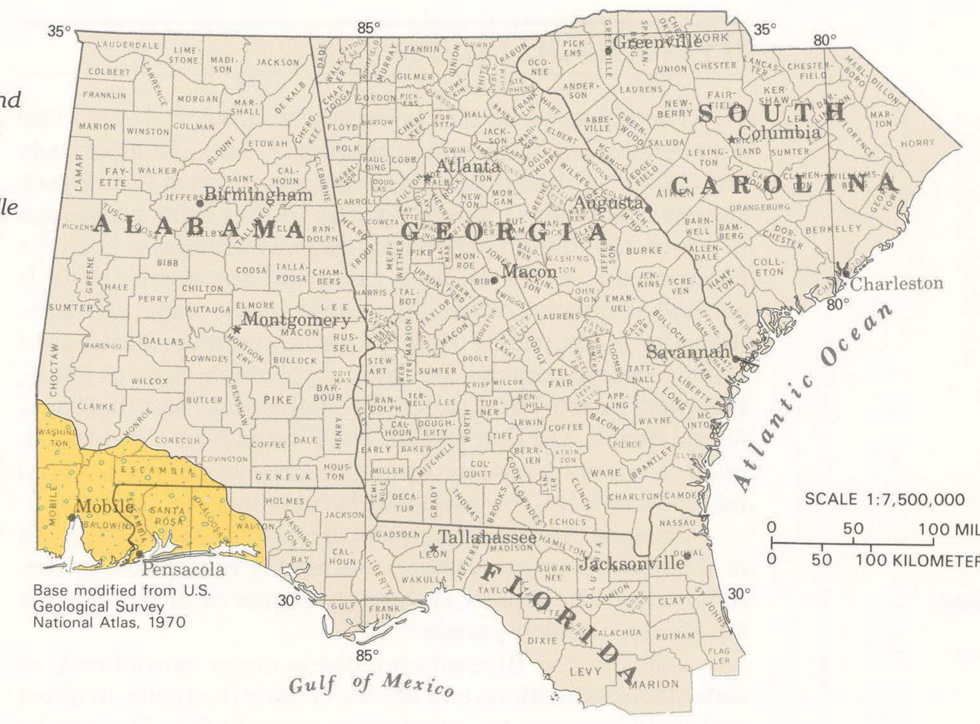


Figure 20. The sand and gravel aquifer is an important source of water in southwestern Alabama and the westernmost part of panhandle Florida.

INTRODUCTION

The sand and gravel aquifer underlies an area of about 6,500 square miles in southwestern Alabama and the westernmost part of panhandle Florida (**fig. 20**). The aquifer is presently (1990) called the Miocene-Pliocene aquifer in Alabama; in the past, it has been called the Citronelle or Citronelle-Miocene aquifer in that State by some authors. In Mississippi, the sand and gravel aquifer grades laterally into part of the Coastal lowlands aquifer system that extends westward into southern Texas. The sand and gravel aquifer is the primary source of water in Baldwin, Washington, and western Escambia Counties, Ala., and in Santa Rosa and Escambia Counties, Fla. The aquifer also supplies most of the water used by small communities in the rural parts of Mobile County, Ala.; the city of Mobile in that county, however, is supplied by surface water. About 150 million gallons per day was withdrawn from the sand and gravel aquifer for all uses during 1985. About 80 percent was withdrawn in the Pensacola, Fla. area, and the majority of the remaining 20 percent was withdrawn in Mobile County, Ala.

As its name indicates, the sand and gravel aquifer consists largely of interbedded layers of sand and gravel. Clay beds and lenses are common in the aquifer and form local confining beds. Water in the aquifer is under unconfined conditions where the clay beds are thin or absent, and is under artesian conditions where such beds are thick. Movement of ground water is generally coastward.

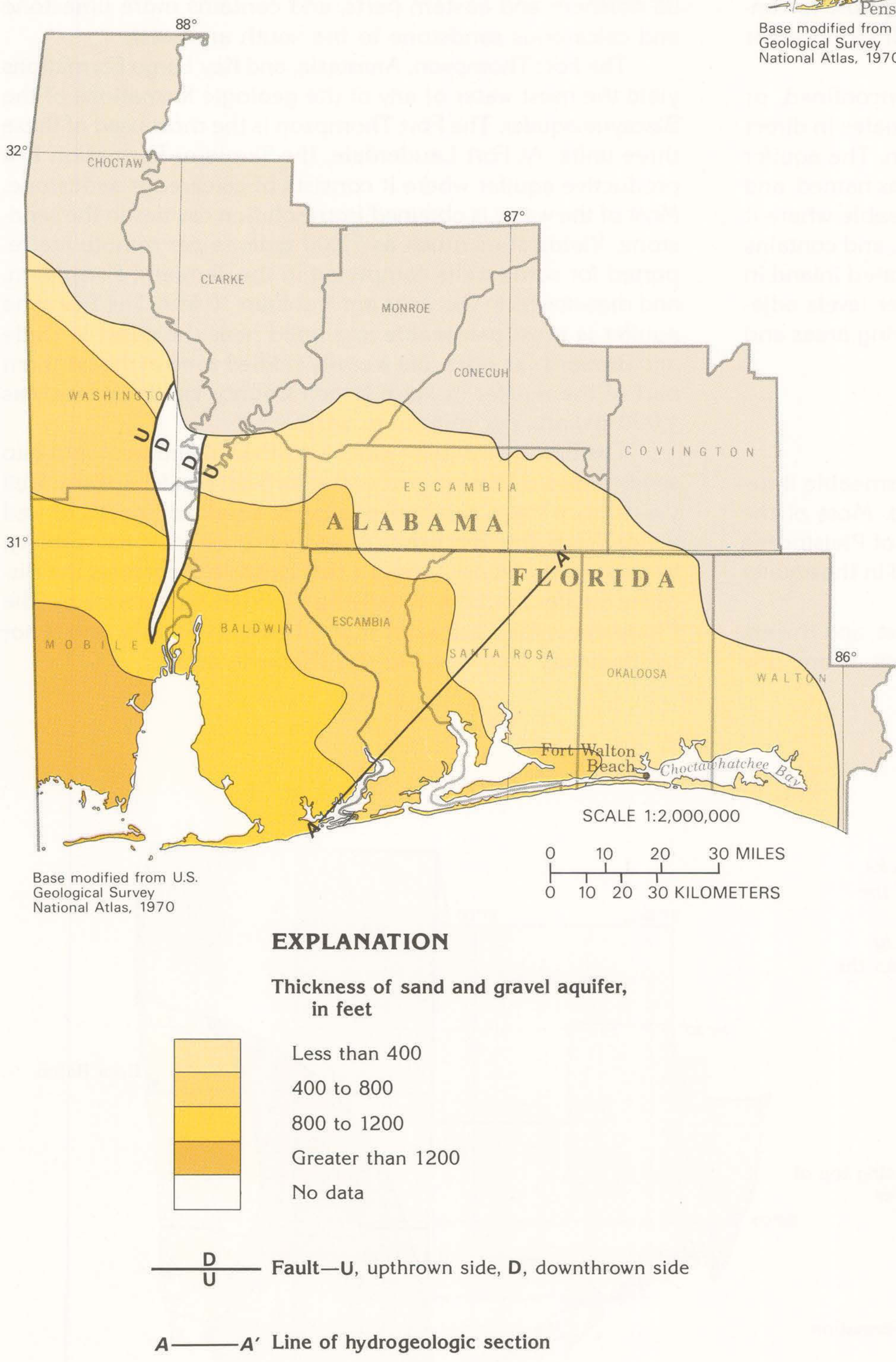


Figure 22. The sand and gravel aquifer thickens to the southwest. In western Alabama, the aquifer is offset by a down-dropped fault block called the Mobile graben.

GEOLOGY

The sand and gravel aquifer consists of rocks ranging in age from middle Miocene to Holocene that were mostly deposited in a deltaic environment. In Alabama, Miocene rocks are all included in the undifferentiated Catahoula Sandstone, a thick, predominantly nonmarine sequence of sand and clay beds. The Miocene units shown in **figure 21** are overlain by the Citronelle Formation of Pliocene age. The Citronelle is mostly fine- to coarse-grained sand that is locally gravelly, and is the most important water-yielding formation in the upper part of the sand and gravel aquifer. The Citronelle locally contains layers of hardpan, or cemented iron oxide, that retard ground-water movement. The principal geologic units that comprise the aquifer in the westernmost part of the panhandle Florida are shown in **figure 21**. The Alum Bluff Group and the Choctawatchee Formation, which were deposited in a more marine environment, are most easily recognizable near the coast. Northward, these beds grade into undifferentiated coarse sand and gravel, which comprise the major water-yielding unit of the lower part of the sand and gravel aquifer.

Series	Stratigraphic and hydrologic units			Lithology
Holocene and Pleistocene	Alluvium and terrace deposits		Sand and gravel aquifer	Undifferentiated silt, sand, and gravel, with some clay. Surficial zone of aquifer
Pliocene	Citronelle Formation		Sand and gravel aquifer	Sand, very fine to very coarse and poorly sorted. Hardpan layers in upper part
Miocene	Unnamed coarse clastics	Choctawhatchee Formation	Sand and gravel aquifer	Sand, shell, and marl
Miocene	Unnamed coarse clastics	Alum Bluff Group Shoal River Formation Chipola Formation	Sand and gravel aquifer	Sand with lenses of silt, clay, and gravel (includes unnamed coarse clastics and Alum Bluff Group). Main producing zone of aquifer
Miocene	Pensacola Clay		Confining unit	Dark to light gray sandy clay. Is basal confining unit in southern one-half of area
Miocene	St. Marks Formation		Floridan aquifer system	Limestone and dolomite--top of the Floridan aquifer system

Modified from Cushman-Roisin and Franks, 1982

Figure 21. Several geologic units of Miocene age and younger comprise the sand and gravel aquifer in the westernmost part of panhandle Florida. The aquifer extends to the land surface throughout its area of occurrence.

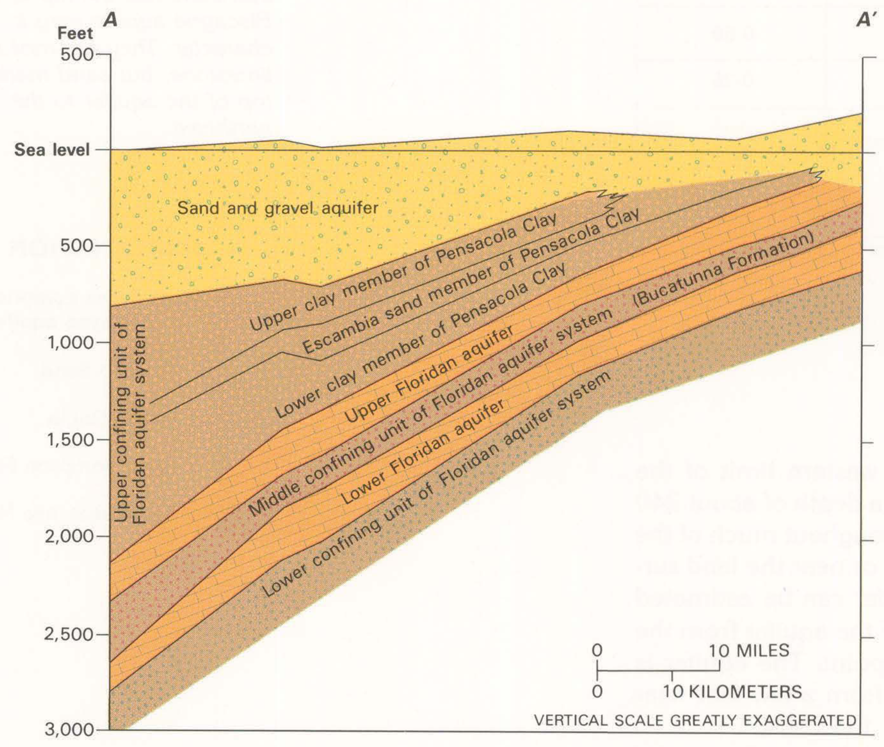


Figure 23. The base of the sand and gravel aquifer is formed by a thick series of clay beds to the southwest; however, the Upper Floridan aquifer is the base of the sand and gravel aquifer to the northeast. The line of the section is shown in figure 22.

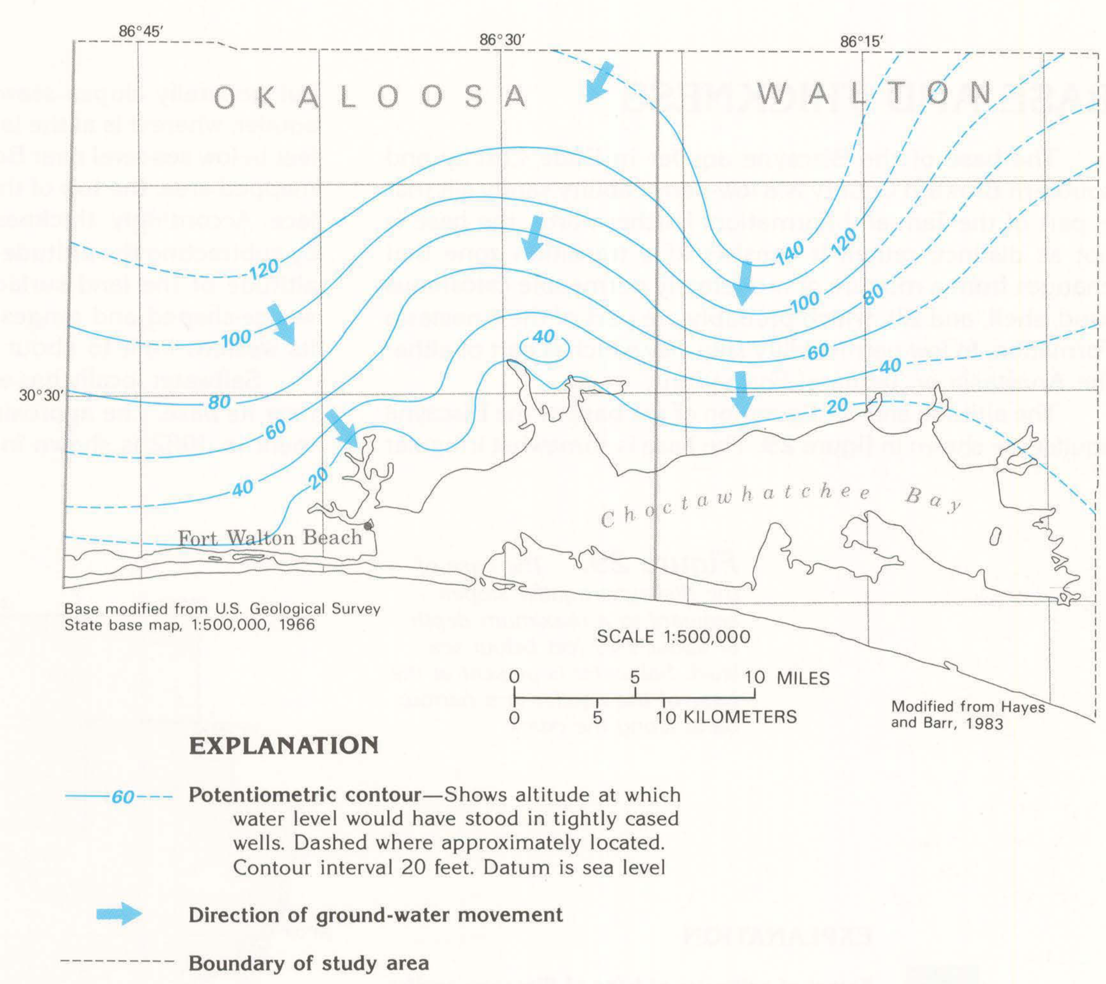


Figure 24. Water in the main producing zone of the sand and gravel aquifer moves toward the coast from inland recharge areas. The water levels were measured in March 1979.

THICKNESS

The sand and gravel aquifer is approximately wedge-shaped and thickens southwestward from a feather edge at its northern and eastern limit to about 1,400 feet in southwestern Alabama (**fig. 22**). Throughout the southern two-thirds of the area underlain by the aquifer, the confining unit forming the base of the aquifer consists of either the upper or lower clay members of the Pensacola Clay (**fig. 23**). Analysis of aquifer-test data, supplemented by the results of laboratory testing of cores from the Pensacola Clay, indicates that the permeability of this confining unit is so small that practically no water passes across it. To the northeast, the clay beds are absent and the sand and gravel aquifer is in direct contact with the Upper Floridan aquifer.

HYDROGEOLOGIC UNITS

In most places, the sand and gravel aquifer can be divided into two high-permeability zones, the upper surficial and lower main producing zones, separated by a less permeable sand and clay unit. The upper, or surficial, zone is mostly fine- to medium-grained sand, with gravel beds and lenses, and contains water that is mostly under unconfined conditions. This zone is recharged directly by precipitation, and ground-water flow in it is mostly lateral along short flowpaths to discharge points along small streams. Some of the water percolates downward and recharges the lower high-permeability zone. The upper zone consists mostly of the Citronelle Formation combined with stream-valley alluvium and terrace deposits. Along major streams, such as the Mobile River, alluvial deposits are as much as 150 feet thick and wells completed in them yield as much as 850 gallons per minute. The upper zone contains clay and hardpan layers that create local perched water tables or, in places, artesian conditions. The upper zone is mostly used for water supply in southern Mobile, southern Baldwin, and southwestern Escambia Counties, Ala., because the lower zone contains much clay in these counties, and, accordingly, yields less water. The hydraulic characteristics of the upper zone are extremely variable. Yields of as much as 1,000 gallons per minute are reported for wells completed in the upper zone, and a transmissivity of 11,000 feet squared per day was reported for the zone based on results of an aquifer test conducted in Escambia County, Ala.

