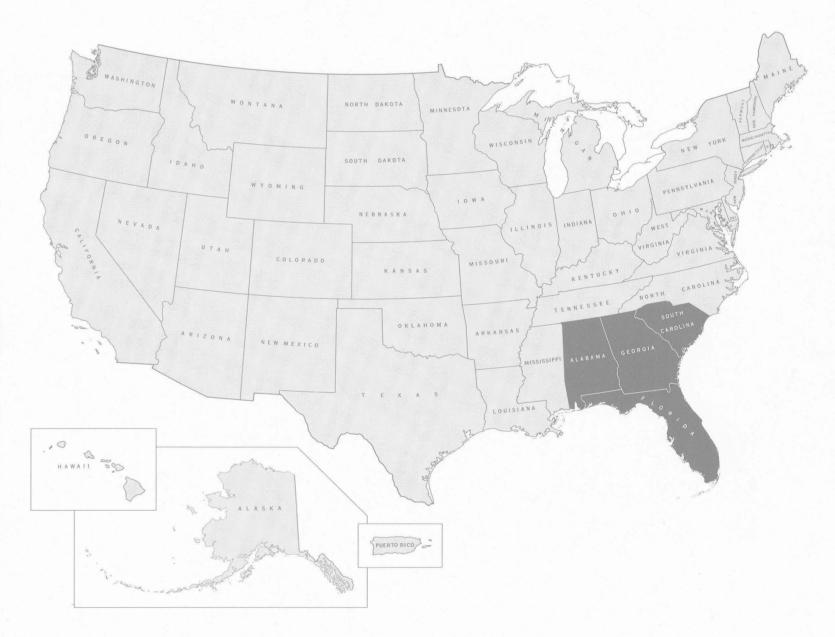
GROUND WATER ATLAS OF THE UNITED STATES

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

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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	Ву	To obtain metric units
	Length	
inch (in)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
foot squared per day (ft²/d)	0.0929	meter squared per day (m²/d)
cubic foot per second (ft³/s)	0.02832	cubic meter per second (m³/s)
mile (mi)	1.609	kilometer (km)
square mile (mi²)	2.590	square kilometer (km²)
	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 (m²/s)
billion gallons per day (Bgal/d)	3.785	million cubic meters per day (Mm³/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.

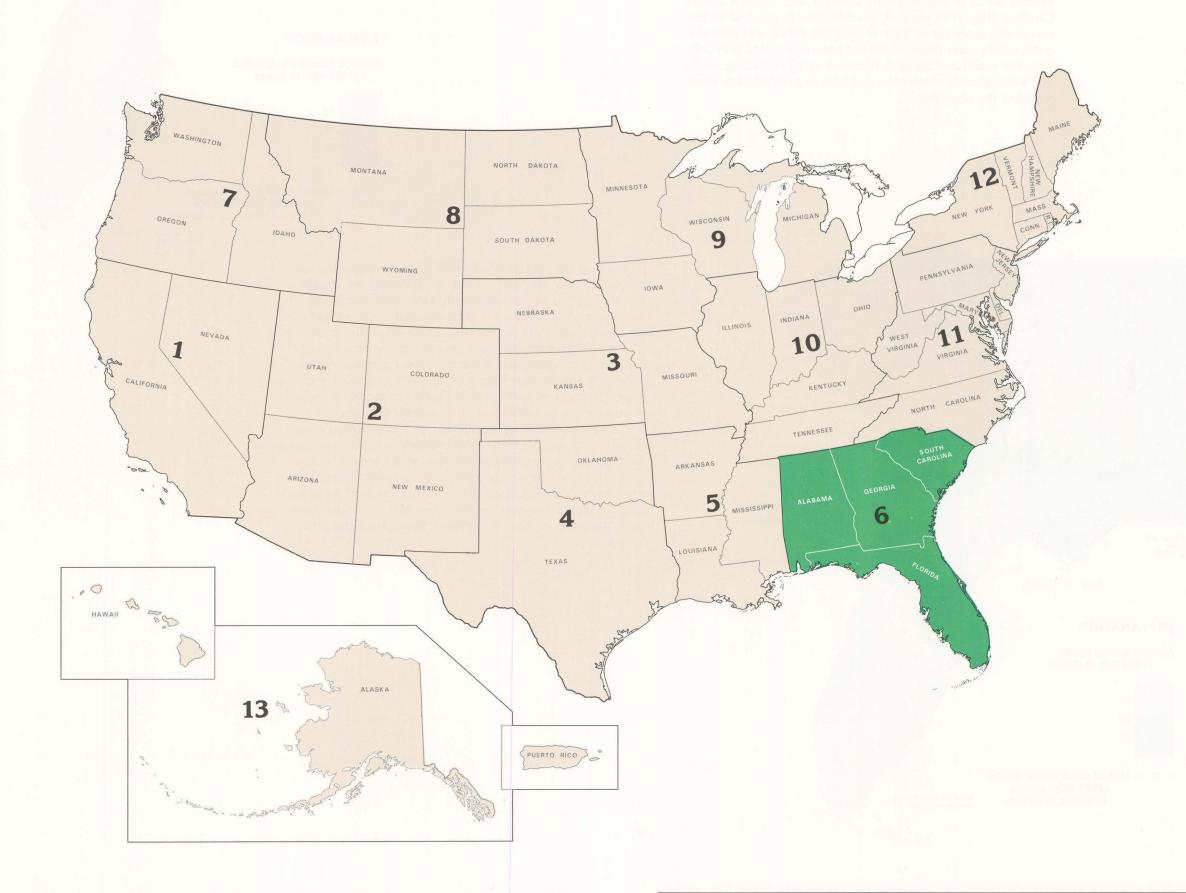
Segment Number	Chapter content	Hydrologic Atlas Chapter			
	Introductory material and nationwide summaries	730-A			
1	California, Nevada	730-B			
2	Arizona, Colorado, New Mexico, Utah	730-C			
3	Kansas, Missouri, Nebraska	730-D			
4	Oklahoma, Texas	730-E			
5	Arkansas, Louisiana, Mississippi	730-F			
6	6 Alabama, Florida, Georgia, South Carolina				
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



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

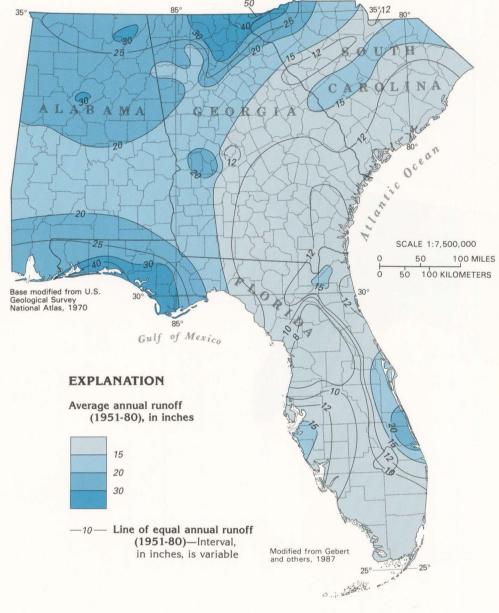
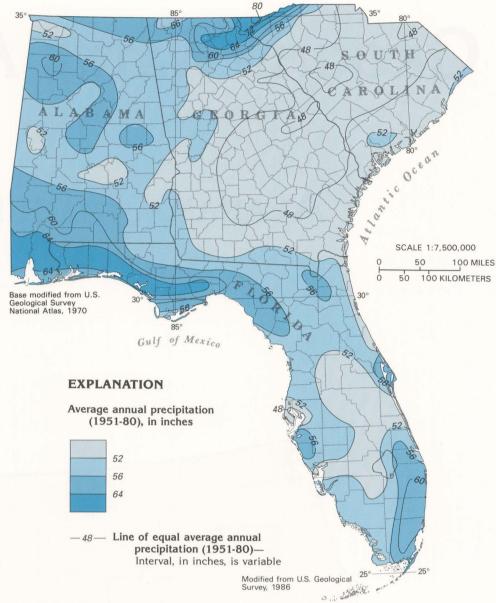


Figure 1. Average annual precipitation (1951-80) ranges from about 48 to about 80 inches.



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 aguifer 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

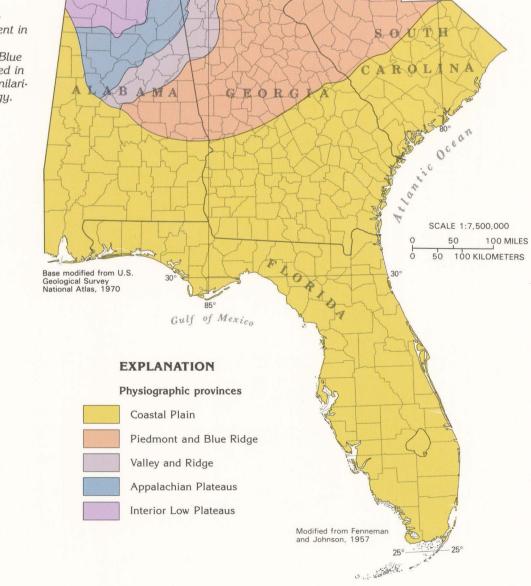
consists of complexly interbedded lenses and layers of coarse sand and gravel, and the Biscayne aquifer consists predominantly of limestone. The intermediate aquifer system consists of sand and limestone and lies between the surficial aquifer system and the Floridan aquifer system. The intermediate aquifer system does not crop out, and, accordingly, is not shown on the map.

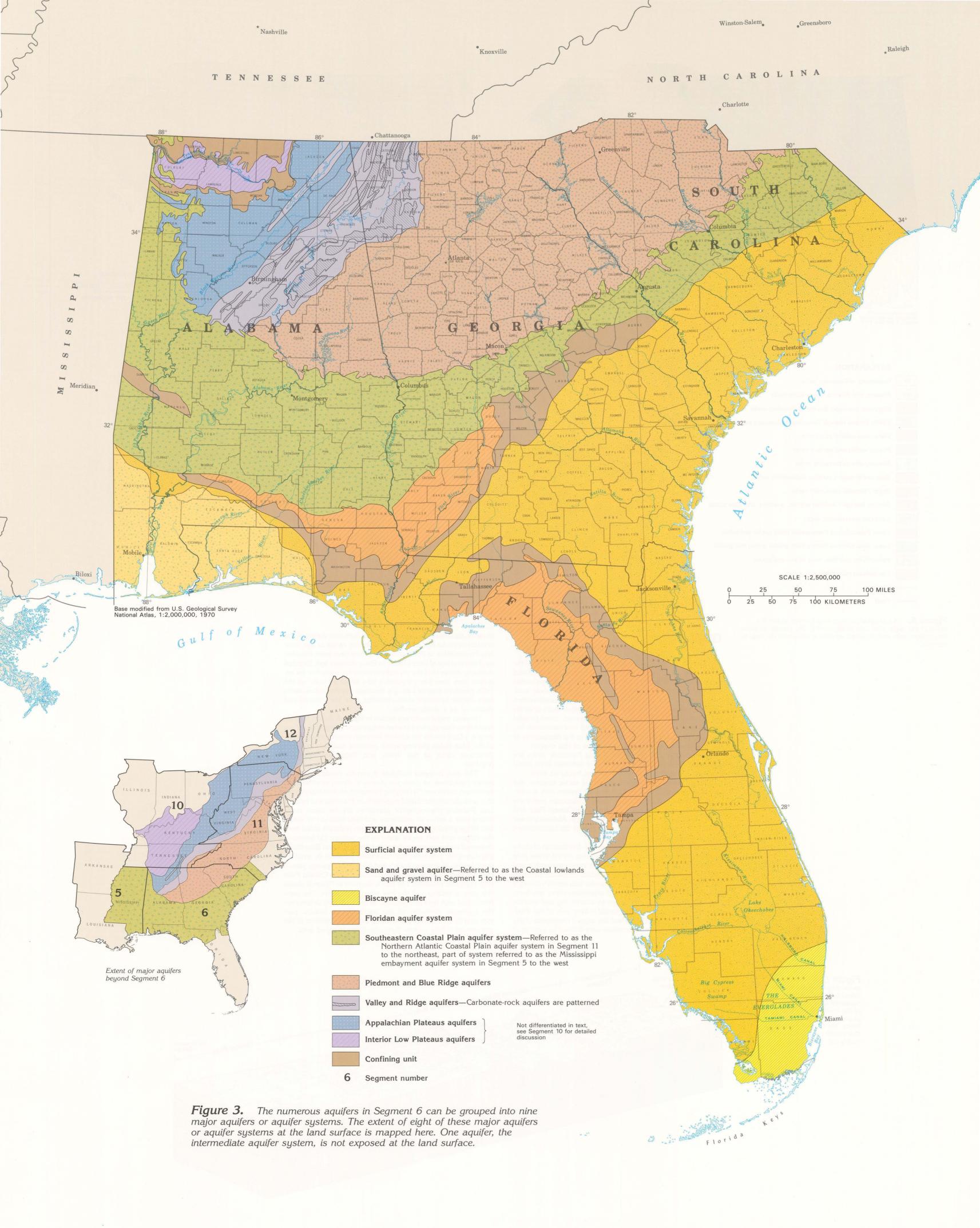
The Floridan aquifer system consists of limestone and dolomite, and is the most productive of the aquifers in the mapped area, in terms of total water yield. The Southeastern Coastal Plain aquifer system consists of four regional aquifers that are predominately sand, but these aquifers also contain some 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.





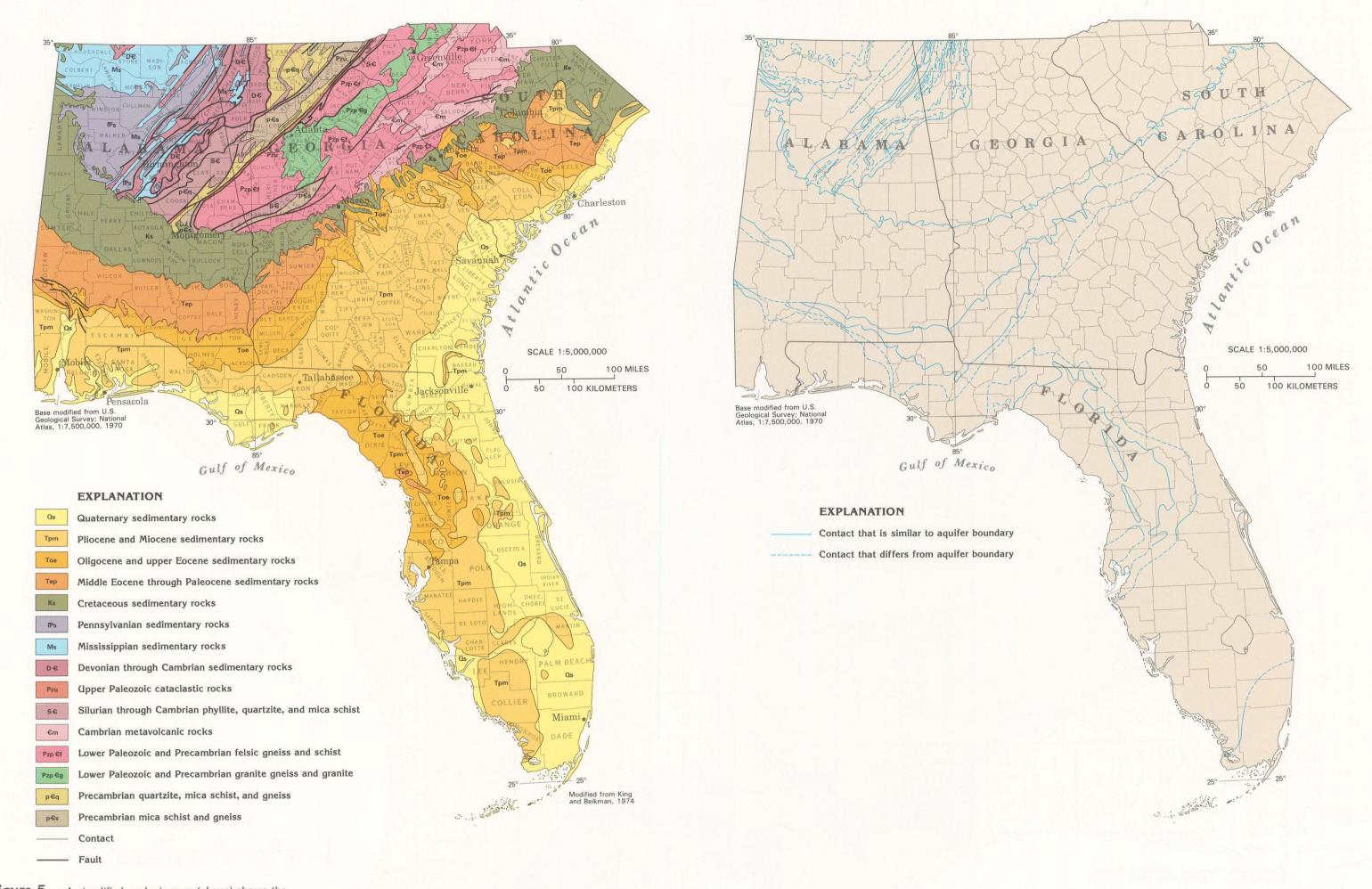


Figure 5. A simplified geologic map (above) shows the extent of the major rock units in Segment 6. The parallel between the geologic units and the major aquifers is shown on the map to the right.

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 sand-stone 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.

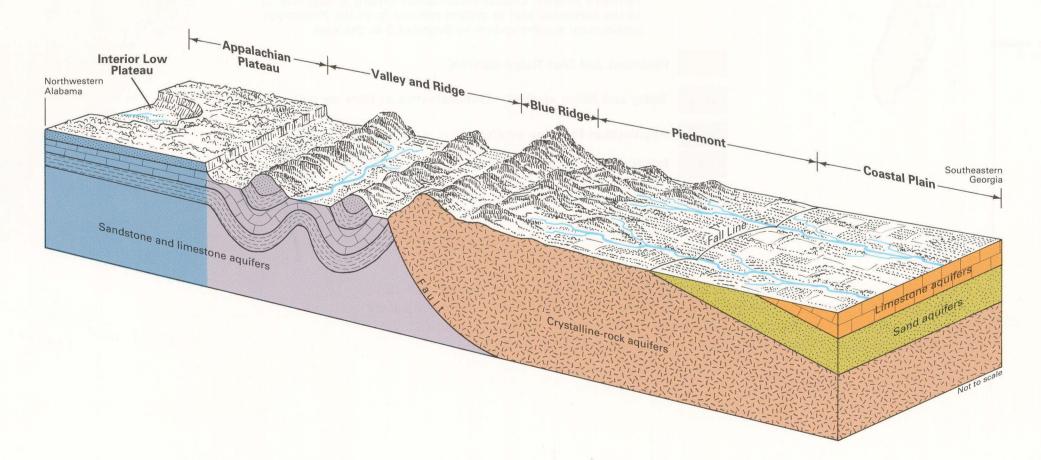
The geologic map (fig. 5) shows the distribution of rocks by major age category and also shows that an extensive area is underlain by crystalline rocks. These are metamorphic and igneous rocks that crop out in a broad, northeast-trending band that widens from eastern Alabama into eastern Georgia and 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 aguifers, the surficial aguifer 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 aguifer 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.

sisting 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 8. The uppermost Coastal Plain rocks are divided

into three aquifers, all con-

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

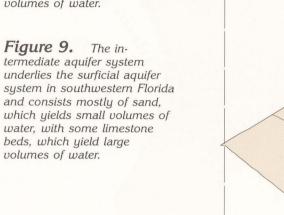
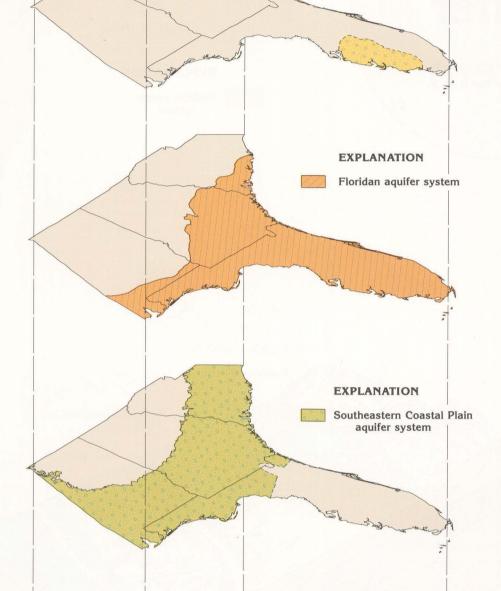


Figure 10. The Floridan aquifer system consists of carbonate rocks and is the most productive water-yielding unit in Segment 6. The Floridan is overlain by the intermediate aguifer system and also by the three younger aquifers shown in figure 8. In most places, the Floridan is separated from these overlying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



EXPLANATION

Biscayne aquifer

EXPLANATION

Intermediate aquifer

Arlantic Ocean

Florida

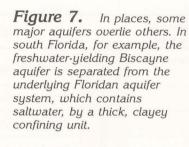
Gulf of Mexico

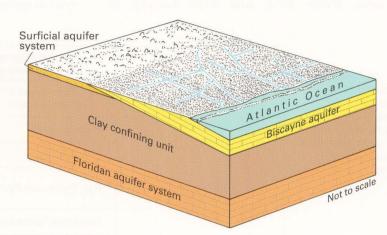
Surficial aquifer system

Sand and gravel aquifer

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 aguifers 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.





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 aguifer system grades laterally into the Mississippi embayment aquifer system in western Alabama (fig. 3). The Southeastern Coastal Plain aguifer 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

Figure 13. Fresh ground-

water withdrawals were

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 aguifers 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.

SOUTH

second most used aquifer.

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 southcentral 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 wateruse 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 aguifer, 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 aguifer 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 aguifer 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.