In the westernmost part of panhandle Florida, the lower of the two high-permeability zones is called the "main producing zone" because most of the ground water used in Santa Rosa and Escambia Counties is withdrawn from this zone. This zone also is the main source of water supply for Washington, northern Mobile, northern Baldwin, and eastern Escambia Counties, Ala. The zone consists mostly of coarse sand and gravel beds, all of Miocene age. Water in this zone is confined everywhere. Recharge to the zone is by downward leakage from the upper zone; discharge is to major streams, bays, sounds, and the Gulf of Mexico. Yields of more than 1,000 gallons per minute are commonly reported for wells completed in this zone, and results of aquifer tests have indicated that the transmissivity of the zone is as much as 20,000 feet squared per day.

GROUND-WATER FLOW

Water enters the sand and gravel aquifer as recharge from precipitation, and moves generally downward and then either discharges to streams or moves coastward in the aquifer. Discharge is primarily to streams, bays, and sounds. Small volumes of water leak upward to the Gulf of Mexico and still smaller volumes are discharged by wells. Most of the well discharge is in Mobile County, Ala., and Escambia and Santa Rosa Counties, Fla.

Water movement in the upper zone of the aquifer is complex because this zone contains numerous discontinuous clay layers and some layers of iron oxide (hardpan). Because of the low permeability of the hardpan and the clay, and the confined conditions they produce, perched water-table conditions, artesian conditions, and true water-table conditions can all exist in one area. Such conditions prohibit drawing a representative map of the potentiometric surface of the aquifer, except for local areas. Where hardpan or clay beds are near the land surface, ponds may be perched on them or springs may issue at the top of such beds where they are exposed in small stream valleys. Some water percolates downward across all these confining beds to recharge deeper permeable zones in the aquifer. Water levels generally decrease with depth in the aquifer, a condition that allows downward leakage almost everywhere.

The saturated thickness of the aquifer is everywhere less than its total thickness because the water table ranges from a few feet to about 50 feet below land surface. The water table is just below land surface in low-lying areas and is deepest under hills and ridges.

The general coastward movement of water in the main producing zone of the sand and gravel aquifer is shown by the potentiometric contours in **figure 24**. The arrows show that the water is moving mostly toward Choctawatchee Bay from recharge areas where water levels are highest. The contours are smooth and evenly spaced because the water in this zone is confined. A similar map for the surficial zone of the aquifer would show the same general seaward movement of water, but the contours would be convoluted because of the effects of topography and streams.

GROUND-WATER QUALITY

Water in the sand and gravel aquifer is suitable for drinking practically everywhere. The quartz-rich sediments that comprise the aquifer are practically insoluble; accordingly, water in the aquifer has concentrations of dissolved solids that ordinarily are less than 50 milligrams per liter. Chloride concentrations also are ordinarily less than 50 milligrams per liter everywhere except in a few locations near the coast and adjacent to large bays and sounds where there is a transition zone of freshwater and saltwater; there, chloride concentrations greater than 1,000 milligrams per liter are reported in water from some wells. Water in the aquifer is usually slightly acidic, with a pH of about 6.0; locally, the water is more acidic (pH 4.5). Dissolved-iron concentrations may locally be objectionable; concentrations as large as 4,300 micrograms per liter have been reported.

The sand and gravel aquifer, like other shallow aquifers, is readily susceptible to contamination. Contamination of the upper zone has occurred at several places in the three westernmost counties of Florida. One such place is a site near Pensacola where creosote waste products from a wood-preserving plant have been detected in a large part of the upper zone of the aquifer.

FRESH GROUND-WATER WITHDRAWALS

Withdrawals of freshwater from the sand and gravel aquifer totaled 150 million gallons per day during 1985. About 44 percent, or about 66 million gallons per day, was withdrawn for public supply (**fig. 25**). About 9 million gallons per day was withdrawn for domestic and commercial uses, and about 18 million gallons per day was withdrawn for agricultural uses. About 57 million gallons per day was withdrawn for industrial, mining, and thermoelectric-power uses.

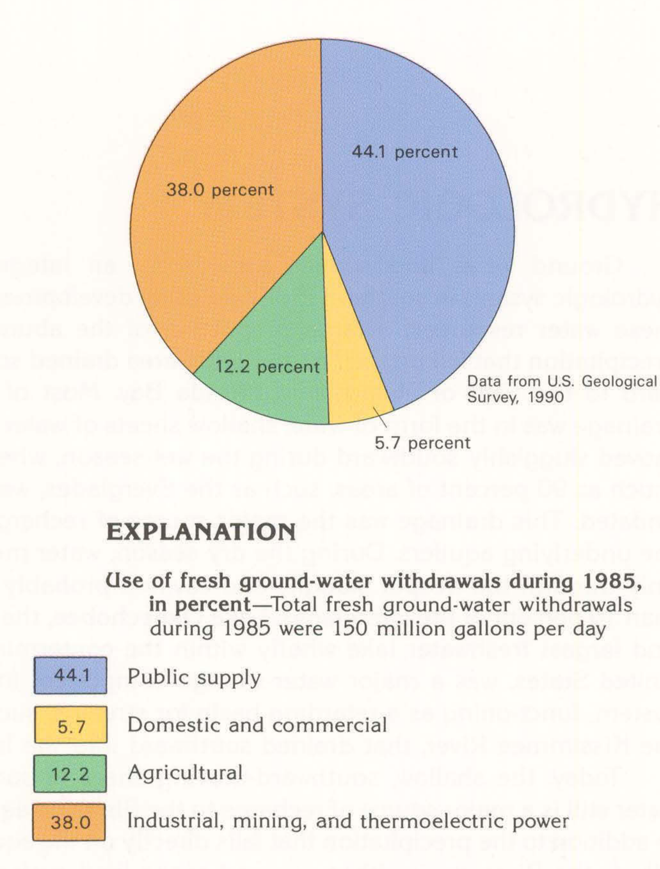


Figure 25. Most of the freshwater withdrawn from the sand and gravel aquifer during 1985 was used for public supply and industrial, mining, and thermoelectric-power purposes.

Biscayne aquifer

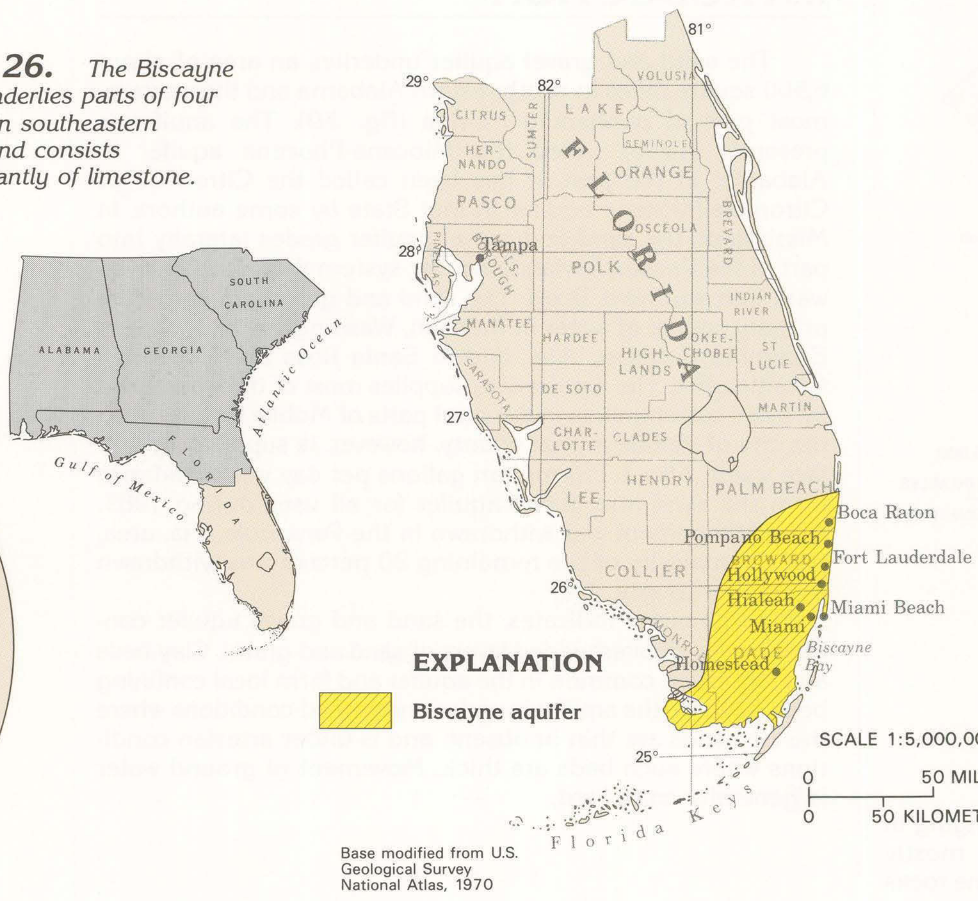


Figure 26. The Biscayne aquifer underlies parts of four counties in southeastern Florida, and consists predominantly of limestone.

INTRODUCTION

The Biscayne aquifer underlies an area of about 4,000 square miles and is the principal source of water for all of Dade and Broward Counties and the southeastern part of Palm Beach County in southern Florida (**fig. 26**). During 1985, an average of about 786 million gallons per day was withdrawn from the Biscayne aquifer for all uses; pumpage at present (1990) is somewhat greater. About 70 percent of the water was withdrawn for public supply. Major population centers that depend on the Biscayne aquifer for water supply include Boca Raton, Pompano Beach, Fort Lauderdale, Hollywood, Hialeah, Miami, Miami Beach, and Homestead. The Florida Keys also are supplied primarily by water from the Biscayne aquifer that is transported from the mainland by pipeline.

Because the Biscayne aquifer is highly permeable and lies at shallow depths everywhere, it is readily susceptible to contamination. The aquifer is the only source of drinking water for about 3 million people.

Water in the Biscayne aquifer is under unconfined, or water-table, conditions and the water table fluctuates in direct and rapid response to variations in precipitation. The aquifer extends beneath Biscayne Bay, from whence it was named, and the Atlantic Ocean. The aquifer is highly permeable where it forms part of the floor of the bay and the ocean, and contains saltwater there. Some of this saltwater has migrated inland in response to the lowering of inland ground-water levels adjacent to canals constructed for drainage of low-lying areas and near large well fields.

HYDROGEOLOGIC UNITS

The Biscayne aquifer consists of highly permeable limestone and less-permeable sandstone and sand. Most of the geologic formations comprising the aquifer are of Pleistocene age but, locally, Pliocene rocks also are included in the aquifer (**fig. 27**).

Most of the formations are thin and lens-like, and the entire sequence shown in **figure 27** is not present at any one place. Some of the units interfinger and some are lateral equivalents of each other. For example, the Anastasia Formation and Key Largo Limestone interfinger with the Fort Thompson Formation; in places, the Miami Oolite is equivalent to the Key Largo Limestone and in other places to the upper part of the Fort Thompson Formation; and so on. The thickest and most extensive geologic unit in the Biscayne aquifer is the Fort Thompson Formation, which is the surficial unit in northwestern Broward County and part of Palm Beach County (**fig. 28**); this unit is the major water-producing unit of the aquifer. The Anastasia Formation comprises much of the Biscayne at Fort Lauderdale and northward into Palm Beach County. However, the Pamlico Sand is the surficial unit in this area (**fig. 28**). The Miami Oolite, although thin, is a very porous, oolitic limestone that is present at the land surface throughout much of Dade County and parts of Broward and Monroe Counties (**fig. 28**). In general, the entire aquifer is more sandy in its northern and eastern parts, and contains more limestone and calcareous sandstone to the south and west.

The Fort Thompson, Anastasia, and Key Largo Formations yield the most water of any of the geologic formations of the Biscayne aquifer. The Fort Thompson is the most used of these three units. At Fort Lauderdale, the Tamiami Formation is a productive aquifer where it consists of calcareous sandstone. Most of the water is obtained from solution cavities in the sandstone. Yields of as much as 7,000 gallons per minute are reported for some wells completed in the Tamiami Formation, and drawdowns in the wells are less than 10 feet. The Biscayne aquifer is most permeable in a band near the coast in Dade and Broward Counties, but a cavity-riddled zone in the northern part of the aquifer in Palm Beach County yields as much as 1,000 gallons per minute to wells.

The Biscayne aquifer grades northward and westward into sandy deposits that are part of the surficial aquifer system. Well yields from these sandy deposits are small compared to well yields from the Biscayne. A sequence of low-permeability, largely clayey deposits about 1,000 feet thick separates the Biscayne aquifer from the underlying Floridan aquifer system. The Floridan contains saltwater in southeastern Florida, and is not hydraulically connected to the Biscayne aquifer.

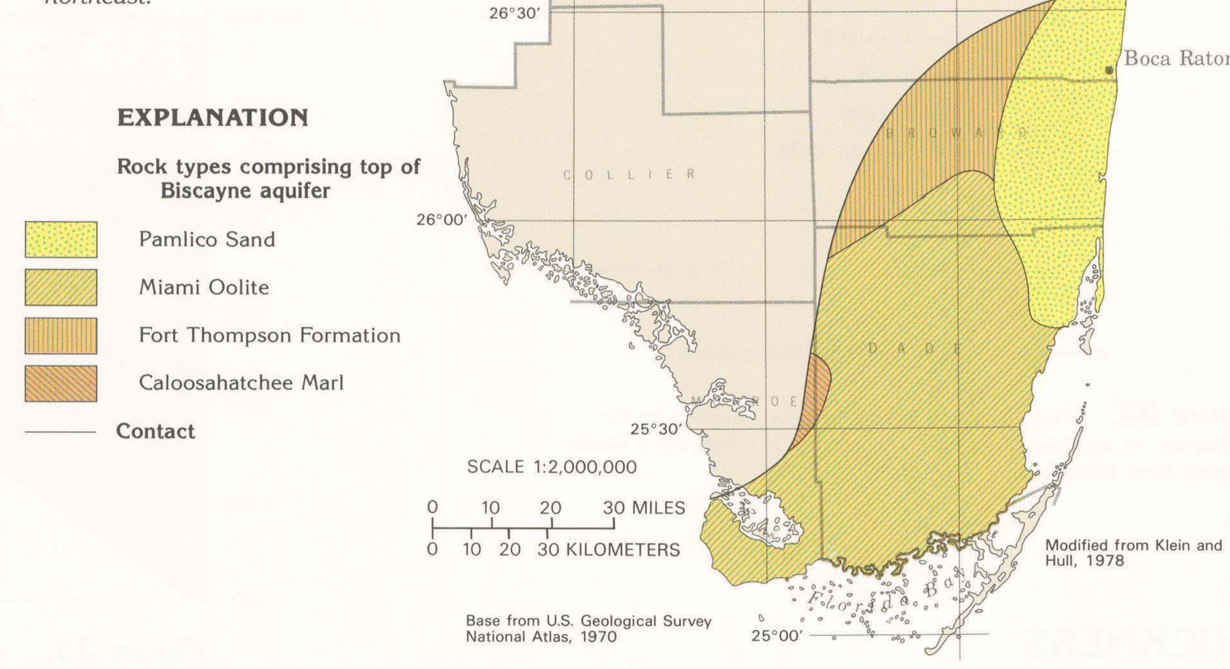
Series	Stratigraphic and hydrologic units		Lithology and water-yielding characteristics	Thickness (feet)
Holocene	Organic soils	Confining unit	Peat and muck; water has high color content. Almost impermeable. Lake Flirt is shelly, calcareous mud	0-18
	Lake Flirt Marl			
Pleistocene[1]	Pamlico Sand	Biscayne aquifer	Quartz sand; water high in iron. Small yields to domestic wells	0-40
	Miami Oolite		Sandy, oolitic limestone. Large yields	0-40
	Fort Thompson Formation		Alternating marine shell beds and freshwater limestone. Generally high permeability. Large yields	0-150
	Anastasia Formation		Coquina, sand, sandy limestone, marl. Moderate to large yields	0-120
	Key Largo Limestone		Coralline reef rock. Large yields	0-60
	Caloosahatchee Marl		Sand, shell, silt, and marl. Moderate yields	0-25
Pliocene	Tamiami Formation	Confining unit	Limestone, clay, and marl. Occasional moderate yields in upper few feet. Remainder forms upper part of basal confining unit.	25-220

[1]Stratigraphic units are equivalent in part. Order does not necessarily reflect relative age.

Modified from Klein and Causaras, 1982

Figure 27. Several geologic units comprise the Biscayne aquifer. Most of these units are of Pleistocene age.

Figure 28. The rocks that comprise the top of the Biscayne aquifer vary in character. They are mostly limestone, but sand marks the top of the aquifer to the northeast.