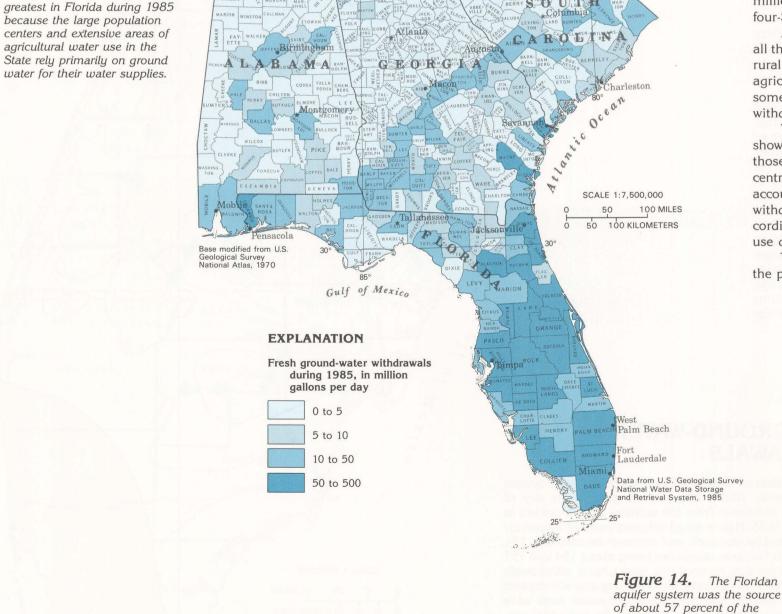
EXPLANATION

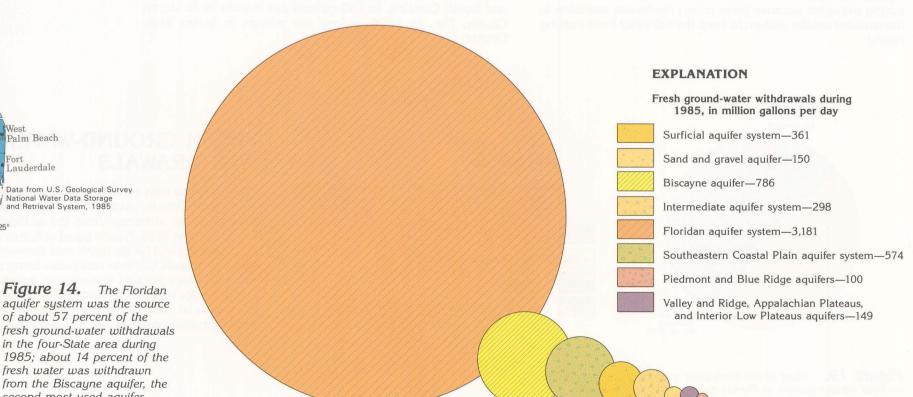
Valley and Ridge aquifers

Piedmont and Blue Ridge aquifers

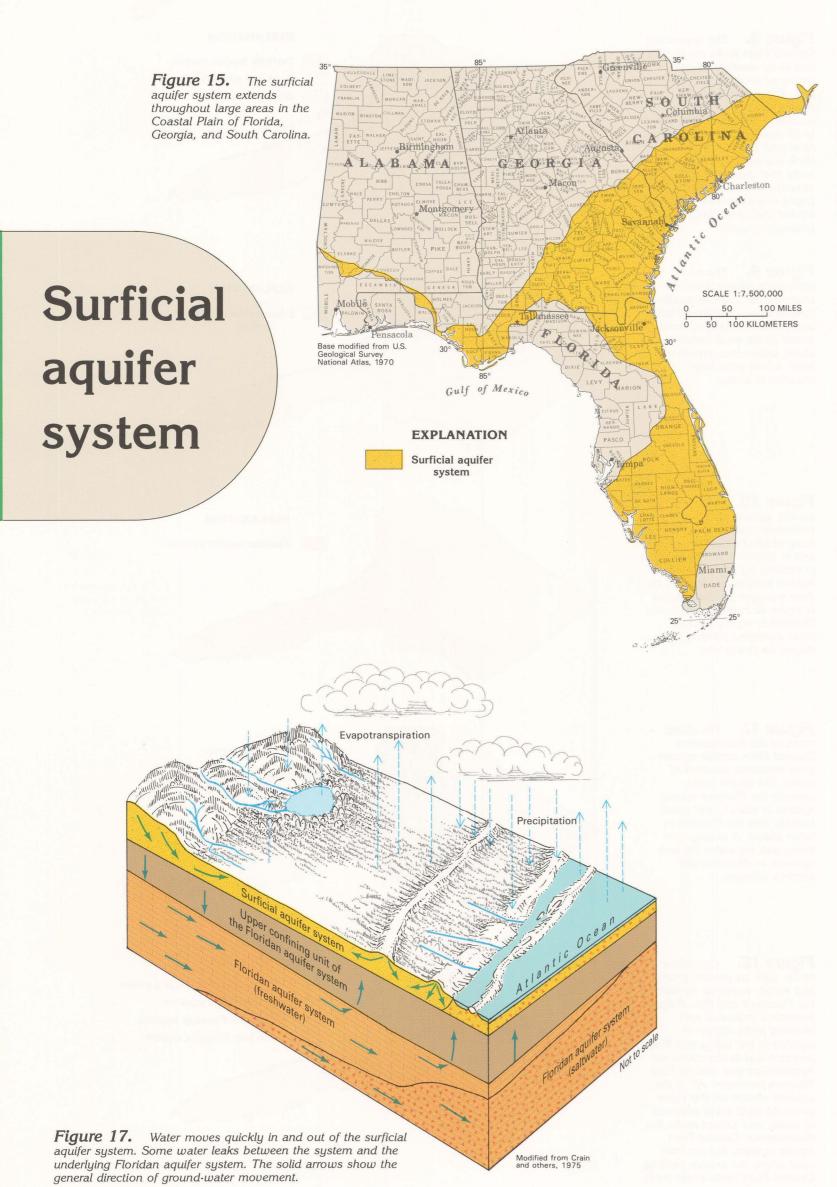
Appalachian Plateaus aquifers

Interior Low Plateaus aquifers





Data from U.S. Geological Survey, 1990



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

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.



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 aguifer 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 aguifers supply large municipalities; the surficial aguifer 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

Figure 16. In Florida, rocks of late Miocene to

Holocene age comprise the

surficial aquifer system. In Alabama, Georgia, and South

younger age comprises the

system.

Carolina, a thin, unnamed sand sequence of Pleistocene and

The surficial aquifer system consists mostly of beds of unconsolidated sand, shelly sand, and shell. Locally, in

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 par-

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

ticularly 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.

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

Modified from Healy, 1982 Stratigraphic units are equivalent in part. Order does not

Figure 18. The water table slopes seaward and toward major rivers from topographically high areas. The arrows show the general direction of ground-water **EXPLANATION** Water-table contour—Shows altitude of water table in surficial aquifer system. Contour interval, in feet, is variable. Datum is sea level Direction of ground-water movement 0 PALM BEACH SCALE 1:2,000,000 20 30 MILES 10 20 30 KILOMETERS Base from U.S. Geological Survey National Atlas, 1970

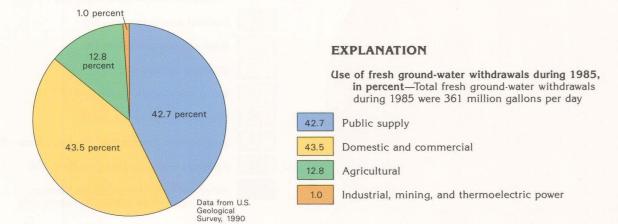
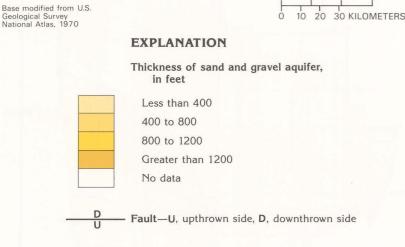


Figure 19. Most of the freshwater withdrawn from the surficial aquifer system in Florida during 1985 was used for public supply and for domestic and commercial supplies.

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.

Figure 20. The sand and SOUTH gravel aquifer is an important source of water in south-CAROLIN western Alabama and the westernmost part of panhandle ALABAMA GEORGIA Florida. Macon **EXPLANATION** SCALE 1:7,500,000 Sand and gravel aquifer 50 100 KILOMETERS Gulf of Mexico **GEOLOGY** The sand and gravel aquifer consists of rocks ranging in OVINGTON



ALABAMA

ORIDA

SCALE 1:2,000,000

30 MILES

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

A-----A' Line of hydrogeologic section

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 aquifertest 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.

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.

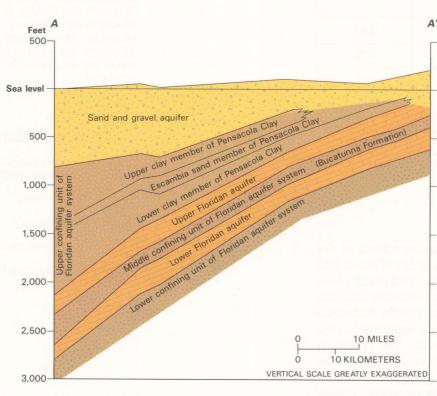


Figure 23. The base of the sand and gravel aquifer is formed by a thick series of clay beds to the southwest; however, the Upper Floridan aquifer is the base of the sand and gravel aquifer to the northeast. The line of the section is shown in figure 22.

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

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 aguifer 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.

Sand and gravel aquifer

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

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.

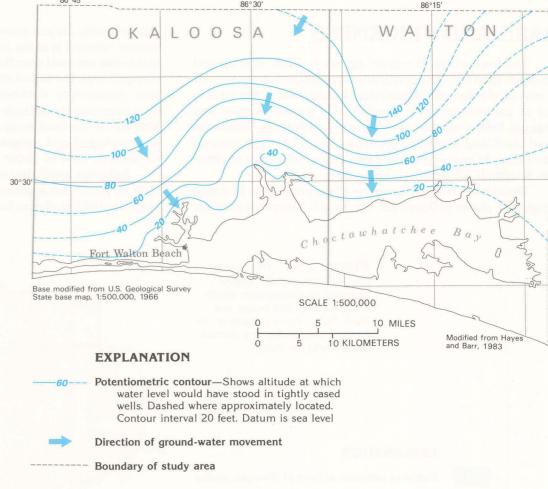


Figure 24. Water in the main producing zone of the sand and gravel aquifer moves toward the coast from inland recharge areas. The water levels were measured in March 1979.

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.

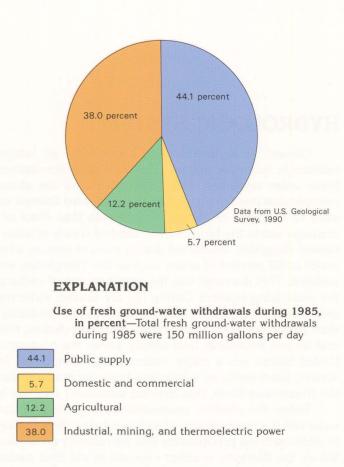
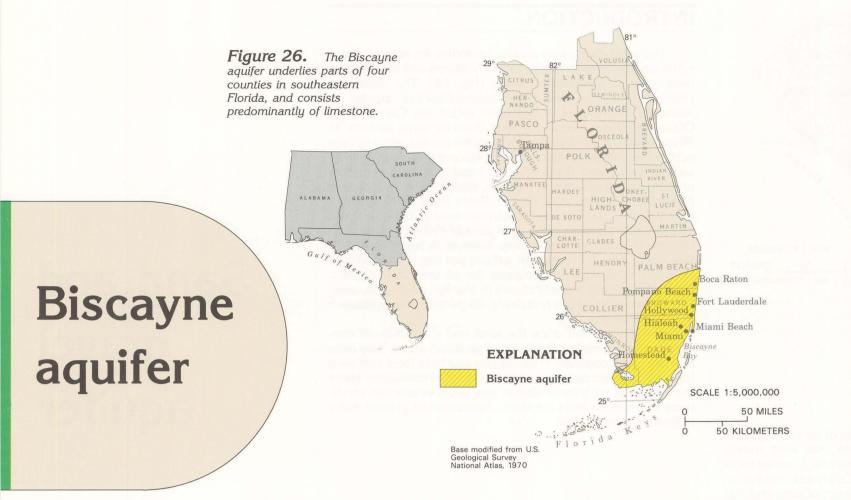


Figure 25. Most of the freshwater withdrawn from the sand and gravel aquifer during 1985 was used for public supply and industrial, mining, and thermoelectric-power purposes.



Series	Stratigraphic and hydrologic units Organic soils Lake Flirt Marl		Lithology and water-yielding characteristics	Thickness (feet)
Holocene			Peat and muck; water has high color content. Almost impermeable. Lake Flirt is shelly, calcareous mud	
	Pamlico Sand		Quartz sand; water high in iron. Small yields to domestic wells	0-40
Pleistocene ¹	Miami Oolite	<u> </u>	Sandy, oolitic limestone. Large yields	0-40
	Fort Thompson Formation	ne aquifer	Alternating marine shell beds and freshwater limestone. Generally high permeability. Large yields	0-150
	Anastasia Formation	Biscayne	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	Limestone, clay, and marl. Occasional moderate yields in upper few feet. Remainder forms upper part of basal confining unit.	25-220

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

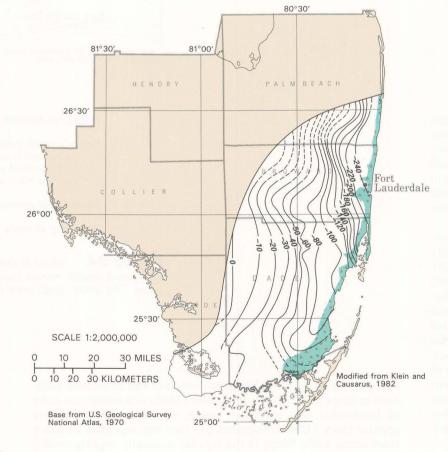
BASE AND THICKNESS

The base of the Biscayne aguifer 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.



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.

Figure 29. The base of



Extent of saltwater at base of Biscayne aquifer

Base-of-aquifer contour—Shows altitude of base of aquifer. Dashed where approximately located. Contour interval 10 and 20 feet. Datum is sea level

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 waterconservation (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

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

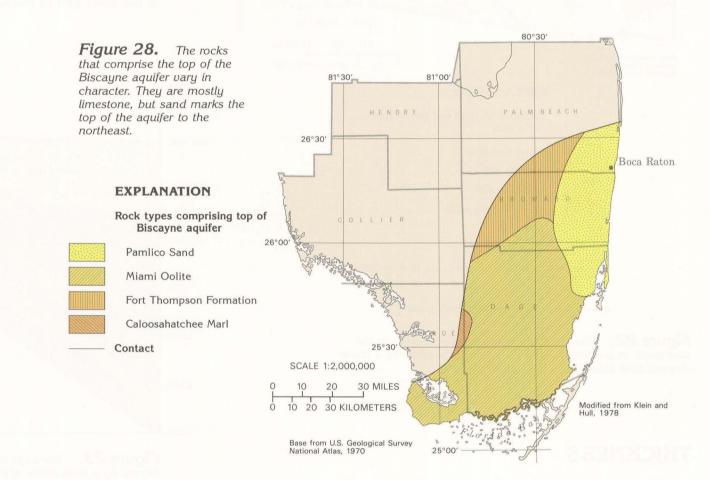
The Biscayne aquifer consists of highly permeable limestone and less-permeable sandstone and sand. Most of the geologic formations comprising the aquifer are of Pleistocene age but, locally, Pliocene rocks also are included in the aguifer

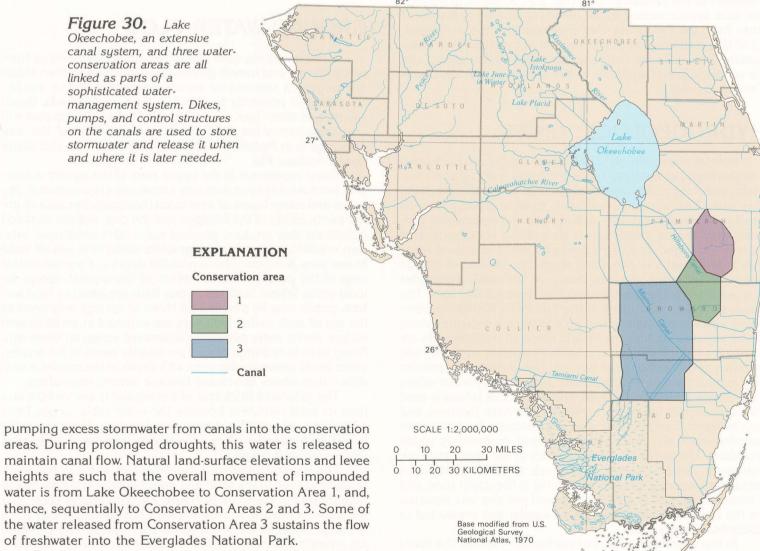
Most of the formations are thin and lens-like, and the entire sequence shown in figure 27 is not present at any one

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 aguifer. 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 aguifer 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 Biscavne 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 aguifer 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.





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 aguifer. 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.

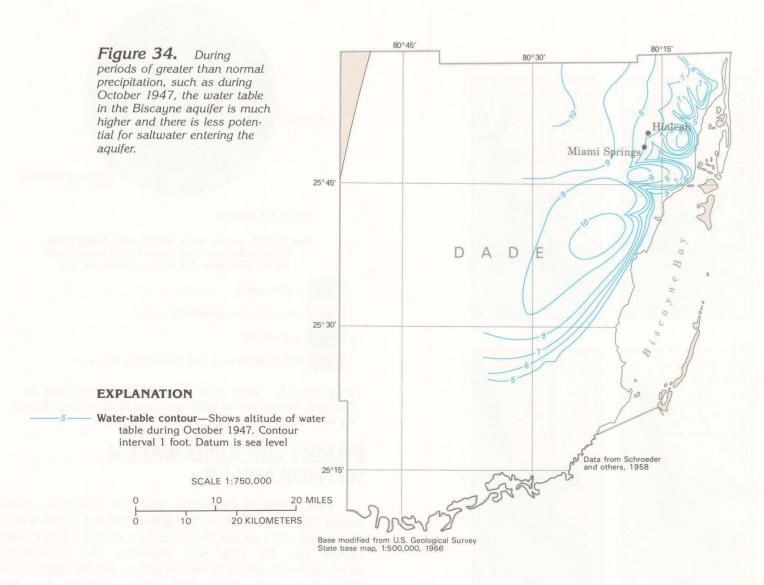
Figure 31. Water in the Biscayne aquifer is unconfined Lake Okeechobe and generally moves from recharge areas toward streams. canals, and the ocean. Some water moves radially in all directions toward shallow cones of depression caused by pumpage in municipal well CONSERVATION CONSERVATION **EXPLANATION** BROWARD Water-table contour-Shows altitude of water table during May 1978. Contour interval 2 feet. Datum is sea level CONSERVATION Direction of ground-water ARFA 3 movement SCALE 1:1,000,000 20 MILES 20 KILOMETERS Modified from Klein and Causarus, 1982

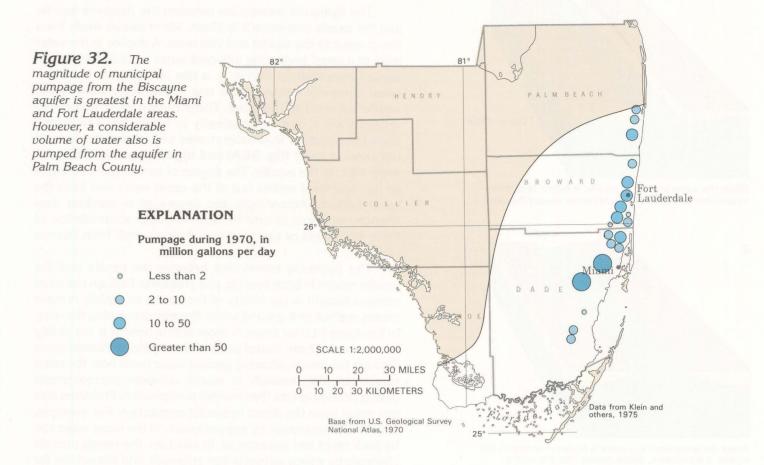
Water-Table Fluctuations

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.





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.

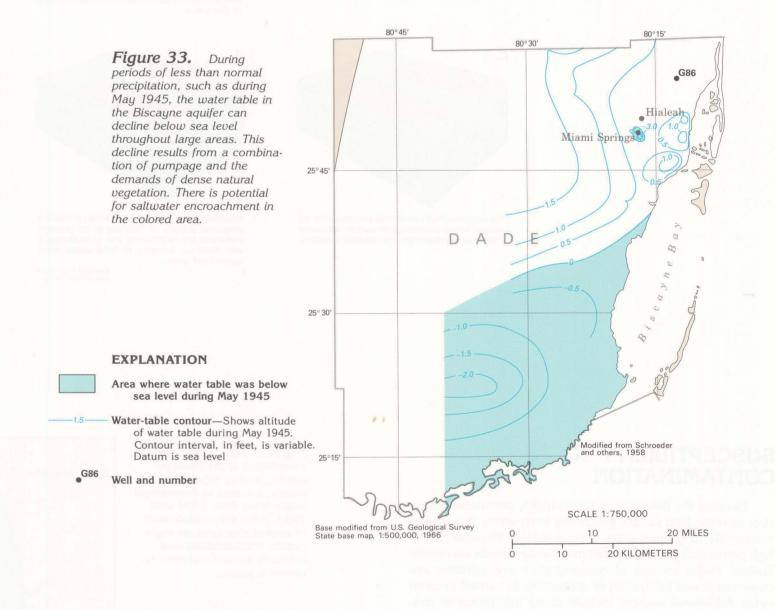
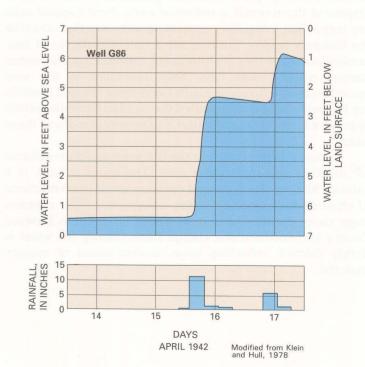
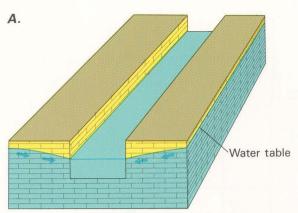


Figure 35. In an unconfined aquifer such as the Biscayne, the water table rises rapidly after intense rainfall. The location of the well is shown in figure 33.

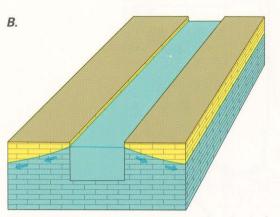
Response to Recharge

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.





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

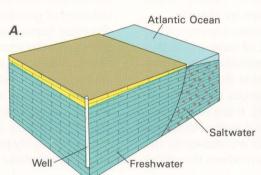


When the water level in a canal is higher than that in the aguifer it penetrates, water moves into the aguifer

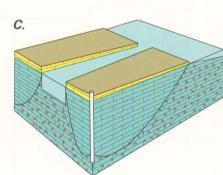
Figure 36. During periods of less than normal precipitation, water passes freely from the aquifer into canals that are dug into it (top diagram). When storm runoff raises canal water levels, the movement of water is reversed (B).

Figure 38. The original, virtually stable freshwatersaltwater 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

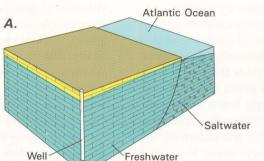
saltwater encroachment.



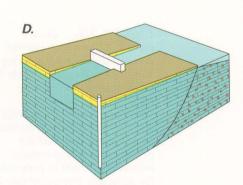
The freshwater-saltwater interface was nearly stable before coastal canals were



An uncontrolled canal that extends into an area of heavy pumping can convey saltwater



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



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.

HYDROLOGIC SYSTEM—Continued Canal-Aquifer Connection

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 aguifer 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

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, aguifer 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.

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.

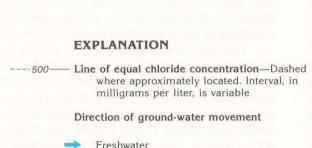
How saltwater can encroach coastal areas as a result of development is shown diagramatically in figure 38. In the natural, balanced condition shown in figure 38A, saltwater is present only near the shoreline and is balanced by a thick inland column of freshwater. Construction of a drainage canal, however (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 wedgeshaped, 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 aguifer 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 groundwater 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 watermanagement practices had reduced the area of saltwater contamination considerably from its maximum extent in 1953.

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

Feet



Saltwater

Sea level Freshwater Base of Biscayne aquifer 120 1,600 1,200 800 400 400 DISTANCE FROM BISCAYNE BAY, IN FEET Modified from U.S. Department of the Interior, 1973

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.