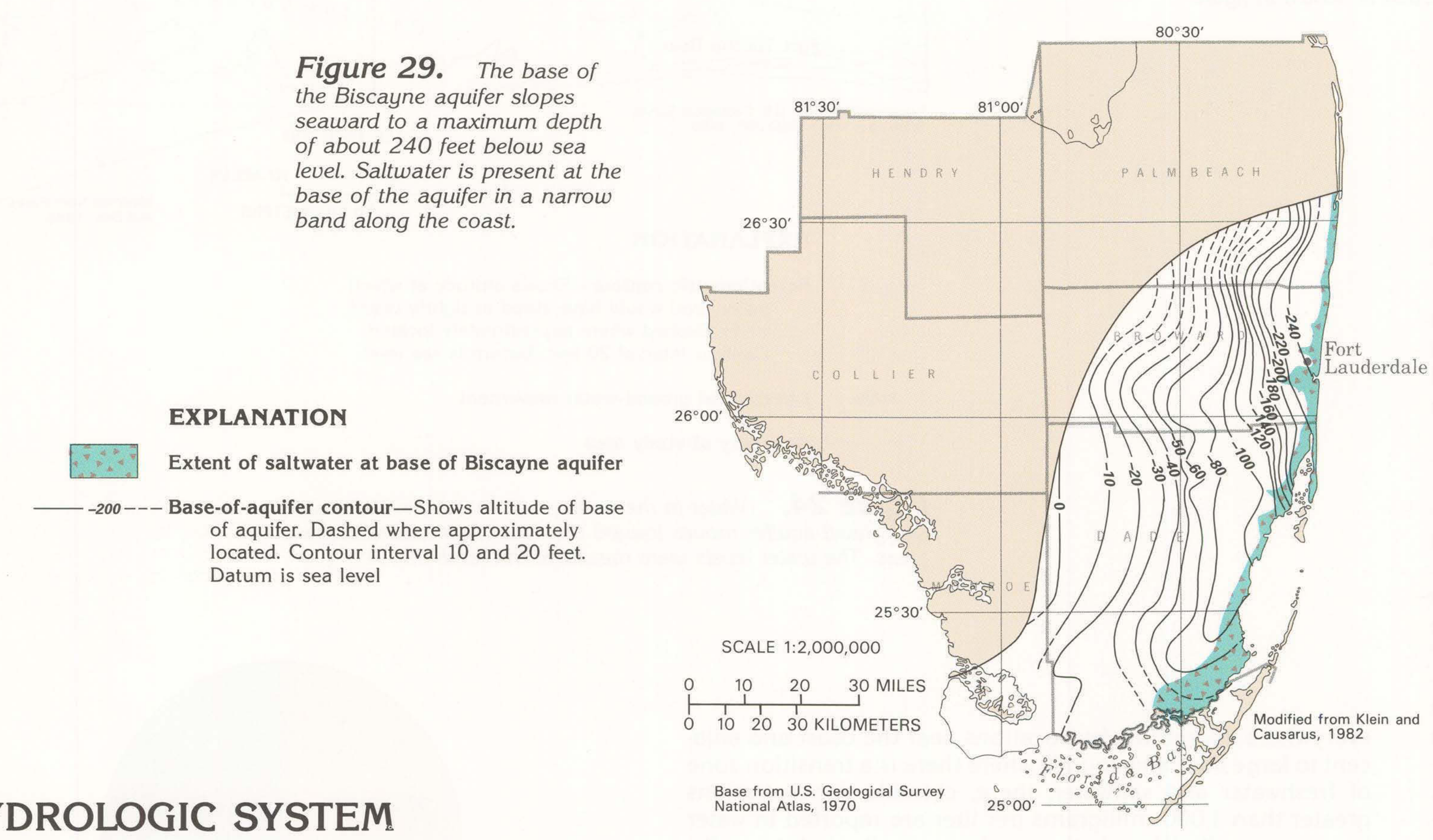
BASE AND THICKNESS

The base of the Biscayne aquifer in Dade County and southern Broward County is a low-permeability sandy silt that is part of the Tamiami Formation. Farther north, the base is not as distinct; rather, it consists of a transition zone that changes from a mixture of moderately permeable calcareous sand, shell, and silt, which probably are part of the Anastasia Formation, to low-permeability silty clay which is part of either the Anastasia or Tamiami Formations.

The altitude and configuration of the base of the Biscayne aquifer are shown in **figure 29**. The base is somewhat irregular but generally slopes seaward from the western limit of the aquifer, where it is at the land surface, to a depth of about 240 feet below sea level near Boca Raton. Throughout much of the mapped area, the top of the aquifer is at or near the land surface. Accordingly, thickness of the aquifer can be estimated by subtracting the altitude of the base of the aquifer from the altitude of the land surface at a given point. The aquifer is wedge-shaped and ranges in thickness from a few feet near its western limit to about 240 feet near the coast.

Saltwater locally has entered the Biscayne aquifer, mostly near its base. The approximate extent of saltwater encroachment in 1982 is shown in color in **figure 29**.

Figure 29. The base of the Biscayne aquifer slopes seaward to a maximum depth of about 240 feet below sea level. Saltwater is present at the base of the aquifer in a narrow band along the coast.



HYDROLOGIC SYSTEM

Ground water and surface water form an integrated hydrologic system in southern Florida. Before development of these water resources, a large proportion of the abundant precipitation that fell on the flat, low-lying area drained southward to the Gulf of Mexico and Florida Bay. Most of this drainage was in the form of wide, shallow sheets of water that moved sluggishly southward during the wet season, when as much as 90 percent of areas, such as the Everglades, was inundated. This drainage was the major source of recharge to the underlying aquifers. During the dry season, water moved only through the deeper sloughs and covered probably less than 10 percent of the Everglades. Lake Okeechobee, the second largest freshwater lake wholly within the conterminous United States, was a major water-storage component in the system, functioning as a retarding basin for streams, such as the Kissimmee River, that drained southward into the lake.

Today, the shallow, southward-moving sheet of surface water still is a major source of recharge to the Biscayne aquifer in addition to the precipitation that falls directly on the aquifer. Where the Biscayne is either exposed at the land surface or is covered only by a veneer of soil, the slowly moving surface water passing over the recharge area of the aquifer is able to readily percolate downward into the aquifer.

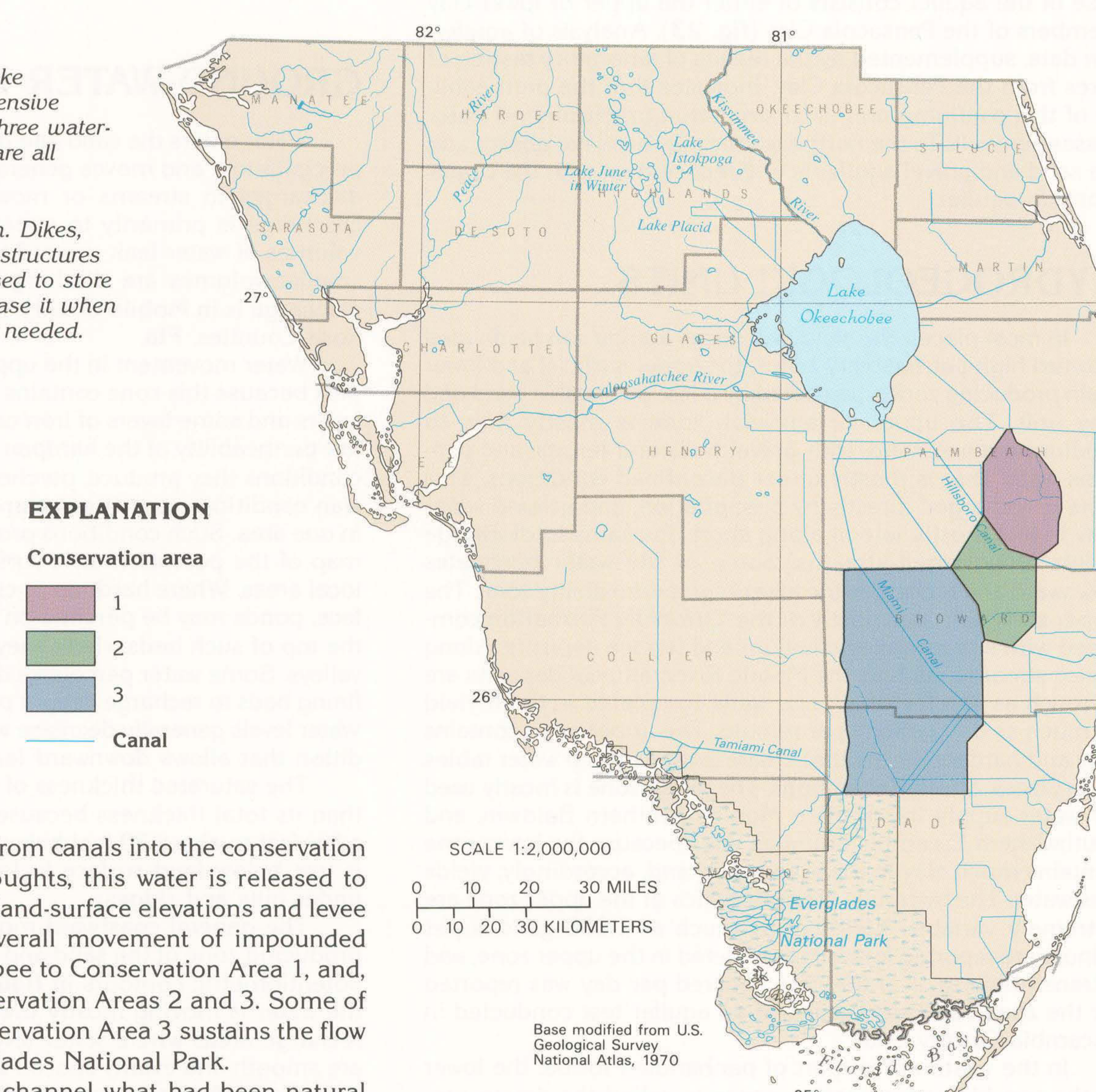
Freshwater Controls

Canals have been used extensively in southern Florida for drainage and flood control. Levees also were constructed, first to prevent flooding from Lake Okeechobee, and subsequently to impound excess water in three large water-conservation areas for later release. These alterations to the natural hydrologic system have culminated in a regional water system; major features of this system are shown in **figure 30**. The South Florida Water Management District utilizes a system of canals, levees, control structures, pumping stations, and water-conservation (storage) areas (Conservation Areas 1 through 3 in **fig. 30**) to manage the freshwater resources of southern Florida. The system conserves freshwater, provides flood control, and minimizes saltwater encroachment.

Impoundments, such as the water-conservation areas, provide water to the extensive canal system during dry periods. Seepage from the canals into the Biscayne aquifer during such periods helps maintain the water level in the aquifer. A network of major pumping stations provides flood protection by pumping excess stormwater from canals into the conservation areas. During prolonged droughts, this water is released to maintain canal flow. Natural land-surface elevations and levee heights are such that the overall movement of impounded water is from Lake Okeechobee to Conservation Area 1, and, thence, sequentially to Conservation Areas 2 and 3. Some of the water released from Conservation Area 3 sustains the flow of freshwater into the Everglades National Park.

Canals concentrate and channel what had been natural sheetflow. The drainage of wetlands is perhaps the most important aspect of the canal network, and was the primary reason for canal construction. However, a network of control structures also allows water to be diverted through the canal system to points where it may be needed to help maintain ground-water levels, such as near municipal well fields. Rapid interchange of water from the canals to the Biscayne aquifer is possible in most places because of the high permeability of the aquifer. Control structures near the coast on the major canals are particularly important in helping to prevent encroachment of saltwater into the canals, and subsequently into the aquifer, during periods of less than normal precipitation.

Figure 30. Lake Okeechobee, an extensive canal system, and three water-conservation areas are all linked as parts of a sophisticated water-management system. Dikes, pumps, and control structures on the canals are used to store stormwater and release it when and where it is later needed.



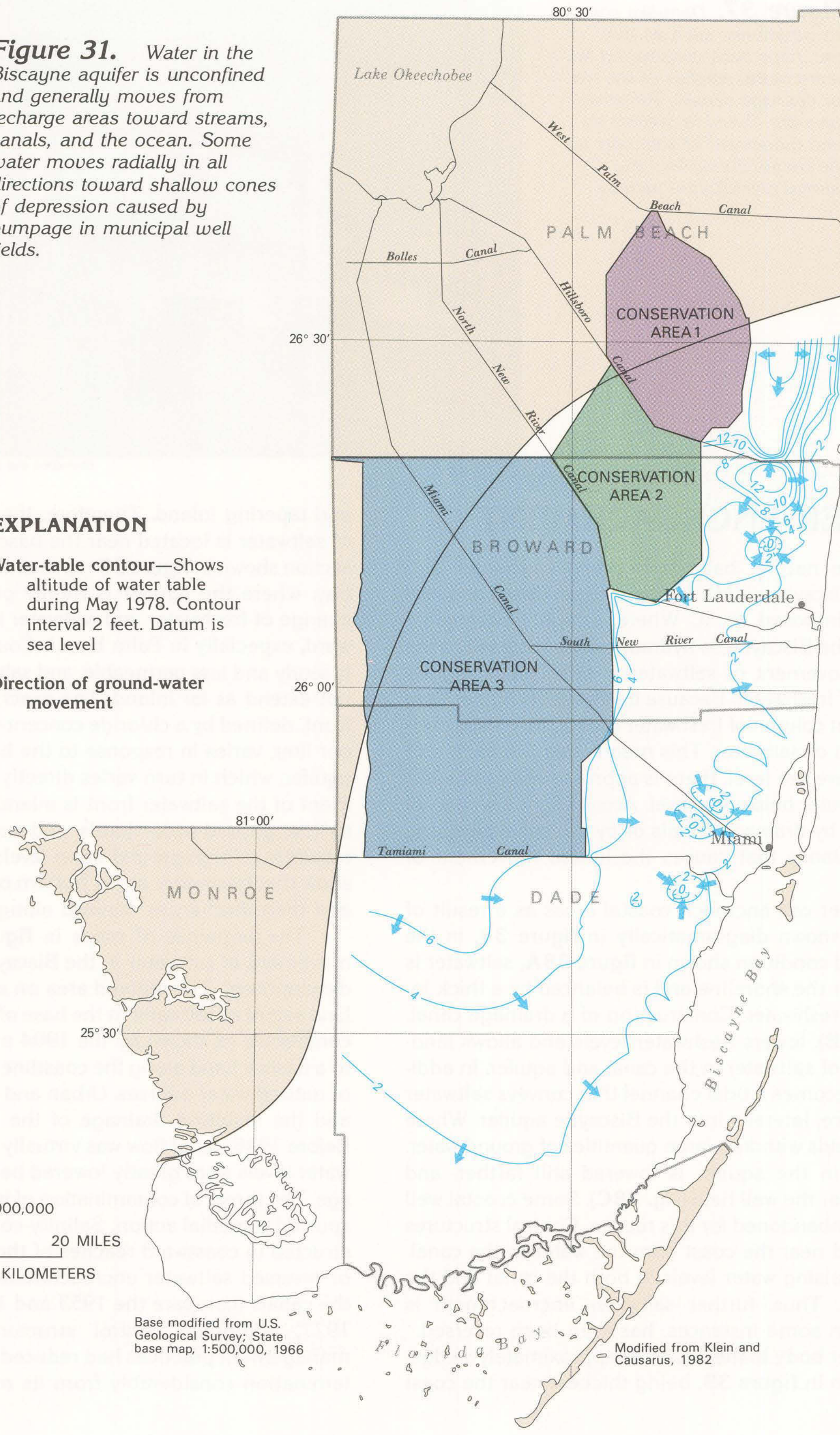


Figure 31. *Water in the Biscayne aquifer is unconfined and generally moves from recharge areas toward streams, canals, and the ocean. Some water moves radially in all directions toward shallow cones of depression caused by pumpage in municipal well fields.*

EXPLANATION

6 — **Water-table contour**—Shows altitude of water table during May 1978. Contour interval 2 feet. Datum is sea level