EXPLANATION

Extent of saltwater encroach-

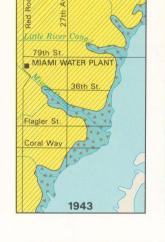
ment at base of Biscayne

aquifer in the Miami area

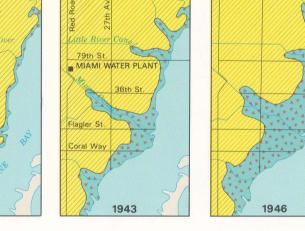
6 KILOMETERS

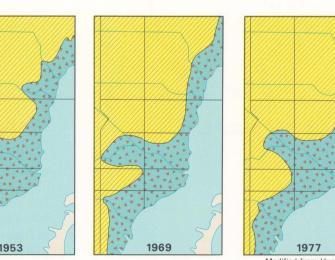
6 MILES

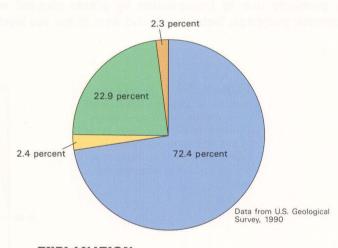












EXPLANATION

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.

SOUTH CAROLIN GEORGIA A L. A. B. A. M.A SCALE 1:7,500,000 100 MILES POR MARIO 50 100 KILOMETERS Gulf of Mexica **EXPLANATION** Intermediate aquifer system Figure 42. The intermediate aquifer system is present in southwestern Florida. Approximate extent of the intermediate aquifer system

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

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 aguifers 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.

Intermediate aquifer system

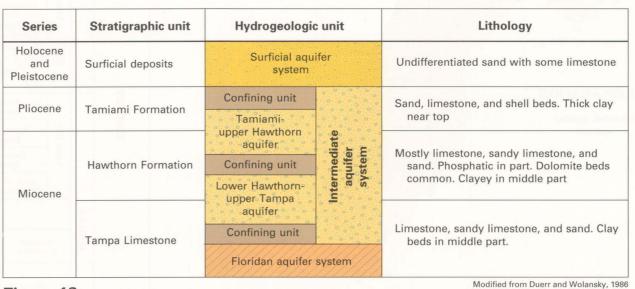


Figure 43. Geologic formations of Miocene and Pliocene age comprise the intermediate aquifer system. The system is covered everywhere by younger deposits.

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

EXPLANATION

7 Top-of-aquifer contour—Shows altitude of top of intermediate aquifer system. Contour interval 50 feet. Datum is sea level

A———A' Line of hydrogeologic section



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.

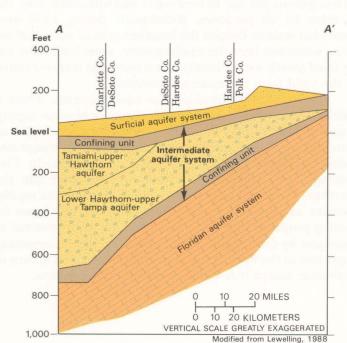


Figure 45. The intermediate aquifer system becomes thick and contains more limestone southward. The line of the section is shown in figure 44.

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.

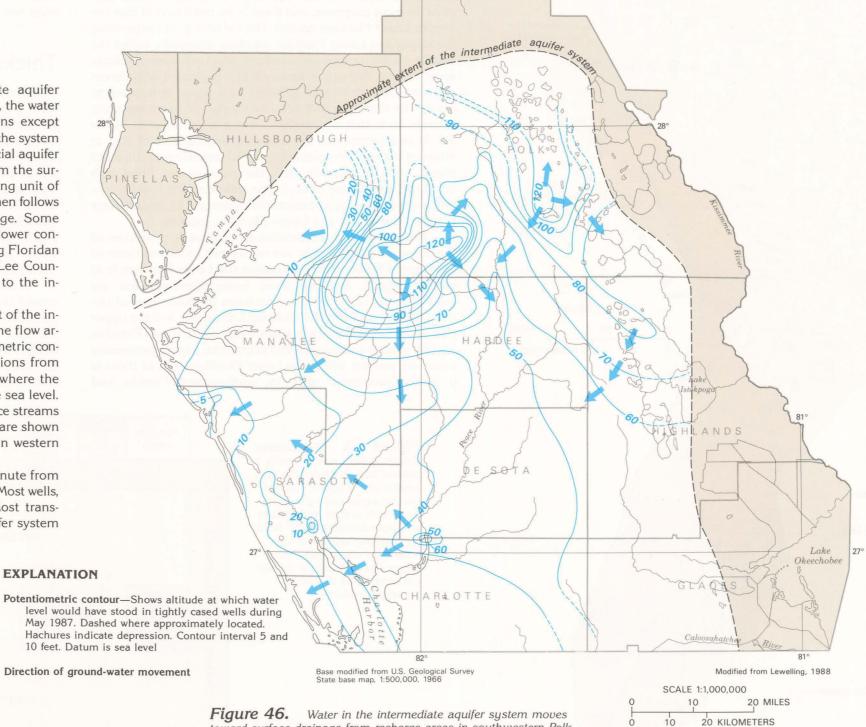
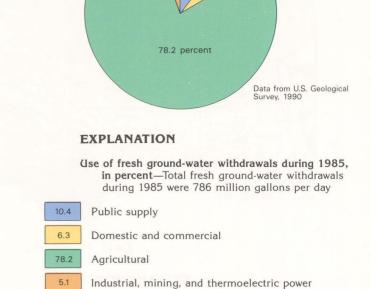


Figure 46. Water in the intermediate aquifer system moves toward surface drainage from recharge areas in southwestern Polk County. Two local pumping centers are located in western Sarasota County.

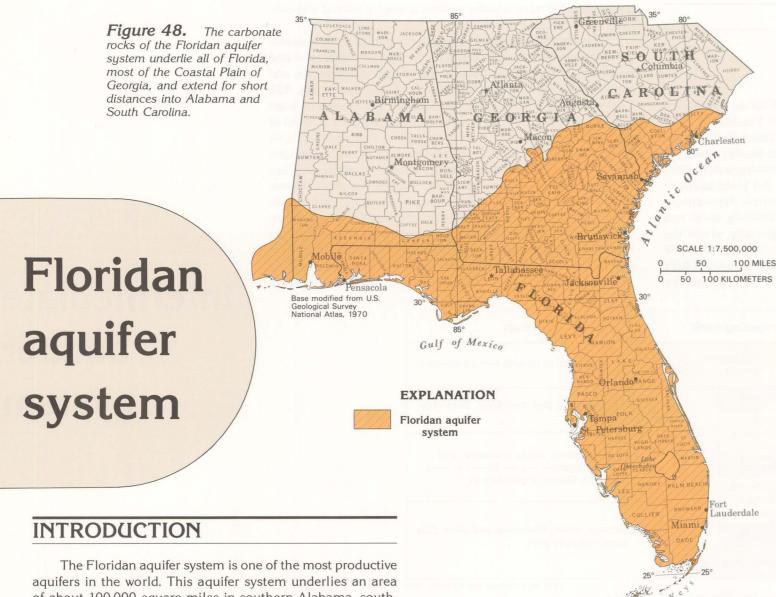


5.1 percent

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.

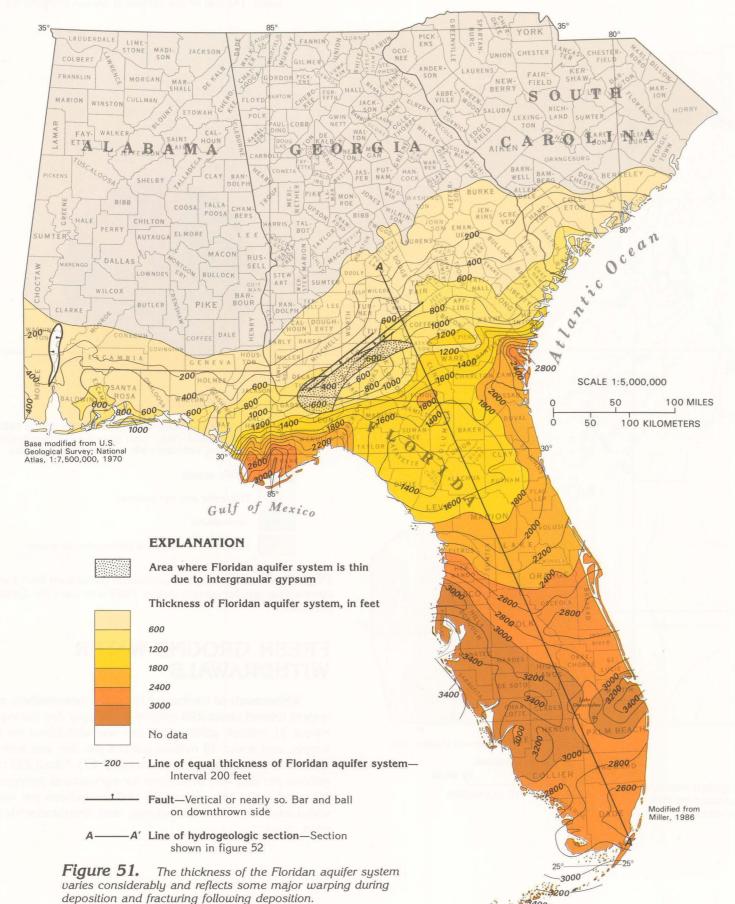


of about 100,000 square miles in southern Alabama, southeastern Georgia, southern South Carolina, and all of Florida (fig. 48). The Floridan aquifer system provides water for several large cities, including Savannah and Brunswick in Georgia; and Jacksonville, Tallahassee, Orlando, and St. Petersburg 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



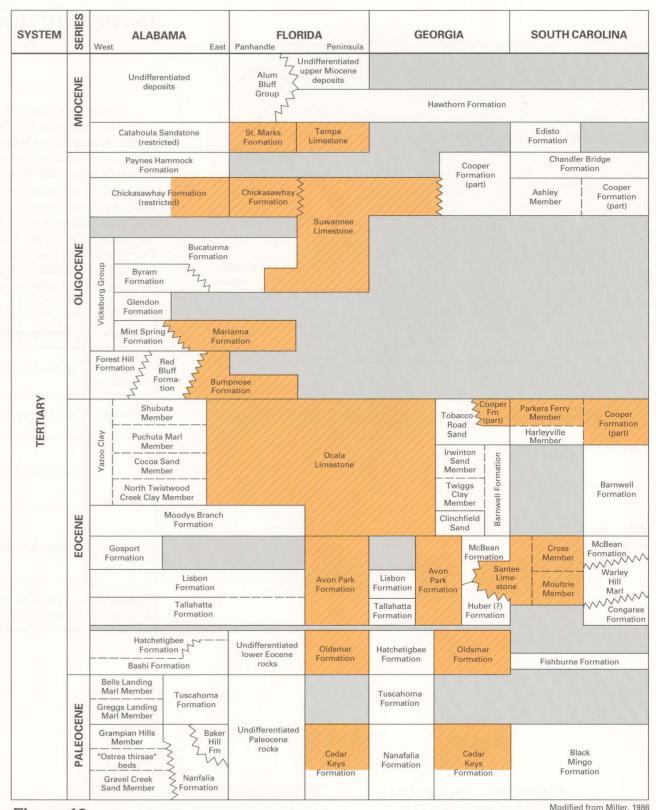


Figure 49. A number of geologic formations comprise the of them are of Eocene age. In places, however, rocks as young as Miocene age and as old as Paleocene age are included in the

Floridan aquifer system. They are all carbonate rocks, and most 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 aguifer 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 aguifers.

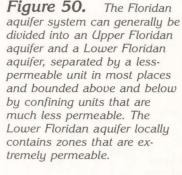
The geologic characteristics and hydraulic properties of the Lower Floridan aquifer are not as well known as those of the Upper Floridan aquifer because the Lower Floridan is at greater depths, and, therefore, fewer borehole data are available. The Lower Floridan includes the lower part of the Avon Park 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 northcentral 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.



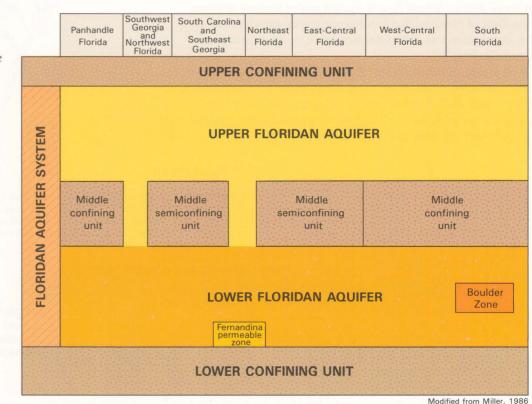
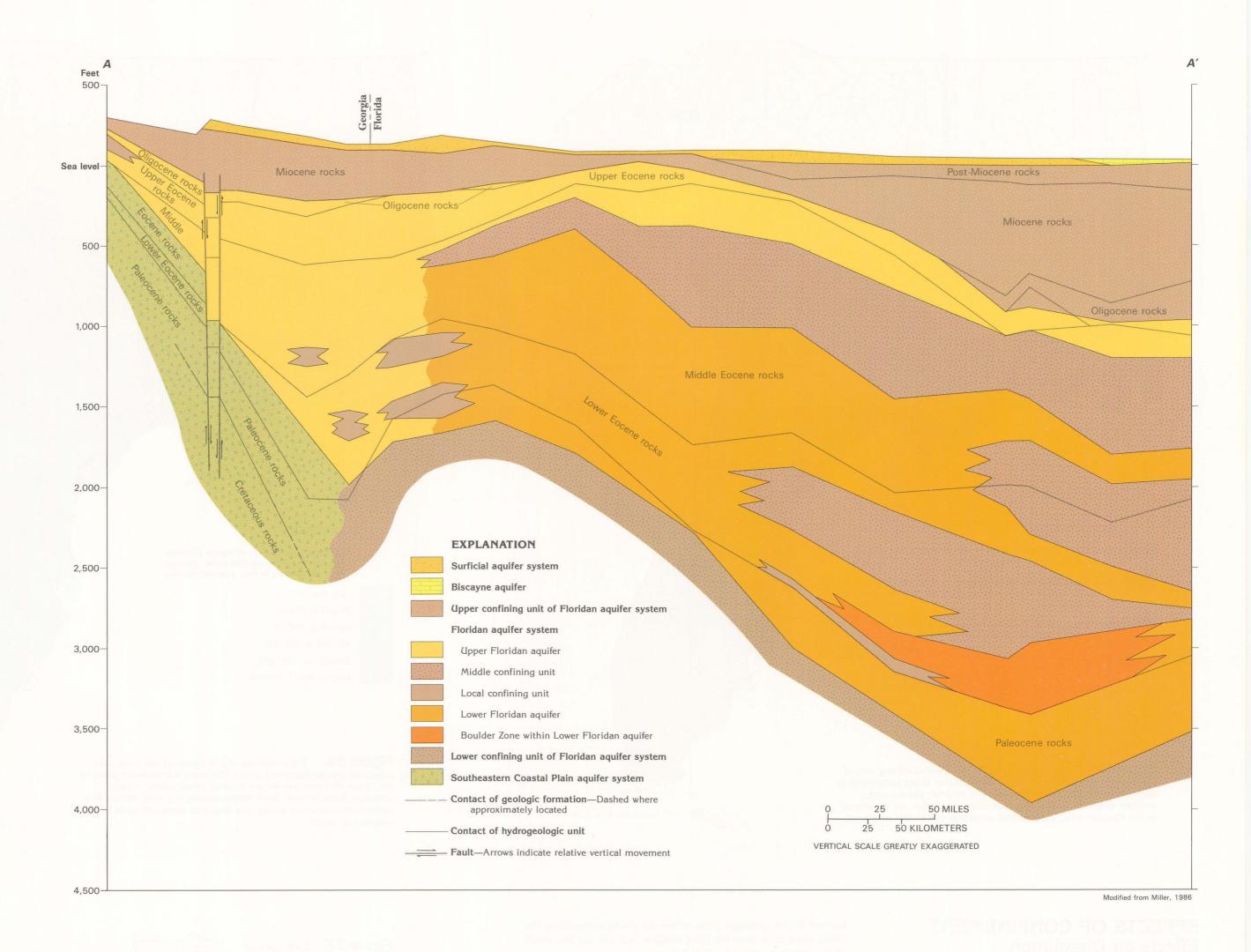


Figure 52. The Floridan aquifer system changes significantly from south-central Georgia to southern Florida. Aquifers and confining units in the system thicken and thin from well to well, and generally resemble complexly interfingering, lens-shaped bodies of rock. The line of the hydrogeologic section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

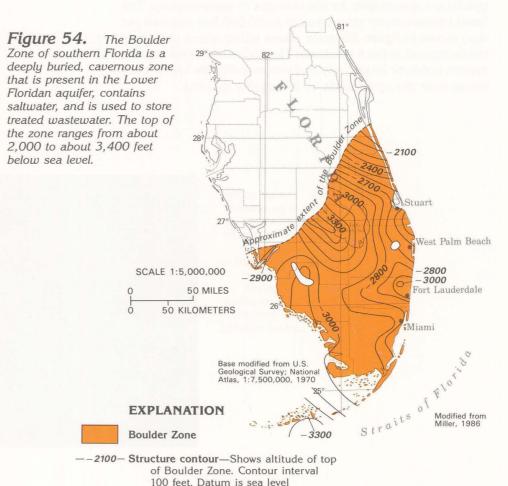
Near the left side of **figure 52**, the Southeastern Coastal Plain aquifer system is shown directly underlying the Floridan aquifer system. Throughout much of southern Georgia, these two aquifer systems are in direct contact, and ground water passes freely between them. The permeability of the aquifers 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.



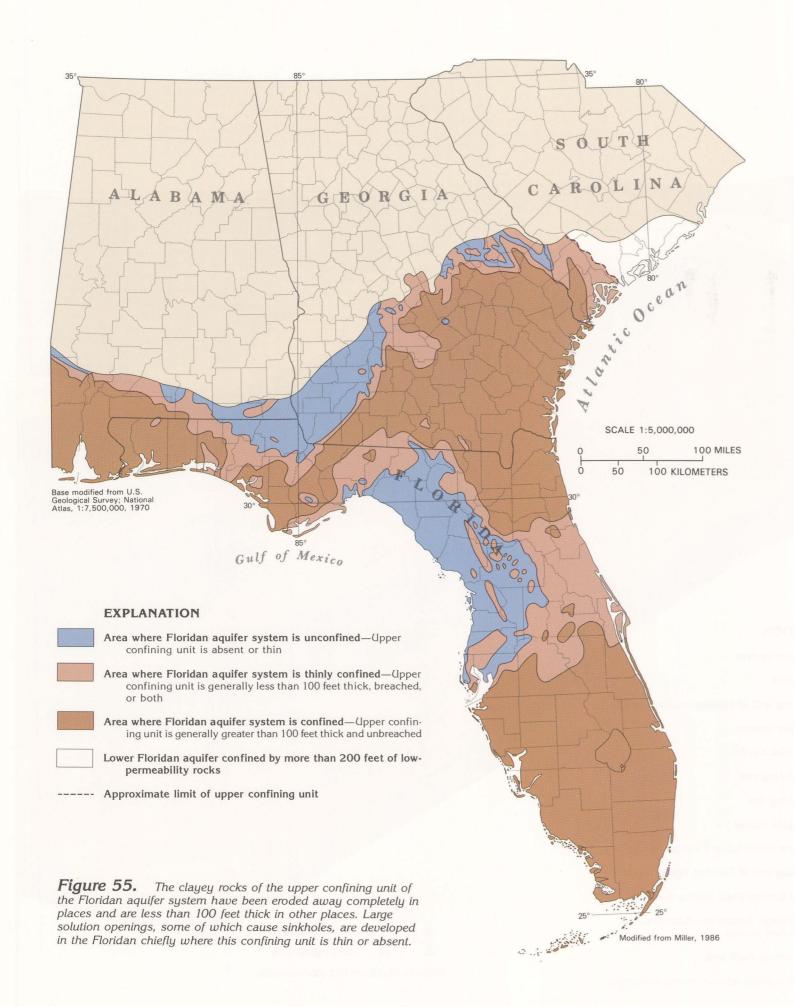
Figure 53. Slightly acidic ground water has dissolved part of the limestone of the Floridan aquifer system, creating large solution openings in the rock.



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.

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 lowpermeability 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.



EFFECTS OF CONFINEMENTEffects on Dissolution

The carbonate rocks of the Floridan aquifer system are readily dissolved where they are exposed at land surface or are overlain by only a thin layer of confining material. Precipitation absorbs some carbon dioxide from the atmosphere as the precipitation falls and much more carbon dioxide from organic matter in soil as the precipitation percolates downward through the soil, thus forming weak carbonic acid. This acidic water dissolves the limestone and dolomite of the Floridan aquifer system, initially by enlarging pre-existing openings such as pores between grains of limestone or fractures (joints) in the rock. These small solution openings become larger as more of the acidic water moves through the aguifer; eventually the openings may be tens of feet in diameter. The end result of dissolution of carbonate rocks is a type of topography called karst, named for the Karst Plateau of Yugoslavia, that is characterized by caves, sinkholes, and other types of openings caused by dissolution, and by few surface streams.

Dissolution of carbonate rocks is greatest where groundwater circulation is most vigorous. Water is able to enter, move through, and discharge from the Floridan aquifer system more readily and rapidly where it is unconfined or where the upper confining unit is thin. Such areas are shown in figure 55. In these unconfined areas, the aquifer is either exposed or, more commonly, is covered by a thin layer of sand or by clayey, residual soil. In adjacent areas, the Floridan is confined, but the upper confining unit is less than 100 feet thick (fig. 55). In these areas, sinkholes that locally breach the confining unit and allow precipitation to move quickly downward into the aquifer are common. Where the confining unit is thick and unbreached (fig. 55), there has been little dissolution of the aquifer system except in deeply buried zones of paleokarst, such as the Fernandina permeable zone of southeastern Georgia and northeastern Florida, and the Boulder Zone of southern Florida. However, these deeply buried zones chiefly

formed in the geologic past, when the rocks comprising the zones were at or near the land surface, and are not the result of the modern ground-water flow system.

Effects on Transmissivity

The large-scale solution porosity that develops as a result of dissolution of the carbonate rocks in the Floridan aquifer system creates large conduits in some places that store and transmit ground water. These conduits, which include caves, solution channels, and sinkholes are like large-diameter pipes or channels in that they allow tremendous volumes of water to pass quickly through the aquifer with little resistance to flow. Transmissivity, or the capacity of an aquifer to transmit water, is one way of measuring the relative ease with which ground water moves. The greater the transmissivity, the more readily water is able to move through the aquifer.

The distribution of transmissivity values in the Upper Floridan aguifer, the best-known part of the Floridan aguifer system, is shown in figure 56. All of the area having a transmissivity greater than 1,000,000 feet squared per day and most of the area having transmissivity from 250,000 to 1,000,000 feet squared per day are where the upper confining unit of the Floridan aguifer system is less than 100 feet thick, or is absent (compare figs. 55 and 56). These areas are where large solution openings developed in the carbonate rocks allow water to be conveyed through the aguifer rapidly. Where the upper confining unit is greater than 100 feet thick, transmissivity values generally are lower and flow is not so rapid. Where the aquifer is more thickly confined and less affected by dissolution, variations in the original porosity of the aquifer chiefly are responsible for the changes in transmissivity. The lower transmissivity values (less than 50,000 feet squared per day) shown in figure 56 mark places either where the upper confining unit is thick (southern Florida) or where the aquifer system is thin or its porosity and permeability are low, or both (areas near the updip limit of the aquifer system).