→ **Direction of ground-water movement**

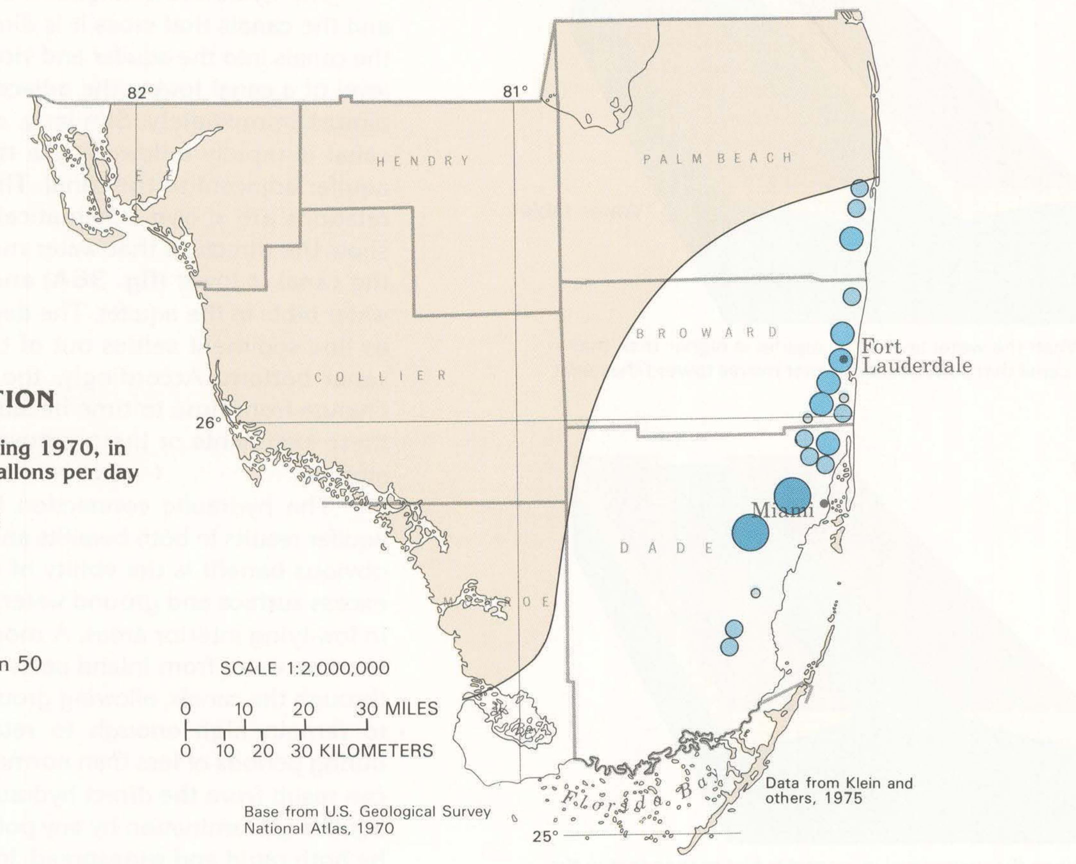


Figure 32. *The magnitude of municipal pumpage from the Biscayne aquifer is greatest in the Miami and Fort Lauderdale areas. However, a considerable volume of municipal water also is pumped from the aquifer in Palm Beach County.*

EXPLANATION

Pumpage during 1970, in million gallons per day

- Less than 2
- 2 to 10
- 10 to 50
- Greater than 50

HYDROLOGIC SYSTEM—Continued
Ground-Water Flow

The major features of the flow system in the Biscayne aquifer are shown by a generalized water-table map (**fig. 31**). The configuration of the water table is a subdued replica of the land surface; that is, the water table is at a higher altitude under hills and at a lower altitude under valleys. The water table fluctuates rapidly in response to variations in recharge (precipitation), natural discharge, and pumpage from wells. Natural discharge is by seepage into streams, canals, or the ocean; by evaporation; and by transpiration by plants.

The contours in **figure 31**, and the arrows superimposed on them, show that the general movement of water in the Biscayne aquifer is seaward. Water levels are generally highest near the water-conservation areas and lowest near the coast. Contours are not drawn in the conservation areas because they represent impoundments, and, accordingly, there is no slope in the water table there. The effects of natural surface drainage and uncontrolled canals on the water table are shown by the irregular patterns of the contours, particularly where they point upstream in a sharp "V" shape, showing that the aquifer is discharging to the canals. Near the coast, the contours point downstream, showing that the aquifer is being recharged from the canals. The water level of an unconfined aquifer typically is markedly affected by surface drainage.

Some of the local variations in the water table are due to other causes. The local high area in eastern Palm Beach County (**fig. 31**), where the water table is higher than 16 feet, is due to a local topographic high. The closed depressions in eastern Broward and Dade Counties reflect large-scale pumpage from major well fields supplying Miami and Fort Lauderdale (compare **figs. 31 and 32**). Withdrawal of large volumes of ground water has locally reversed the natural flow direction (note westward-pointing arrows adjacent to depressions), thereby increasing the possibility of saltwater encroachment. The wide spacing of contours in Dade County and southeastern Broward County indicates a slight gradient (slope) in the water table, as compared to a steep gradient to the north where the contours are closely spaced. The wide spacing of contours reflects areas where the Biscayne aquifer consists mostly of highly permeable limestone; permeability is less in the steep-gradient areas where the aquifer is sandier.

Water-Table Fluctuations

Major fluctuations in the water table of the Biscayne aquifer result from variations in recharge and natural or artificial discharge, or both. Fluctuations may range from 2 to 8 feet per year, depending primarily on variations in precipitation and pumpage. Pumpage is generally greater during periods of less than normal precipitation, as farmers and homeowners apply irrigation water to maintain crop production and lawn growth. Extremely low water-table conditions, such as those shown in **figure 33**, result from prolonged periods of less than normal precipitation. Total precipitation for the 2 years preceding the date of the water levels shown in **figure 33** barely exceeded the long-term average precipitation for a single year. As a result, water levels declined slightly below sea level throughout a large area in southern Dade County, primarily due to transpiration by plants coupled with domestic pumpage. Water levels also were below sea level in a smaller area at Miami Springs, due to pumpage from the municipal well field. Under these conditions, saltwater migrated inland for considerable distances. Most of the drainage canals also were uncontrolled at the time (1940's) represented by **figure 33**, thus the lowering of the water table; saltwater encroachment was accelerated by continuous drainage to canals.

Extensive flooding also occurs during periods of greater than average precipitation, such as that preceding the high-stage water levels of October 1947, shown in **figure 34**. Water overflowed the banks of many of the canals, and a large part of the inland area was inundated. West of Biscayne Bay, water levels were almost 11 feet higher than those shown in **figure 33**. In Hialeah, water levels that had declined to about 0.5 foot above sea level in 1945 rose to almost 9 feet above sea level in 1947. The numerous types of control structures in southern Florida were constructed largely to avoid the problems associated with such extreme water-level fluctuations as those indicated by these two figures.

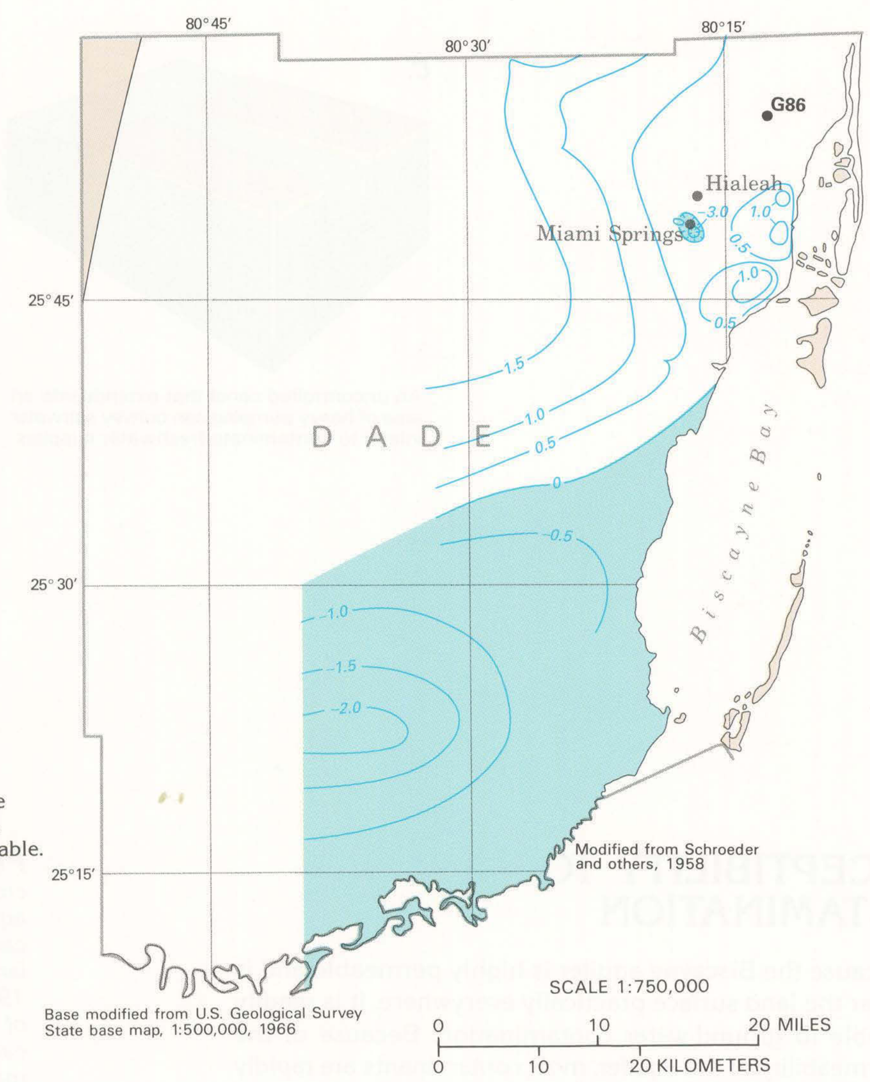


Figure 33. *During periods of less than normal precipitation, such as during May 1945, the water table in the Biscayne aquifer can decline below sea level throughout large areas. This decline results from a combination of pumpage and the demands of dense natural vegetation. There is potential for saltwater encroachment in the colored area.*

EXPLANATION

Area where water table was below sea level during May 1945

1.5 — **Water-table contour**—Shows altitude of water table during May 1945. Contour interval, in feet, is variable. Datum is sea level

● G86 **Well and number**

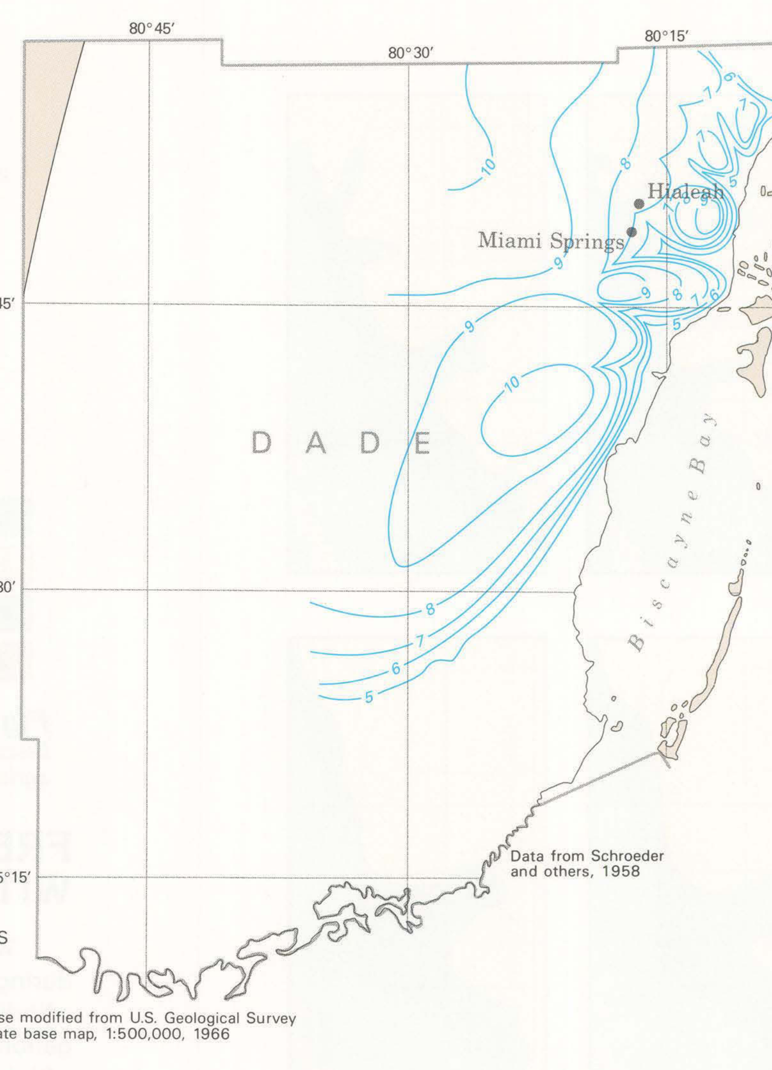


Figure 34. *During periods of greater than normal precipitation, such as during October 1947, the water table in the Biscayne aquifer is much higher and there is less potential for saltwater entering the aquifer.*

EXPLANATION

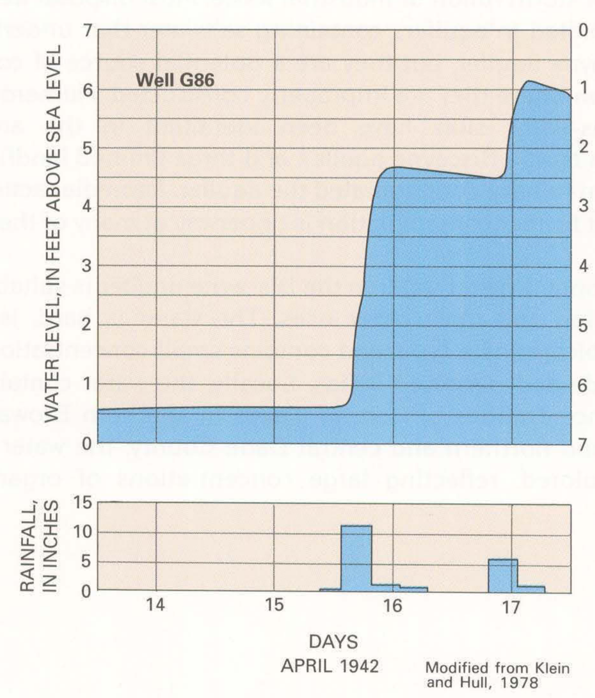
5 — **Water-table contour**—Shows altitude of water table during October 1947. Contour interval 1 foot. Datum is sea level

SCALE 1:750,000

0 10 20 MILES

0 10 20 KILOMETERS

Figure 35. *In an unconfined aquifer such as the Biscayne, the water table rises rapidly after intense rainfall. The location of the well is shown in figure 33.*



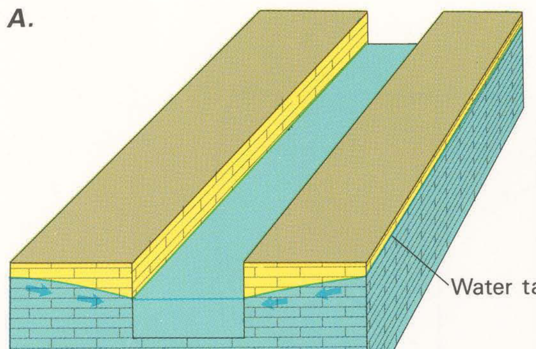
Response to Recharge

The highly permeable rocks of the Biscayne aquifer are covered in most places only by a veneer of porous soil. Accordingly, water levels in the aquifer rise rapidly in response to rainfall. The rise in the water level in well G-86, located in Miami, following two periods of intense rainfall in April 1942, is shown in **figure 35**. Eleven inches of rainfall during a 4-hour period in the early morning of April 16 produced a 4.5-foot rise in the water level in the well within a few hours. Six inches of rainfall during the late morning and early afternoon of April 17 was responsible for an additional rise of 1.5 feet in the water level in the well, also within only a few hours.

HYDROLOGIC SYSTEM—Continued

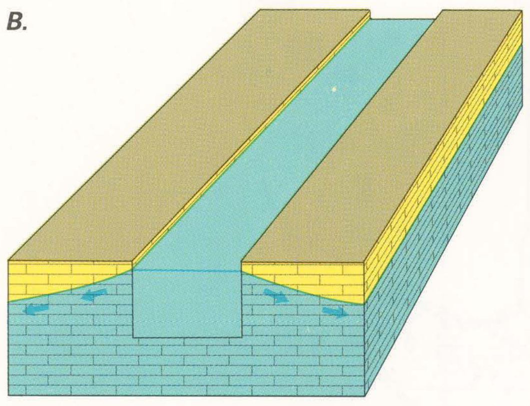
Canal-Aquifer Connection

A.



When the water level in an aquifer is higher than that in a canal that penetrates it, water moves toward the canal.

B.



When the water level in a canal is higher than that in the aquifer it penetrates, water moves into the aquifer.

Modified from Klein and others, 1975

Figure 36. *During periods of less than normal precipitation, water passes freely from the aquifer into canals that are dug into it (top diagram). When storm runoff raises canal water levels, the movement of water is reversed (B).*

The hydraulic connection between the Biscayne aquifer and the canals that cross it is direct. Water passes freely from the canals into the aquifer and vice versa. A decline in the water level of a canal lowers the adjacent water table of the aquifer almost immediately. Similarly, a rise in the water level in a canal is rapidly followed by a rise in the water table of the aquifer adjacent to the canal. These canal-aquifer water-level relations are shown schematically in **figure 36**. The arrows show the direction that water moves when the water level of the canal is lower (**fig. 36A**) and higher (**fig. 36B**) than the water table in the aquifer. The degree of connection decreases as fine sediment settles out of the canal water and lines the canal bottom. Accordingly, the degree of connection may change from time to time because of either accumulation of these sediments or their removal during runoff from intense storms.