Figure 58. Large springs may issue from huge solution openings in the limestone that comprises the Floridan aquifer system. These springs are major discharge points, and are a dominant control on the ground-water flow system. Some of them, such as Silver Spring shown here, form the headwaters of surface streams.



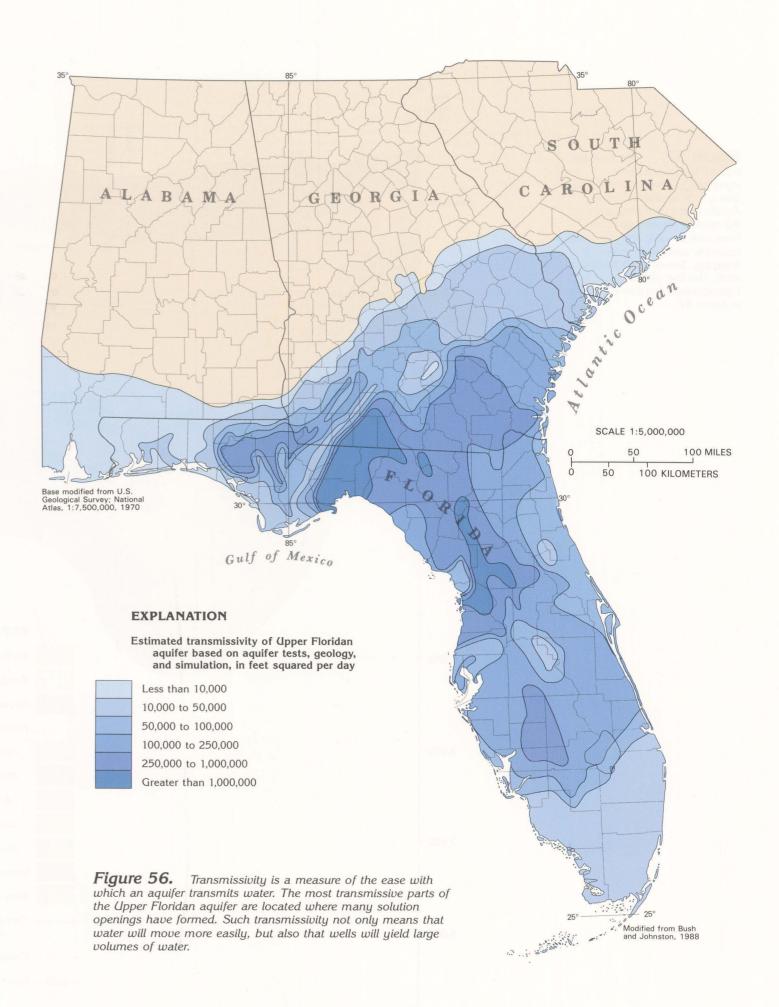
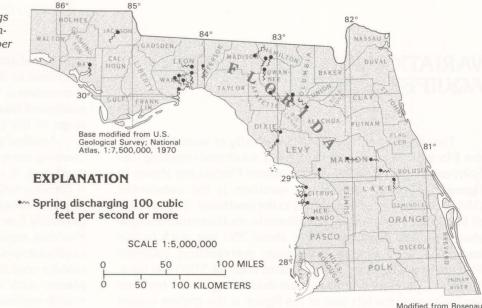


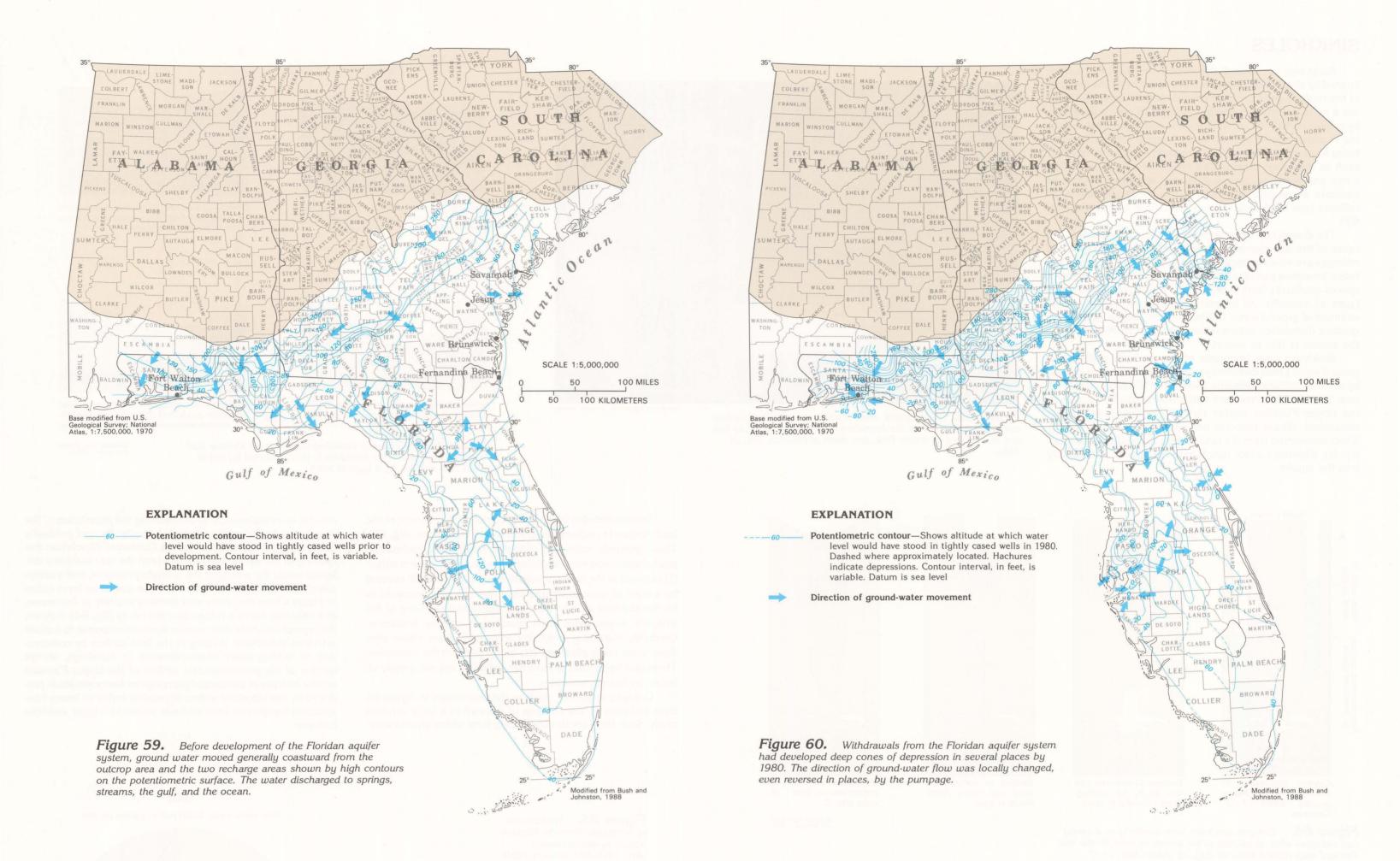
Figure 57. Large springs issue from large solution openings developed where the upper confining unit of the Floridan aquifer system is thin or absent.



Effects on Springs

Springs are places where ground water discharges through natural openings in the ground. Springs may vary greatly in the volume of water they discharge; some springs are small enough to be expressed only as seeps where water oozes slowly from the aquifer, whereas others are large enough to form the headwaters of large rivers. The water discharged by a spring may be from an aquifer that is unconfined (water-table conditions) or confined (artesian conditions). Springs issuing from an unconfined aquifer tend to have a small, extremely variable flow and are directly and quickly affected by variations in precipitation. These springs may cease flowing during periods of less than normal precipitation. In contrast, springs issuing from a confined aquifer have a more constant flow because their flow is supplied by a much greater replenishment area. Accordingly, such springs tend to be unaffected by variations in precipitation unless there is prolonged drought. Springs are common in areas of karst topography. Spring flow is controlled by the size of the replenishment area, the difference in altitude between the spring opening or openings and the water level in the aquifer, and the size of the opening or openings through which the springs issue. Factors that have lesser effects on spring flow include atmospheric-pressure changes, earth and oceanic tides, and pumping of wells located near springs.

Florida has 27 first-magnitude springs (springs with a flow of 100 cubic feet per second or more) out of a total of 78 in the entire Nation. The location of these springs is shown in figure 57. All of them issue from the Upper Floridan aquifer, and practically all of them are located in areas where the upper confining unit of the Floridan aquifer system either is less than 100 feet thick or is absent. The distribution of large springs discharging from the Floridan aquifer system, like the areas of greatest transmissivity within the aquifer system, is the direct result of dissolution of carbonate rocks, which results in the development of large conduits. Many of these caverns channel the ground water to the point where they are exposed at land surface and become the orifices of major springs (fig. 58).



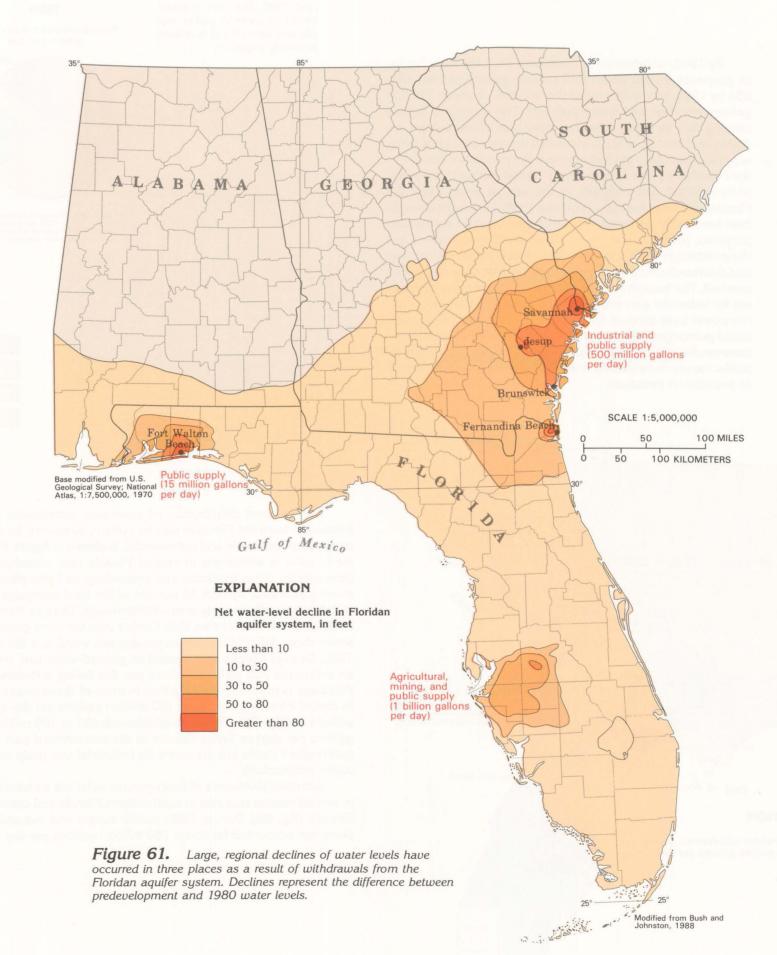
GROUND-WATER FLOW

The existence of a regional ground-water flow system in the Floridan aquifer system was first recognized in peninsular Florida in the 1930's and, by the 1940's, this system was known to extend into Georgia and South Carolina. The major features of this ground-water flow system can be illustrated by a map of the potentiometric surface of the Upper Floridan aquifer. The contours shown in figure 59 represent the altitude and configuration of the potentiometric surface of the Upper Floridan aquifer before development (that is, the condition before substantial withdrawals from the aquifer began). The altitude and configuration of the potentiometric surface in 1980, when withdrawals had changed the configuration of the surface considerably, is shown in figure 60. In both figures, the contours represent lines of equal altitude of the potentiometric surface or water level. The arrows superimposed on the maps show the direction of ground-water movement, which generally is perpendicular to the contours.