The hydraulic connection between the canals and the aquifer results in both benefits and problems. Perhaps the most obvious benefit is the ability of the canals to rapidly remove excess surface and ground water, thereby preventing flooding in low-lying interior areas. A more subtle benefit is the ability to move water from inland parts of the aquifer to coastal areas through the canals, allowing ground-water levels near the coast to remain high enough to retard saltwater encroachment during periods of less than normal precipitation. Problems also can result from the direct hydraulic connection. For example, aquifer contamination by any pollutants in the canal water can be both rapid and widespread. In addition, the canals provide channels by which saltwater can encroach into the aquifer for considerable distances inland during periods of low water. The latter problem has been greatly alleviated by the construction of large-scale canal control structures near the coastal ends of the major canals (**fig. 37**). These structures prevent the movement of saltwater up the canals when water levels in the canals are low.

Sherwood and others, 1973

Figure 37. *Dam-like control structures, such as this one, have been constructed in near-coastal reaches of the major drainage canals. The structures are closed to prevent inland movement of saltwater up the canals during less than normal precipitation periods.*

SALTWATER ENCROACHMENT

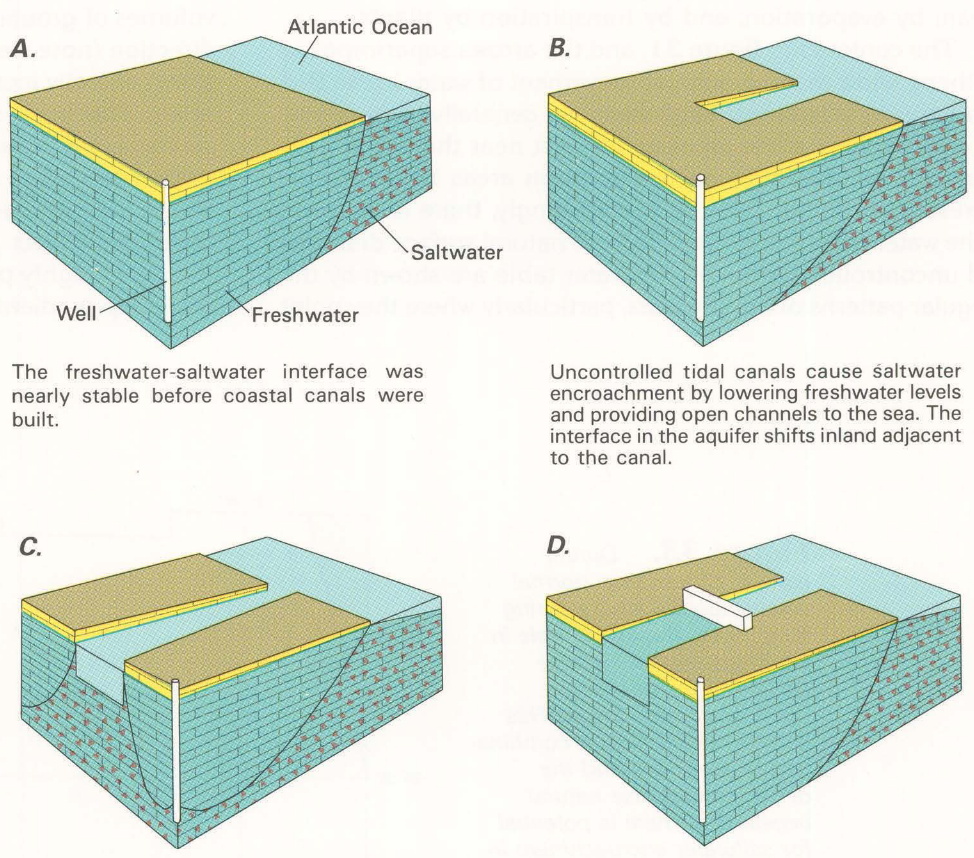
The delicate natural balance between freshwater and saltwater in the Biscayne aquifer is tipped when canals and well fields are superimposed on it. Where a highly permeable aquifer, such as the Biscayne, is hydraulically connected to the ocean, inland movement of saltwater is offset by a slightly higher column of freshwater. Because freshwater is lighter than saltwater, a 41-foot column of freshwater is necessary to balance a 40-foot column of saltwater. This means that, for each foot of freshwater above sea level, there is approximately a 40-foot column of freshwater below sea level. Accordingly, lowering of freshwater levels by drainage canals or by intensive pumping creates an imbalance that causes the inland movement of saltwater.

How saltwater can encroach coastal areas as a result of development is shown diagrammatically in **figure 38**. In the natural, balanced condition shown in **figure 38A**, saltwater is present only near the shoreline and is balanced by a thick inland column of freshwater. Construction of a drainage canal, however (**fig. 38B**), lowers freshwater levels and allows landward movement of saltwater in the canal and aquifer. In addition, the canal becomes a tidal channel that conveys saltwater inland and, thence, laterally into the Biscayne aquifer. Where municipal well fields withdraw large quantities of ground water, the water level in the aquifer is lowered still farther, and saltwater can enter the well field (**fig. 38C**). Some coastal well fields have been abandoned for this reason. Control structures (**fig. 38D**) placed near the coast dam the water in the canal, thus, artifically raising water levels in both the canal and the adjacent aquifer. Thus, further saltwater encroachment is prevented and, in some instances, has even been reversed.

The saltwater body in the aquifer is approximately wedge-shaped, as shown in **figure 39**, being thickest near the coast and tapering inland. Therefore, the maximum inland extent of saltwater is located near the base of the aquifer. The cross section shown in **figure 39** represents conditions near Biscayne Bay, where the aquifer is highly permeable and free interchange of freshwater and saltwater is possible. Farther northward, especially in Palm Beach County, the Biscayne aquifer is sandy and less permeable, and saltwater encroachment does not extend as far inland. The exact position of the saltwater front, defined by a chloride concentration of 1,000 milligrams per liter, varies in response to the height of freshwater in the aquifer, which in turn varies directly with precipitation. Movement of the saltwater front is inland and upward in response to low ground-water levels and seaward and downward in response to high ground-water levels. The arrows in **figure 39** show that freshwater at the bottom of the aquifer flows upward and then discharges seaward along the saltwater front.

The sequence of maps in **figure 40** shows the inland movement of saltwater in the Biscayne aquifer in response to development. The colored area on all the maps shows the inland extent of saltwater at the base of the aquifer. Under natural conditions, as shown by the 1904 map, saltwater was limited to a narrow band along the coastline and to short tidal reaches of natural water courses. Urban and agricultural development and the resulting drainage of the land had not yet begun. Before 1946, canal flow was virtually uncontrolled and ground-water levels were greatly lowered because of extensive pumpage. The threat of contamination of inland municipal well fields spurred remedial action. Salinity-control structures were constructed in coastward reaches of the major canals and halted or reversed saltwater encroachment, particularly adjacent to the canals (compare the 1953 and 1969 maps of **fig. 40**). By 1977, additional control structures and effective water-management practices had reduced the area of saltwater contamination considerably from its maximum extent in 1953.

Figure 38. *The original, virtually stable freshwater-saltwater interface (A) was disturbed by construction of drainage canals (B). Uncontrolled canals (C) are open conduits, allowing saltwater to migrate inland, contaminating the aquifer, and, in places, encroaching into pumped wells. A properly located control structure (D) prohibits the saltwater encroachment.*



A. The freshwater-saltwater interface was nearly stable before coastal canals were built.

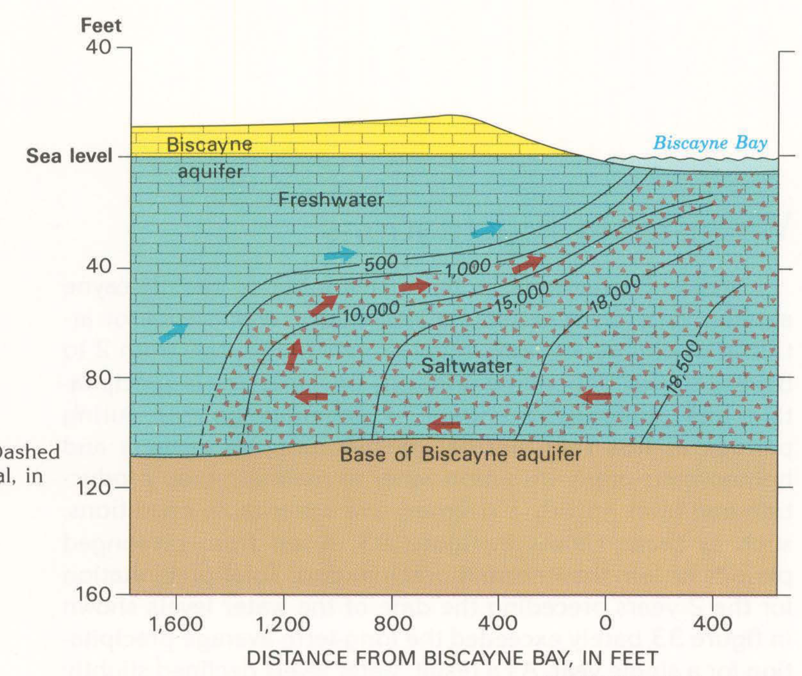
B. Uncontrolled tidal canals cause saltwater encroachment by lowering freshwater levels and providing open channels to the sea. The interface in the aquifer shifts inland adjacent to the canal.

C. An uncontrolled canal that extends into an area of heavy pumping can convey saltwater inland to contaminate freshwater supplies.

D. In contrast, a controlled canal can provide a perennial supply of freshwater to prevent saltwater encroachment and to recharge a well field by bringing in freshwater from upgradient areas.

Modified from Klein and others, 1975

Figure 39. *Saltwater extends farther inland near the base of the Biscayne aquifer rather than near the top of it.*



Modified from U.S. Department of the Interior, 1973

EXPLANATION

---- 500 — **Line of equal chloride concentration**—Dashed where approximately located. Interval, in milligrams per liter, is variable

Direction of ground-water movement

→ Freshwater

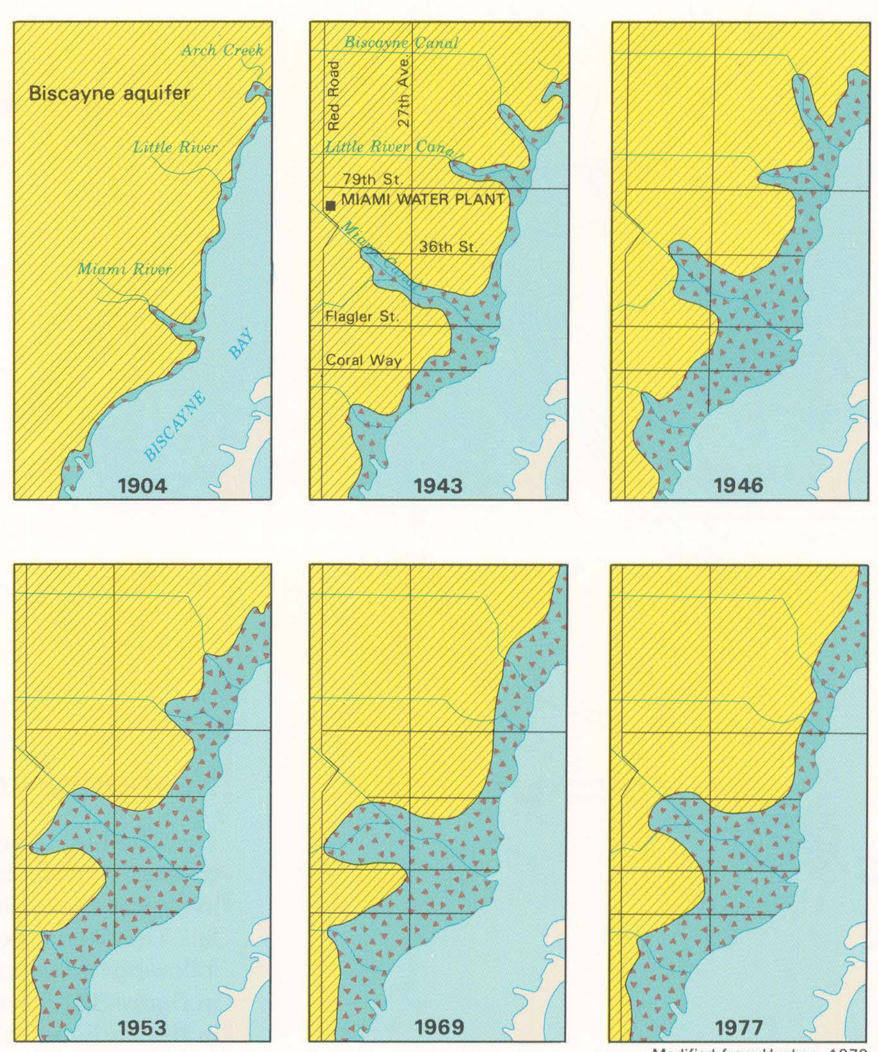
→ Saltwater

SUSCEPTIBILITY TO CONTAMINATION

Because the Biscayne aquifer is highly permeable and is at or near the land surface practically everywhere, it is readily susceptible to ground-water contamination. Because of the high permeability of the aquifer, most contaminants are rapidly flushed. Major sources of contamination are saltwater encroachment and infiltration of contaminants carried in canal water. Additional sources include direct infiltration of contaminants, such as chemicals or pesticides applied to or spilled on the land, or fertilizer carried in surface runoff; landfills; septic tanks; sewage-plant treatment ponds; and wells used to dispose of storm runoff or industrial waste. Most disposal wells are completed in aquifers containing saltwater that underlie the Biscayne aquifer, but they are a potential source of contamination where they are improperly constructed. Numerous hazardous-waste sites have been identified in the area underlain by the Biscayne aquifer, and three unlined landfills are known to have contaminated the aquifer. Remedial action to prevent further contamination is underway at many of these sites.

Uncontaminated water in the Biscayne aquifer is suitable for drinking and most other uses. The water is hard, is a calcium bicarbonate type, and contains small concentrations of chloride and dissolved solids. Locally, the water contains large concentrations of iron. In places in southern Broward County and northern and central Dade County, the water is darkly colored, reflecting large concentrations of organic material.

Figure 40. *Saltwater encroachment in the Biscayne aquifer, mainly adjacent to canals, occurred in increasingly larger areas from 1904 until 1953. After the emplacement of control structures on major canals, encroachment was markedly slowed and even reversed in places.*



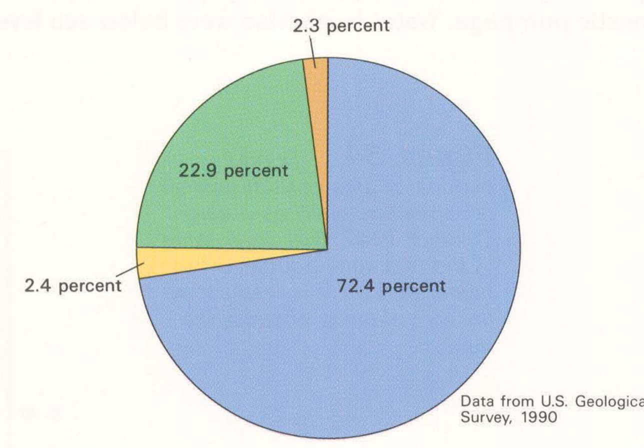
Modified from Hughes, 1979

EXPLANATION

Extent of saltwater encroachment at base of Biscayne aquifer in the Miami area

0 2 4 6 MILES

0 2 4 6 KILOMETERS



Data from U.S. Geological Survey, 1990

EXPLANATION

Use of fresh ground-water withdrawals during 1985, in percent—Total fresh ground-water withdrawals during 1985 were 786 million gallons per day

72.4	Public supply
2.4	Domestic and commercial
22.9	Agricultural
2.3	Industrial, mining, and thermoelectric power

Figure 41. *Most of the freshwater withdrawn from the Biscayne aquifer during 1985 was used for public supply and agricultural purposes.*

FRESH GROUND-WATER WITHDRAWALS

Withdrawals of freshwater from the Biscayne aquifer during 1985 totaled 786 million gallons per day. Public-supply withdrawals were almost three-quarters, or about 569 million gallons per day, (**fig. 41**). Domestic and commercial withdrawals were about 19 million gallons per day. Agricultural withdrawals were about 180 million gallons per day. Withdrawals for industrial, mining, and thermoelectric-power uses were about 18 million gallons per day.

Intermediate aquifer system

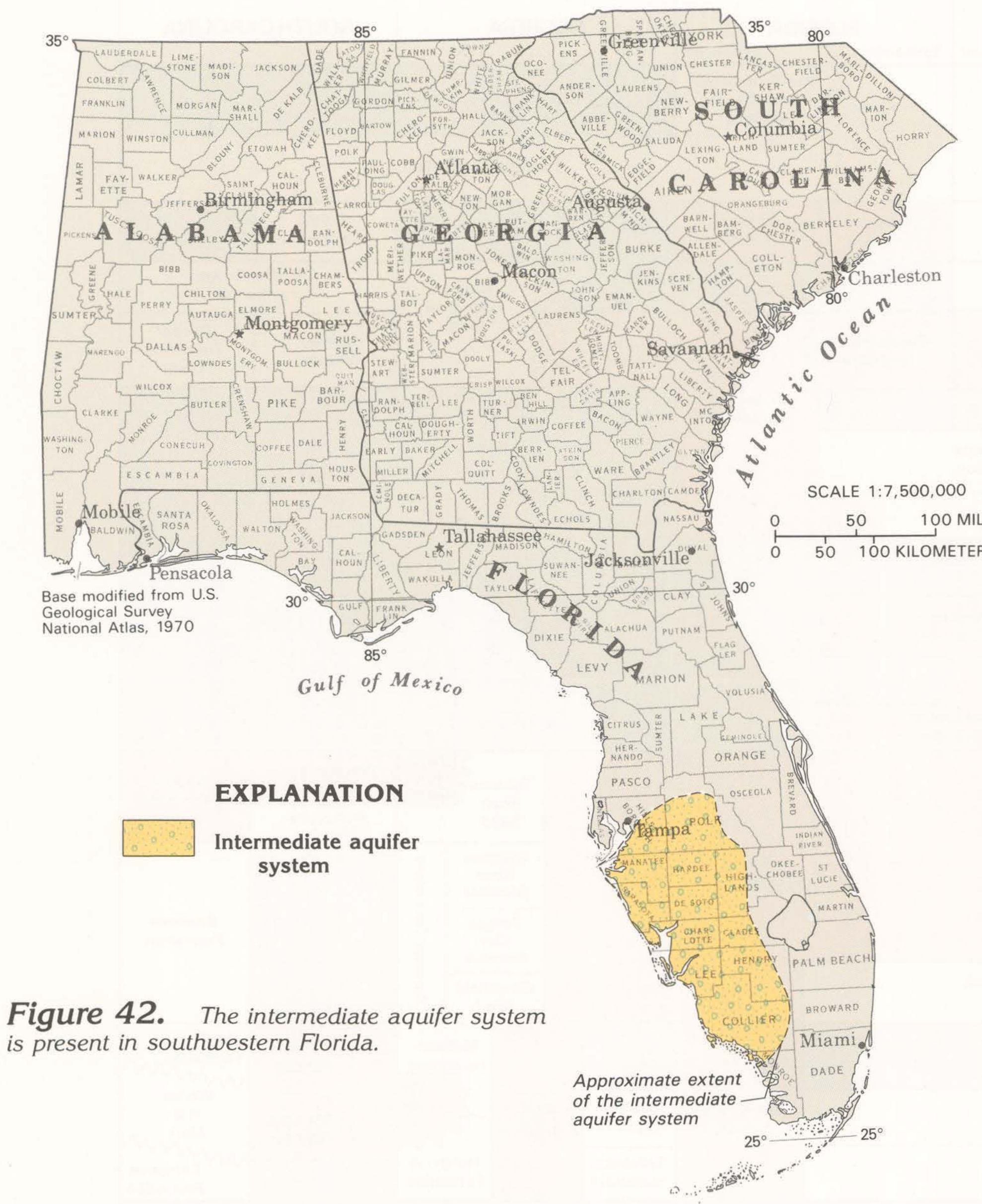


Figure 42. The intermediate aquifer system is present in southwestern Florida.

INTRODUCTION

Collectively, aquifers in southwestern Florida that lie between the surficial aquifer system and the Floridan aquifer system are called the intermediate aquifer system in this Atlas. The approximate extent of the intermediate aquifer system is shown in **figure 42**. This aquifer system contains water under confined, or artesian, conditions, but does not yield as much water as the underlying Floridan aquifer system. Accordingly, the intermediate aquifer system is not extensively used, and its characteristics are not well known, especially where the Floridan is near the land surface and contains freshwater. The intermediate aquifer system is the main source of water supply in Sarasota, Charlotte, and Lee Counties, Fla., where the underlying Floridan aquifer system is deeply buried and contains brackish or saltwater.

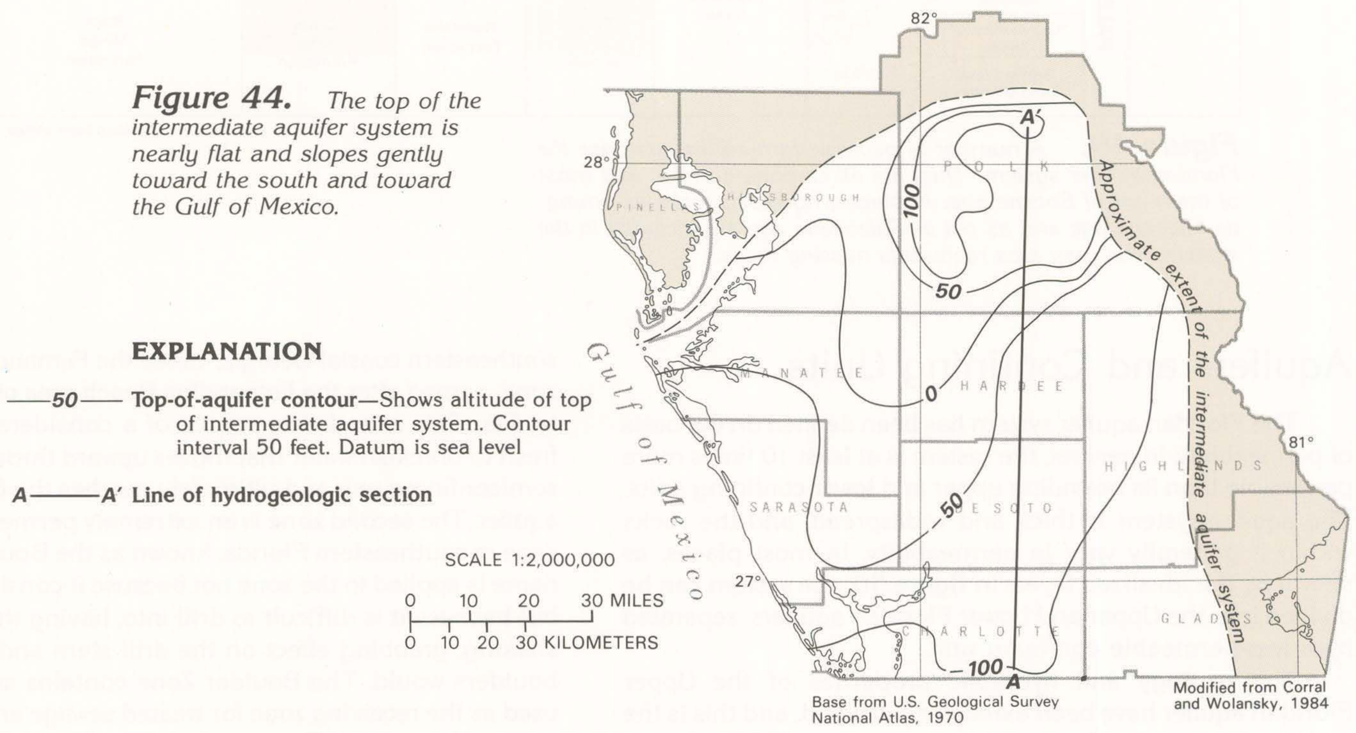
The intermediate aquifer system consists of sand beds and limestone lenses that are parts of the Tampa Limestone and Hawthorn Formation of Miocene age; and sand, limestone, and shell beds of the Tamiami Formation of Pliocene age (**fig. 43**). Clay confining units isolate the aquifers in the system from the Floridan and surficial aquifer systems. Where the rocks of the intermediate aquifer system grade into slightly yielding or nonyielding clayey beds, they become part of the upper confining unit of the Floridan aquifer system. Locally, in Clay, Brevard, and Indian River Counties, Fla., the Hawthorn Formation yields water, but its water-yielding beds are not continuous. In Glynn County, Ga., sand beds in the Hawthorn Formation are pumped locally for water supplies where the underlying Floridan aquifer system contains brackish water. These local aquifers in southeastern Georgia and northeastern Florida are not considered to be part of the intermediate aquifer system.

Series	Stratigraphic unit	Hydrogeologic unit		Lithology
Holocene and Pleistocene	Surficial deposits	Surficial aquifer system		Undifferentiated sand with some limestone
Pliocene	Tamiami Formation	Confining unit	Intermediate aquifer system	Sand, limestone, and shell beds. Thick clay near top
		Tamiami-upper Hawthorn aquifer		
Miocene	Hawthorn Formation	Confining unit		Mostly limestone, sandy limestone, and sand. Phosphatic in part. Dolomite beds common. Clayey in middle part
		Lower Hawthorn-upper Tampa aquifer		
	Tampa Limestone	Confining unit		Limestone, sandy limestone, and sand. Clay beds in middle part.
		Floridan aquifer system		

Modified from Duerr and Wolansky, 1986

Figure 43. Geologic formations of Miocene and Pliocene age comprise the intermediate aquifer system. The system is covered everywhere by younger deposits.

Figure 44. The top of the intermediate aquifer system is nearly flat and slopes gently toward the south and toward the Gulf of Mexico.



HYDROGEOLOGIC UNITS

The top of the intermediate aquifer system slopes gently southward and southwestward. Its top is highest in western Polk County, Fla., and lowest in southern Charlotte County, Fla. (**fig. 44**). South of the area shown in **figure 44**, the top of the aquifer system becomes flatter, then rises slightly.

In many places, the intermediate aquifer system can be divided into two aquifers, the Tamiami-upper Hawthorn and the lower Hawthorn-upper Tampa aquifer, separated in most places by an unnamed confining unit. The aquifer system thickens southward from Polk County into Charlotte County, Fla., (**fig. 45**). Farther southward in Collier County, the aquifer system thins as the lower Hawthorn-upper Tampa aquifer becomes predominately a clay with little permeability. The Tamiami-upper Hawthorn aquifer is the principal water-yielding part of the intermediate aquifer system in Glades, Hendry, Charlotte, Lee, and Collier Counties; elsewhere, the lower Hawthorn-upper Tampa aquifer is the major source of supply.

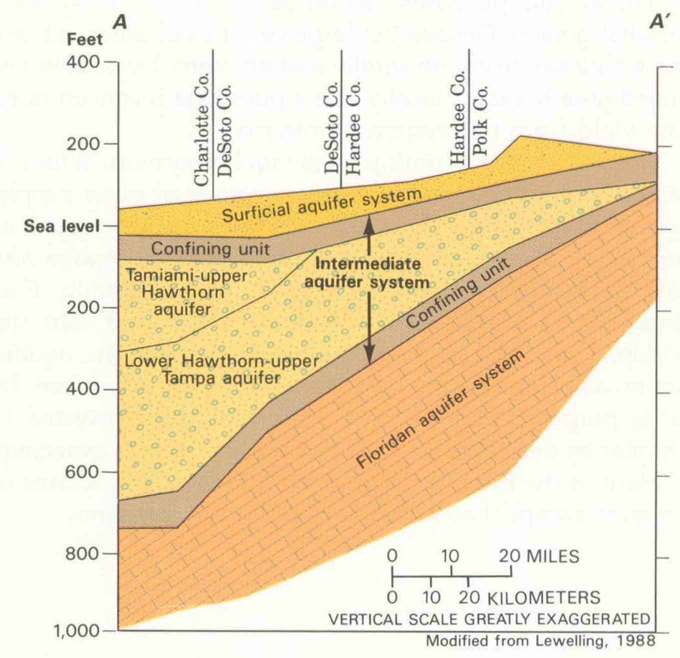


Figure 45. The intermediate aquifer system becomes thick and contains more limestone southward. The line of the section is shown in figure 44.

GROUND-WATER FLOW

The water-yielding beds of the intermediate aquifer system lie between clayey confining units. Therefore, the water in the aquifer system is under confined conditions except locally, where the upper confining unit is absent and the system is in direct hydraulic contact with the overlying surficial aquifer system. In most places, water moves downward from the surficial aquifer system and through the upper confining unit of the intermediate aquifer system; most of this water then follows short flowpaths and discharges to surface drainage. Some water, however, percolates downward through the lower confining unit of the system to recharge the underlying Floridan aquifer system. Locally, in western Charlotte and Lee Counties, some water leaks upward from the Floridan to the intermediate aquifer system.

The lateral direction of water movement in part of the intermediate aquifer system is shown in **figure 46**. The flow arrows, which are drawn perpendicular to the potentiometric contours, show that water moves outward in all directions from two recharge areas in southwestern Polk County, where the potentiometric surface is more than 120 feet above sea level. From these points, lateral flow is toward major surface streams and the Gulf of Mexico. Two local pumping centers are shown by the depressions in the potentiometric surface in western Sarasota County.

Well yields of as much as 1,800 gallons per minute from the intermediate aquifer system have been reported. Most wells, however, yield 200 gallons per minute or less. Most transmissivity values reported for the intermediate aquifer system are 10,000 feet squared per day or less.

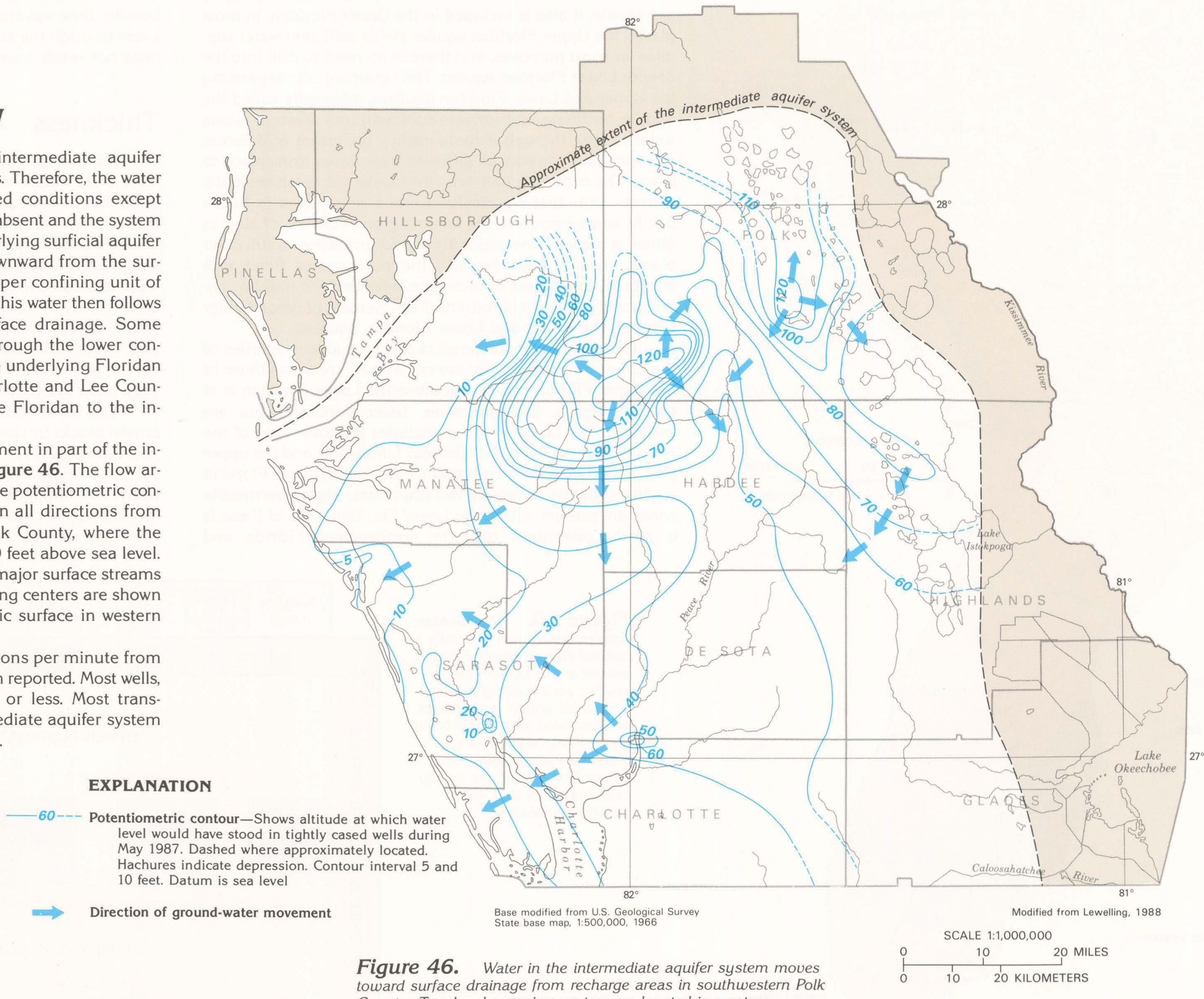


Figure 46. Water in the intermediate aquifer system moves toward surface drainage from recharge areas in southwestern Polk County. Two local pumping centers are located in western Sarasota County.

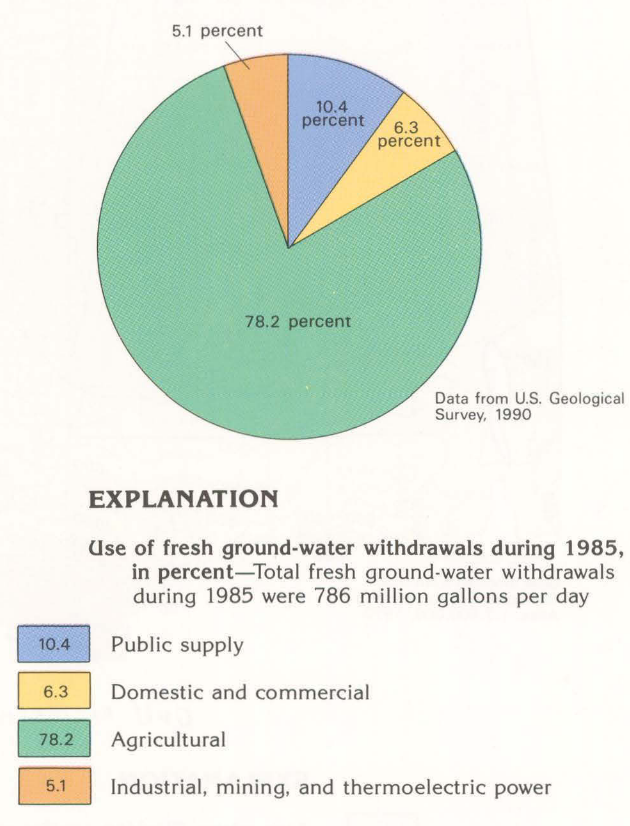


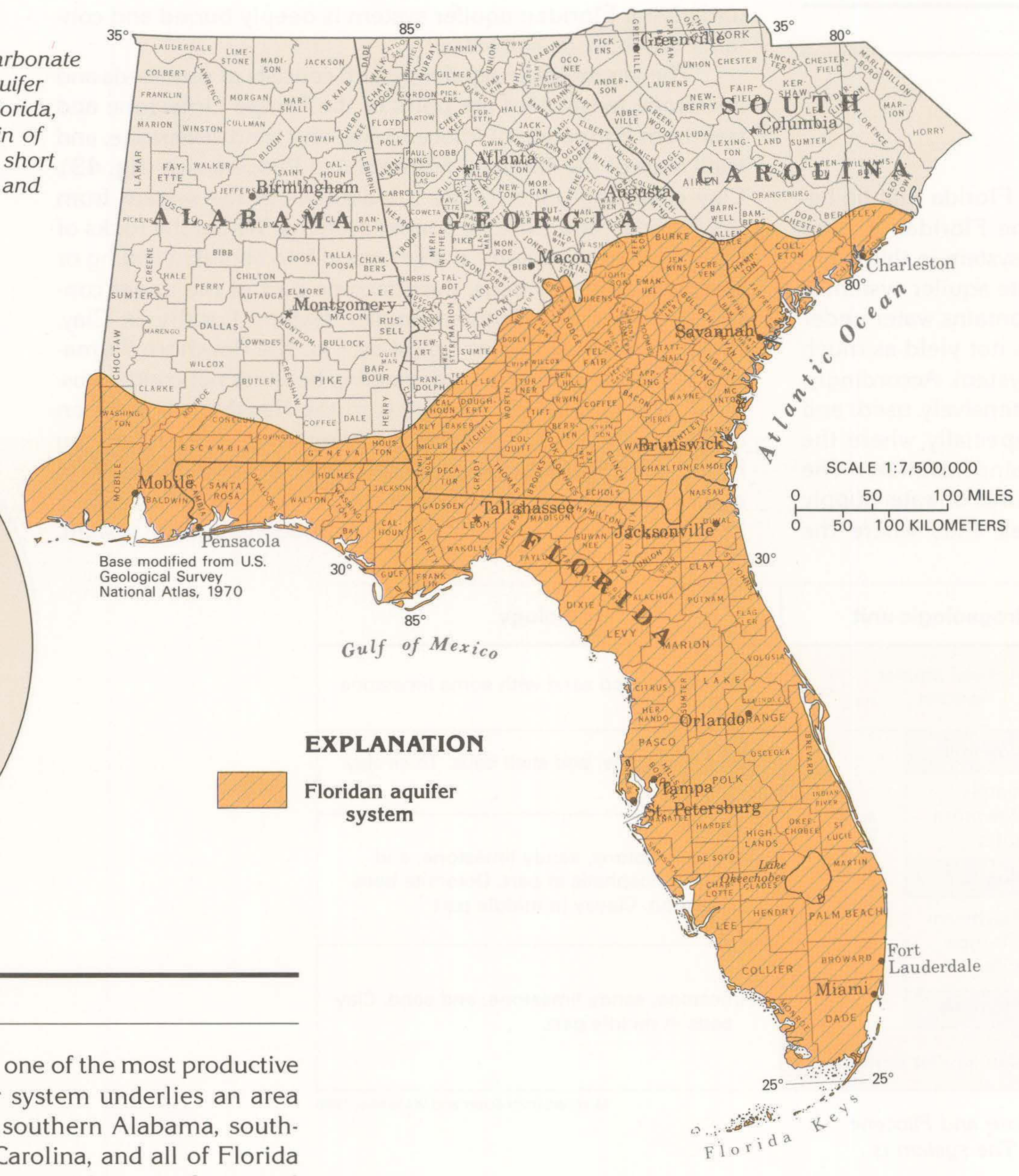
Figure 47. Most of the freshwater withdrawn from the intermediate aquifer system during 1985 was used for agricultural purposes.

FRESH GROUND-WATER WITHDRAWALS

Withdrawals of freshwater from the intermediate aquifer system totaled about 298 million gallons per day during 1985. About 31 million gallons per day was withdrawn for public supply, and about 19 million gallons per day was withdrawn for domestic and commercial uses (**fig. 47**). About 233 million gallons per day, was withdrawn for agricultural purposes, the principal water use. About 15 million gallons per day was withdrawn for industrial, mining, and thermoelectric-power uses.

Floridan aquifer system

Figure 48. The carbonate rocks of the Floridan aquifer system underlie all of Florida, most of the Coastal Plain of Georgia, and extend for short distances into Alabama and South Carolina.



INTRODUCTION

The Floridan aquifer system is one of the most productive aquifers in the world. This aquifer system underlies an area of about 100,000 square miles in southern Alabama, southeastern Georgia, southern South Carolina, and all of Florida (**fig. 48**). The Floridan aquifer system provides water for several large cities, including Savannah and Brunswick in Georgia; and Jacksonville, Tallahassee, Orlando, and St. Petersburg in Florida. In addition, the aquifer system provides water for hundreds of thousands of people in smaller communities and rural areas. Locally, the Floridan is intensively pumped for industrial and irrigation supplies. During 1985, an average of about 3 billion gallons per day of freshwater was withdrawn from the Floridan for all purposes. Withdrawals during 1988 were somewhat greater. Despite the huge volumes of water that are being withdrawn from the aquifer system, water levels have not declined greatly except locally where pumpage is concentrated or the yield from the system is minimal.

The Floridan is a multiple-use aquifer system. Where it contains freshwater, it is the principal source of water supply. In several places where the aquifer contains saltwater, such as along the southeastern coast of Florida, treated sewage and industrial wastes are injected into it. Near Orlando, Fla., drainage wells are used to divert surface runoff into the Floridan. South of Lake Okeechobee in Florida, the aquifer contains saltwater. Some of this saltwater is withdrawn for cooling purposes and some is withdrawn and converted to freshwater by desalinization plants. Desalinization is especially important in the Florida Keys, which have no other source of freshwater except that which is imported by pipeline.

HYDROGEOLOGIC UNITS

A thick sequence of carbonate rocks (limestone and dolomite) of Tertiary age comprise the Floridan aquifer system. The thickest and most productive formations of the system are the Avon Park Formation and the Ocala Limestone of Eocene age (**fig. 49**). The Suwannee Limestone (Oligocene age) also is a principal source of water, but it is thinner and much less areally extensive than the Eocene formations. The Tampa Limestone of Miocene age is part of the Floridan in only a few places where it is sufficiently permeable to be an aquifer. Both the Suwannee and the Tampa Limestones are discontinuous. The lower part of the Avon Park Formation, the Oldsmar Formation of early Eocene age, and the upper part of the Cedar Keys Formation of Paleocene age also are included in the Floridan where they are highly permeable. Limestone beds in the lower part of the Hawthorn Formation of Miocene age are considered part of the Floridan by some, but are excluded from it in this Atlas because the permeability of these beds is thought to be minimal. The base of the aquifer system in much of Florida consists of nearly impermeable anhydrite beds in the Cedar Keys Formation. In northern peninsular Florida, the Paleocene and lowermost Eocene rocks contain sand and are much less permeable than the carbonate rocks of the Floridan. Due to the contrast in permeability, these sandy strata form the base of the Floridan aquifer system in this area. Locally, in south-central Georgia and northern peninsular Florida, evaporite minerals have filled the pore spaces in upper Eocene rocks, and these low-permeability beds comprise the base of the system.

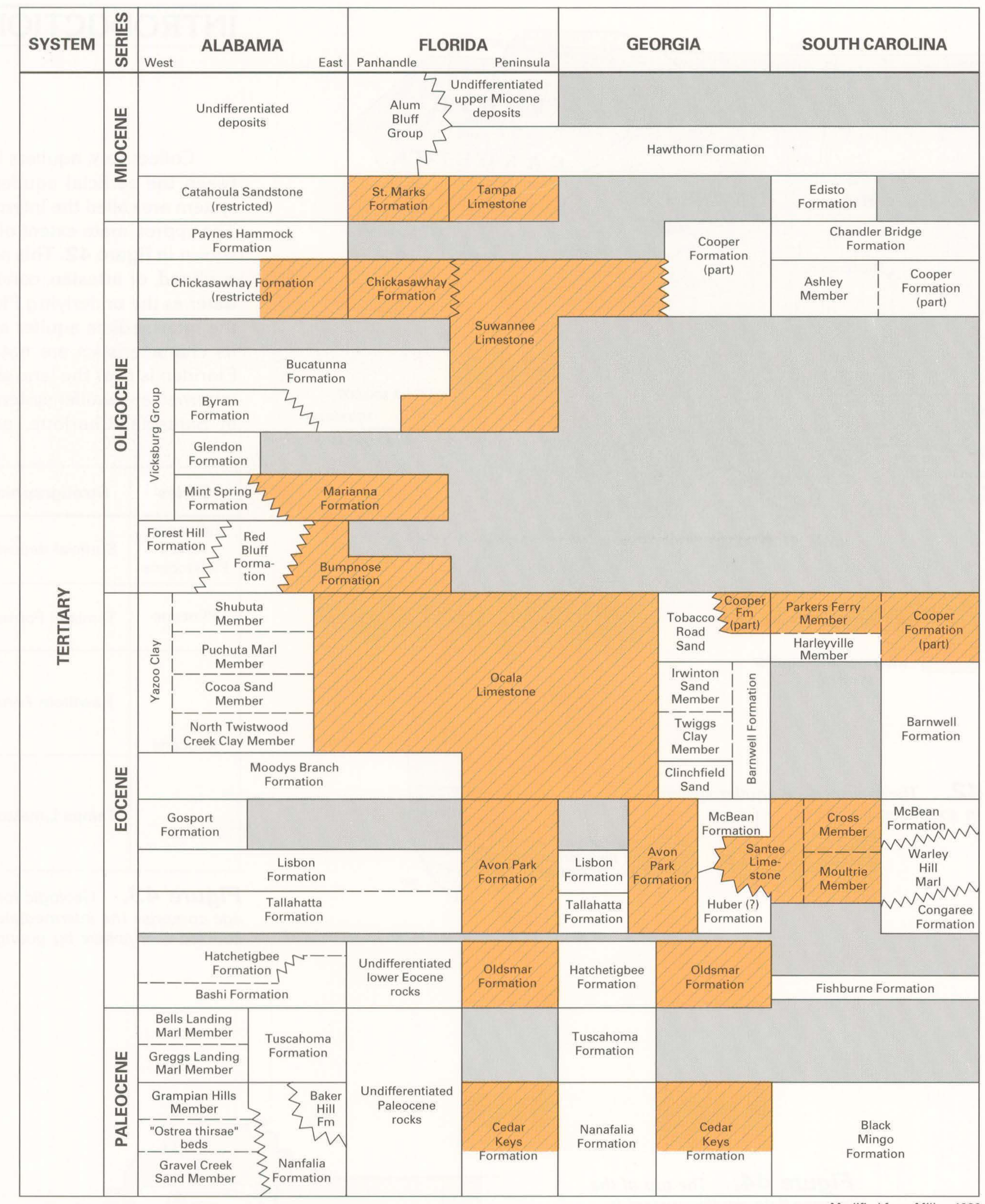


Figure 49. A number of geologic formations comprise the Floridan aquifer system. They are all carbonate rocks, and most of them are of Eocene age. In places, however, rocks as young as Miocene age and as old as Paleocene age are included in the system. The gray area represents missing rocks.

Aquifers and Confining Units

The Floridan aquifer system has been defined on the basis of permeability. In general, the system is at least 10 times more permeable than its bounding upper and lower confining units. The aquifer system is thick and widespread, and the rocks within it generally vary in permeability. In most places, as shown by the idealized layers in **figure 50**, the system can be divided into the Upper and Lower Floridan aquifers, separated by a less-permeable confining unit.

The geology and hydraulic properties of the Upper Floridan aquifer have been extensively studied, and this is the part of the system described by most reports. The Upper Floridan is highly permeable in most places and includes the Suwannee and Ocala Limestones, and the upper part of the Avon Park Formation. Where the Tampa Limestone is highly permeable, it also is included in the Upper Floridan. In most places, the Upper Floridan aquifer yields sufficient water supplies for most purposes, and there is no need to drill into the deeper Lower Floridan aquifer. The confining unit separating the Upper and Lower Floridan aquifers, informally called the middle confining unit (or semiconfining unit where it allows water to leak through it more easily), is present at different altitudes and consists of different rock types from place to place. The confining unit actually consists of seven separate, discrete units that are idealized into a single layer in **figure 50**. At some locations, the confining unit consists of clay; at others, it is a very fine-grained (micritic) limestone; at still other places, it is a dolomite with the pore spaces filled with anhydrite. Regardless of rock type, wherever the middle confining unit is present, it restricts the movement of ground water between the Upper and Lower Floridan aquifers.

The geologic characteristics and hydraulic properties of the Lower Floridan aquifer are not as well known as those of the Upper Floridan aquifer because the Lower Floridan is at greater depths, and, therefore, fewer borehole data are available. The Lower Floridan includes the lower part of the Avon Park Formation, the Oldsmar Limestone, and the upper part of the Cedar Keys Formation. Much of the Lower Floridan aquifer contains saltwater. Two important, highly permeable zones are present within the Lower Floridan. One of these is a partly cavernous zone in northeastern Florida and southeastern coastal Georgia, called the Fernandina permeable zone, named after the Fernandina Beach area of Nassau County, Fla. This zone is the source of a considerable volume of fresh to brackish water that moves upward through the middle semiconfining unit and ultimately reaches the Upper Floridan aquifer. The second zone is an extremely permeable cavernous zone in southeastern Florida, known as the Boulder Zone. This name is applied to the zone not because it consists of boulders, but because it is difficult to drill into, having the same rough, shaking, grabbing effect on the drill stem and drilling rig as boulders would. The Boulder Zone contains saltwater and is used as the receiving zone for treated sewage and other wastes disposed through injection wells in the Miami-Fort Lauderdale area. The zone is overlain in most places by a confining unit that prevents upward movement of the injected waste. The cavernous nature of the Fernandina permeable zone and the Boulder Zone was created by the vigorous circulation of ground water through the carbonate rocks in the geologic past, and does not result from the present ground-water flow system.

Thickness

The Floridan aquifer system generally thickens seaward from a thin edge near its northern limit. The variations in thickness of the aquifer system are shown in **figure 51**. The contours represent the combined thicknesses of the Upper and Lower Floridan aquifers, and the middle confining unit where it is present. Some of the large-scale features on the thickness map are related to geologic structures. For example, the thick areas in Glynn County, Ga., and in Gulf and Franklin Counties, Fla., coincide with two downwarped areas, the Southeast and Southwest Georgia embayments, respectively. In north-central peninsular Florida, the limestone units that comprise the aquifer system are thin over the upwarped Peninsular arch.

A series of small faults bounds downdropped, trough-like crustal blocks (grabens) in southern Georgia and southwestern Alabama (**fig. 51**). Within these grabens, respectively called the Gulf Trough and Mobile graben, clayey sediments have been downdropped opposite permeable limestone of the Floridan aquifer system. This juxtaposition creates a damming effect that restricts the flow of ground water across the grabens.

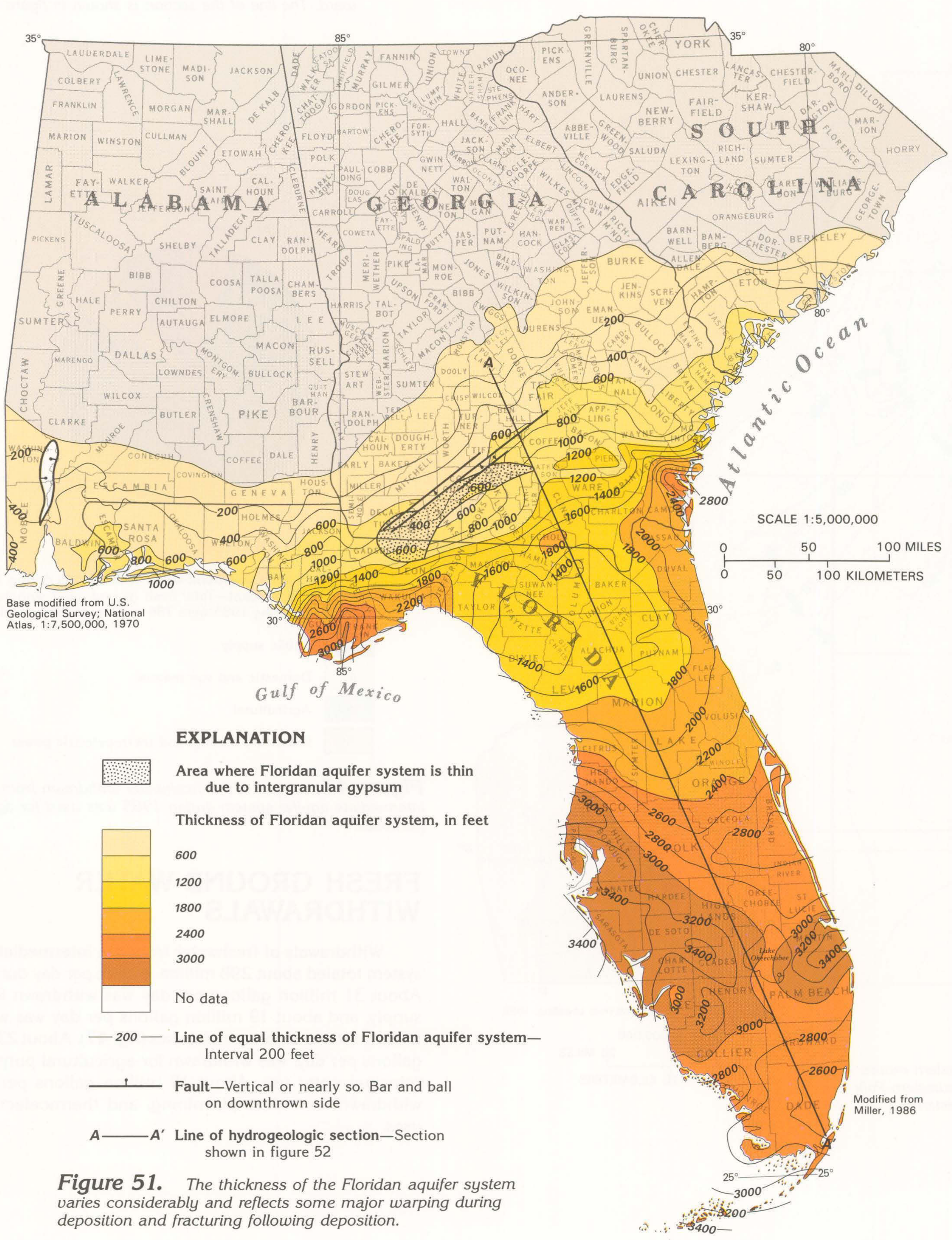
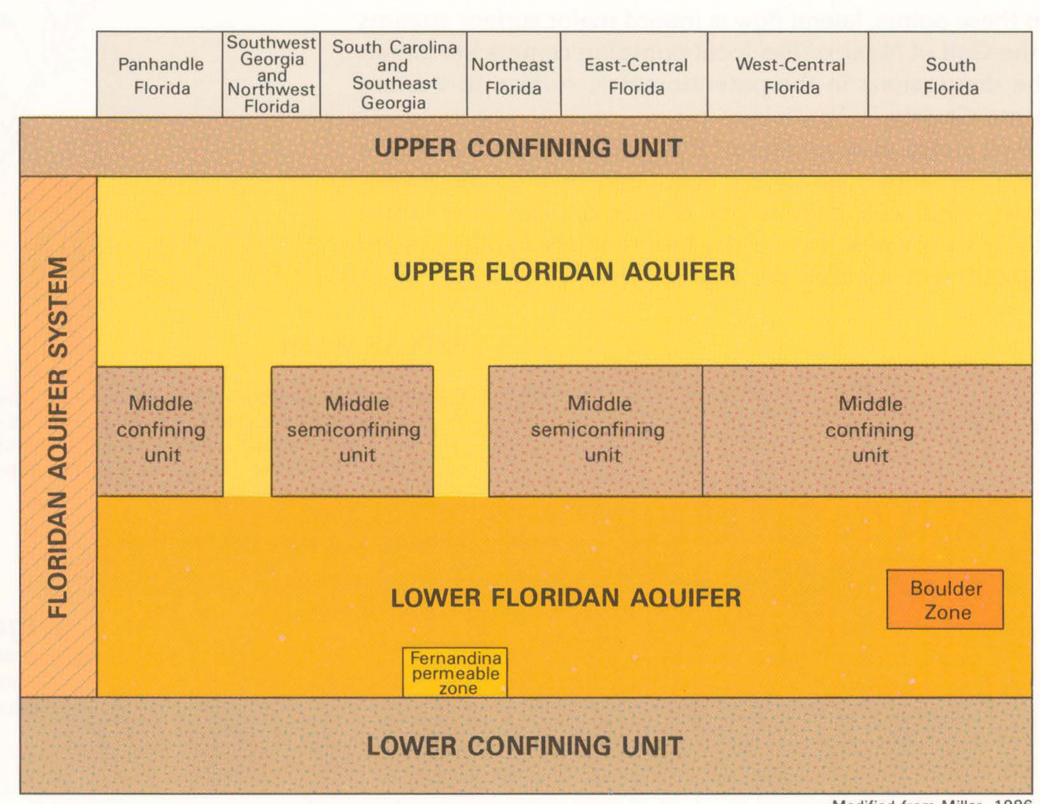


Figure 51. The thickness of the Floridan aquifer system varies considerably and reflects some major warping during deposition and fracturing following deposition.

Figure 50. The Floridan aquifer system can generally be divided into an Upper Floridan aquifer and a Lower Floridan aquifer, separated by a less-permeable unit in most places and bounded above and below by confining units that are much less permeable. The Lower Floridan aquifer locally contains zones that are extremely permeable.



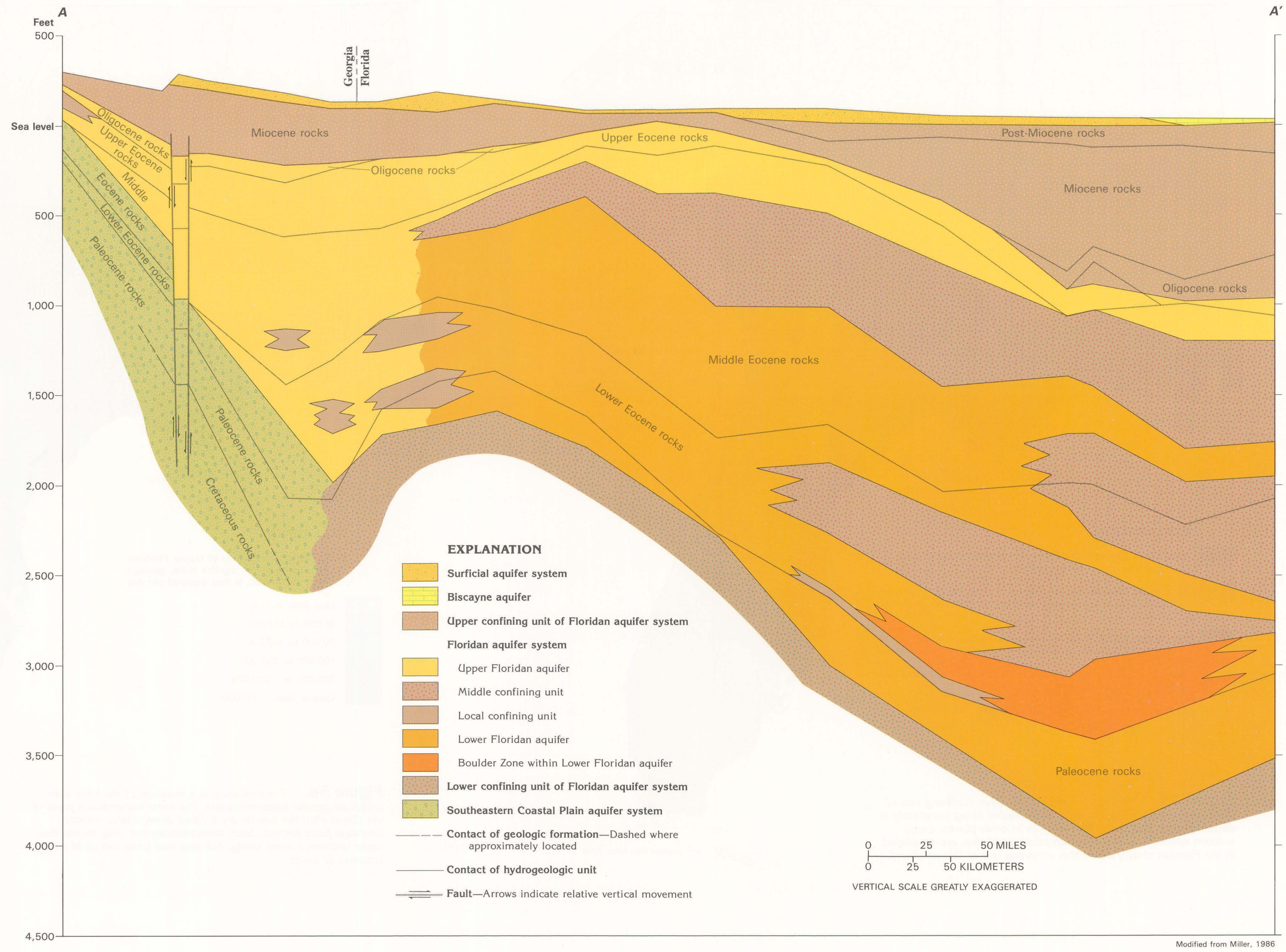


Figure 52. *The Floridan aquifer system changes significantly from south-central Georgia to southern Florida. Aquifers and confining units in the system thicken and thin from well to well, and generally resemble complexly interfingering, lens-shaped bodies of rock. The line of the hydrogeologic section is shown in figure 51.*

VARIATIONS IN THE FLORIDAN AQUIFER SYSTEM

The variations among and complexity of various parts of the Floridan aquifer system along a southeast-trending line from south-central Georgia to southern Florida are shown in **figure 52**. The most obvious variation is the substantial thickening of the aquifer system to the southeast. The left side of the figure, representing conditions in south-central Georgia, shows that the Floridan is only about 250 feet thick in this area. The right side of the figure, representing southern Florida, shows that the aquifer system is about 3,000 feet thick in places. The break in this gradual thickening, shown between the faults near the left side of the figure, is the graben known as the Gulf Trough. The downward movement of this crustal block produced a depression where a greater than average thickness of the clayey upper confining unit of the Floridan accumulated, thus restricting or partially damming the southward flow of ground water. This damming is reflected on maps of the potentiometric surface of the Floridan.

Another prominent feature shown in **figure 52** is the increasing complexity of the Floridan aquifer system toward the southeast. In south-central Georgia, where the system is thin, it contains only scattered, local confining units or none at all. In such areas, the system is hydraulically connected and generally functions as a single water-yielding unit, the Upper Floridan aquifer. Near the Georgia-Florida State line and southeastward, the aquifer system contains regionally-extensive middle confining units that separate it into two aquifers. In places, such as in southern Florida, two or three of these middle confining units are stacked. All of the regional and local confining units within the Floridan consist of carbonate rocks that are less permeable than the main, water-yielding parts of the aquifer system, and all of these confining units retard or partially restrict the movement of ground water in the system.

The Boulder Zone, a deeply-buried, cavernous zone filled with saltwater and used as a receiving zone for injected wastes, is shown near the right side of **figure 52** along with the confining bed that overlies it. Also shown in southern Florida is the Biscayne aquifer, which is separated from the Floridan aquifer system by a clayey confining unit that is about 1,000 feet thick in this area.

Near the left side of **figure 52**, the Southeastern Coastal Plain aquifer system is shown directly underlying the Floridan aquifer system. Throughout much of southern Georgia, these two aquifer systems are in direct contact, and ground water passes freely between them. The permeability of the aquifers in the Southeastern Coastal Plain aquifer system, however, is generally much lower than that of the aquifers in the Floridan aquifer system. The carbonate rocks of the Floridan either had substantial intergranular porosity when they were first formed, or pores in the rocks were enlarged by the dissolving action of circulating, slightly acidic ground water, or both (**fig. 53**). As these carbonate rocks grade northward into the predominantly clastic rocks of the Southeastern Coastal Plain system, the porosity and permeability of the rocks decreases and they yield less water than the more productive aquifers of the Floridan aquifer system.

Southeastward from about the Georgia-Florida State line, the confining unit that forms the base of the Floridan consists of beds of anhydrite in the Cedar Keys Formation of Paleocene age. These beds consist of calcium sulfate, which, when dissolved, contributes excessive concentrations of sulfate to the ground water. When the sulfate is chemically reduced to hydrogen sulfide, an objectionable, "rotten-egg" taste and odor are produced.

A. F. Randazzo, Gainesville, Florida

Figure 53. *Slightly acidic ground water has dissolved part of the limestone of the Floridan aquifer system, creating large solution openings in the rock.*

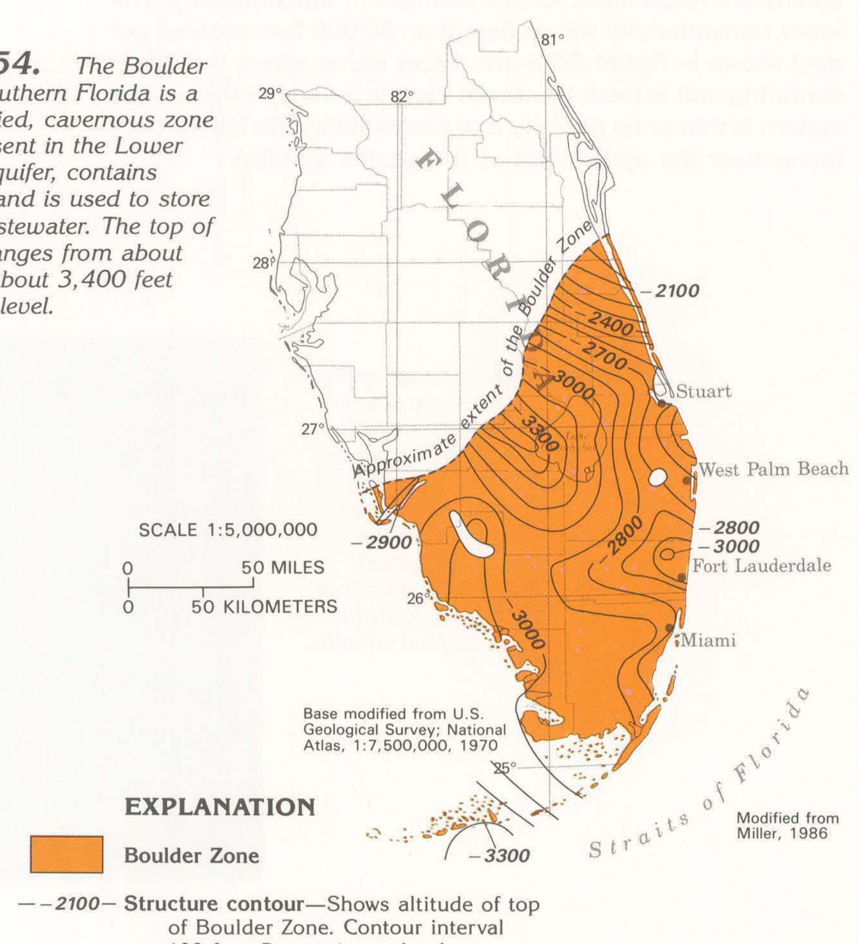


Figure 54. *The Boulder Zone of southern Florida is a deeply buried, cavernous zone that is present in the Lower Floridan aquifer, contains saltwater, and is used to store treated wastewater. The top of the zone ranges from about 2,000 to about 3,400 feet below sea level.*

BOULDER ZONE

The deeply buried zone of cavernous permeability, called the Boulder Zone, developed in fractured dolomite in the Lower Floridan aquifer, underlies a 13-county area in southern Florida (**fig. 54**). The Boulder Zone is not a single, simple, almost flatlying horizon of caves; rather, as shown by the contours in **figure 54**, its top is irregular and is as shallow as about 2,000 feet below sea level and as deep as about 3,400 feet below sea level. The zone is thought to represent caverns developed at several different levels and connected by vertical "pipes" or solution tubes similar to a modern cave system. A 90-foot high cavern reported in the subsurface in southern Florida probably is one of these vertical solution tubes rather than a large cavern.

The permeability of the Boulder Zone is extremely high because of its cavernous nature. This anomalous permeability, which prevents pressure buildup in injection wells, coupled with the fact that the Boulder Zone contains saltwater, makes it an ideal zone for receiving injected wastes. The Boulder Zone has been used for years to store vast quantities of treated sewage injected into it by Miami, Fort Lauderdale, West Palm Beach, and Stuart. Because the salinity and temperature of the water in the Boulder Zone are similar to those of modern seawater, the zone is thought to be connected to the Atlantic Ocean, possibly about 25 miles east of Miami where the sea floor is almost 2,800 feet deep along the Straits of Florida. The Boulder Zone is overlain by 500 to 1,000 feet of low-permeability limestone and dolomite, which retard the upward movement of injected fluids to shallower parts of the Floridan aquifer system that contain fresher although still brackish water.