Water in the Upper Floridan aquifer moves from high to low areas on the potentiometric surface. The highest areas on the Upper Floridan's potentiometric surface are located: (1) in a band where the aquifer is exposed at the land surface near its landward, updip limit and (2) in an area in central peninsular Florida (figs. 59 and 60). Water moves coastward from the outcrop area of the aquifer and outward in all directions from the potentiometric high in central Florida. Although recharge to the aquifer takes place throughout more than onehalf of its area, recharge tends to be concentrated in outcrop areas and at potentiometric highs. Rates of recharge vary from less than 1 inch to more than 20 inches per year, depending on local geologic and hydrologic conditions. For example, in Lowndes County in south-central Georgia, the aquifer is hydraulically connected to the Withlacoochee River through swallow holes (sinkholes that develop in a bed of a stream) in the streambed and captures much or all of the streamflow during dry seasons. Recharge here is estimated to be between 10 and 20 inches per year. In contrast, little recharge (an estimated 1 to 5 inches per year) takes place at the potentiometric high in central peninsular Florida.

Before development, nearly 90 percent of the discharge from the Floridan aquifer system was to springs and streams. Upward leakage across confining units, especially in coastal areas, accounted for slightly more than 10 percent of the discharge. Discharge to offshore springs was common on both the gulf and ocean sides of the northern part of peninsular Florida where onshore hydraulic heads were 10 feet or less. Contours that extend offshore from coastal Georgia and adjacent northeastern Florida are based on freshwater heads measured during recent test drilling.

The degree of confinement of the Floridan aquifer system is the characteristic that most greatly affects the distribution



of recharge and discharge, and is reflected in the character of the potentiometric surface. Where the system is unconfined or the upper confining unit is thin, there is substantial hydraulic connection between the aquifer and surface drainage. In such areas, the potentiometric surface is irregular, complex, and has many closed highs and lows. Contours are commonly distorted where they cross surface streams or where there are groups of springs. In areas of thick confinement, the aquifer is not affected by surface streams because of the intervening confining unit. Smooth contours are, accordingly, associated with confined conditions. Examples of such places are southeastern Georgia and South Carolina, western panhandle Florida, and southern peninsular Florida.

The band of closely spaced contours trending northeast across south-central Georgia (fig. 59) is located just upgradient from the Gulf Trough, a graben filled with a greater than average thickness of the clayey upper confining unit. Faults bounding this graben extend through the Floridan aquifer system and have allowed confining-unit material to be downdropped opposite the aquifer, thus impeding ground-water flow. This damming effect is represented by the closely spaced potentiometric contours.

The effect of ground-water withdrawals on the potentiometric surface of the Upper Floridan aquifer is illustrated by a map of that surface as it existed in 1980 (fig. 60). The major features of the potentiometric surface are the same as those of the predevelopment surface. That is, the direction of flow in South Carolina and Georgia was still east or southeast from outcrop areas to the Atlantic Ocean and Florida. In peninsular Florida, the general flow direction was still toward the gulf and ocean. However, the effect of withdrawals is shown by deep cones of depression at Savannah, Jesup, and Brunswick, Ga., and at Fernandina Beach and Fort Walton Beach, Fla. Also, hydraulic heads have been lowered 30 feet or more throughout a five-county area southeast of Tampa Bay on the west coast of Florida as a result of withdrawals for irrigation and industrial needs. Regional declines of more than 10 feet have occurred in three broad areas surrounding pumping centers (fig. 61): (1) southeastern Georgia and adjacent parts of northeastern Florida and southern South Carolina; (2) west-central peninsular Florida; and (3) western panhandle Florida. Predevelopment potentiometric gradients have been locally reversed in some coastal areas, creating the potential for encroachment of saltwater from the gulf or ocean or from deep parts of the aquifer that contain saltwater. However, saltwater encroachment was limited to a few localized areas as of 1986.

The major characteristics of the predevelopment flow system have not been greatly altered by ground-water development. The dominant form of discharge remains springflow and discharge to streams. The withdrawal of more than 3 billion gallons per day of freshwater during the early 1980's accounts for less than 20 percent of the total discharge of the Floridan aquifer system.

SINKHOLES

Sinkholes are closed depressions in the land surface formed by dissolution of near-surface rocks or by the collapse of the roofs of underground channels and caverns. Sinkholes are a natural, common geologic feature in places underlain by soluble rocks such as the limestone and dolomite that form the Floridan aquifer system. Under natural conditions, sinkholes form slowly and expand gradually. However, activities, such as dredging, constructing reservoirs, diverting surface water, and pumping ground water can accelerate the rate of sinkhole expansion, resulting in the abrupt formation of collapse-type sinkholes, some of which are spectacular (fig. 62).

The dissolution of carbonate rocks by acidic water is the cause of the subsidence that creates all sinkholes. The water enlarges pre-existing openings ranging from pore spaces between limestone particles to fractures in the rock. The enlarged spaces eventually form a network of caves, pipes, and other types of conduits, all of which collect and channel large volumes of ground water. In the Floridan aquifer system, the greatest dissolution occurs where the upper confining unit of the system is thin or absent.

Sinkholes have important effects on both surface and ground water. Lakes commonly occupy the depressions created by sinkhole collapse. Streams, such as the Withlacoochee River near Valdosta, Ga., lose their entire flow at low-flow stages to the Upper Floridan aquifer through swallow holes in the streambed. Where they are not plugged, sinkholes form a direct connection from the land surface to the Upper Floridan aquifer, allowing surface runoff to move directly and quickly into the aquifer.



Figure 62. Spectacular, sudden collapse of the land surface commonly accompanies the formation of a sinkhole, such as this one that formed at Winter Park, just north of Orlando, Fla., in

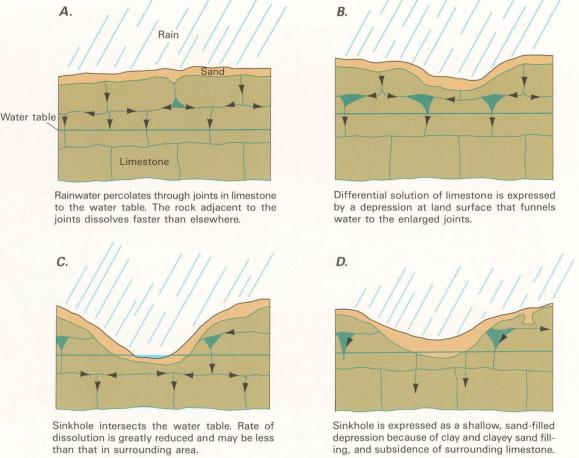


Figure 63. Gradually subsiding sinkholes are shallow and form at places where the limestone is thinly covered by soil or where it is overlain by a layer of sand.

Modified from Sincle

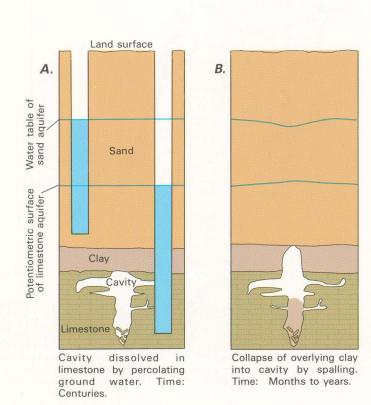
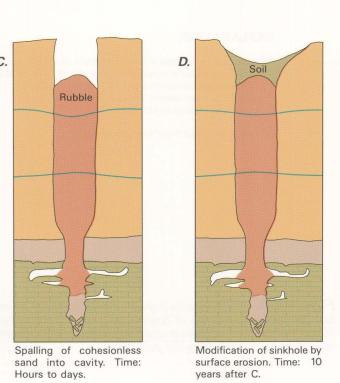


Figure 64. Collapse sinkholes form suddenly as a cavity roof collapses after dissolution of the limestone beneath the roof. The roof may consist either of clay, as shown here, or of limestone.



Modified from Bed

GROUND-WATER DEVELOPMENT

Ground-water development of the Floridan aquifer system began in the 1880's when Savannah, Ga., and Jacksonville, Fla., first constructed wells for municipal supply. By the early 1900's, several other cities, including Brunswick, Ga., and Daytona Beach, Fernandina Beach, Fort Meyers, Orlando, St. Petersburg, Tallahassee, and Tampa, Fla., were obtaining water supplies from the Floridan. Many of these early wells flowed because hydraulic heads initially were high. However, increased use soon caused the hydraulic head in the Upper Floridan aquifer to decline until installation of pumps and deepening of supply wells became necessary. Starting in the 1930's, industrial withdrawals from the Floridan became an important factor as pulp- and paper-processing plants in southeastern Georgia and northeastern Florida, and phosphate mining and citrusprocessing operations in west-central Florida, began to withdraw large volumes of ground water.

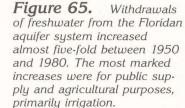
By 1950, withdrawals of freshwater from the Floridan for all purposes totaled about 630 million gallons per day (fig. 65); by 1980, nearly five times this volume, or about 3 billion gallons per day, was being pumped. The dominant factors causing this increase were the expansion of agriculture, industry, and mining, and the increased demand for public water supplies, especially in Florida where the population served by the Floridan aquifer system nearly tripled during this 30-year period. Significant changes in the use of water from the Floridan occurred between 1950 and 1980. The major changes have been in the percentage of withdrawal used for agricultural purposes, primarily irrigation, which more than tripled, and the percentage withdrawn for self-supplied industrial, mining, and thermoelectric power uses, which decreased by more than one-half. The majority of the withdrawals in the latter category are for industrial use; withdrawals for mining and thermoelectric power uses account for only about 3 percent of the combined pumpage. The percentage withdrawn for domestic and commercial uses remained practically the same, but that for public supply increased by one-third, directly reflecting trends in population increases.

Some sinkholes form by slow, gradual subsidence of the land surface in response to dissolution of limestone (fig. 63). These gradually subsiding sinkholes are usually shallow and bowl-shaped, and form in places where the limestone is either: (1) exposed at the land surface or thinly covered or (2) covered by a layer of unconsolidated sand that slumps downward to fill the sinkhole as it forms. In the latter case, infilling of the sinkhole keeps pace with dissolution of the limestone. Gradually subsiding sinkholes commonly form where slow dissolution takes place, mostly along joints in the limestone. These sinkholes tend to form naturally and are not greatly affected by human activities.

Collapse sinkholes, such as the one shown in **figure 64** form suddenly by the collapse of the roof of a large solution cavity. Such large cavities commonly form where ground water

circulation is vigorous, thus accelerating the dissolution of the limestone. As the cavity expands laterally, its roof gradually flakes off under the effect of gravity. Continued dissolution and spalling of the cavity roof proceed until the roof suddenly collapses under the weight of the overlying material, and a steepsided, circular sinkhole forms. Collapse sinkholes form either in places where the cavity roof consists entirely of limestone, or where clay forms a bridge over the cavity (fig. 64); they are the type of sinkhole that usually forms in response to human activities. Additional loading of the land surface by construction of surface-water impoundments or buildings, abrupt decline of the potentiometric surface of the Upper Floridan aguifer in areas of substantial pumpage or harmonic loads produced by the vibratory action of passing trains or heavy construction equipment have all been known to trigger sinkhole collapse.

1980



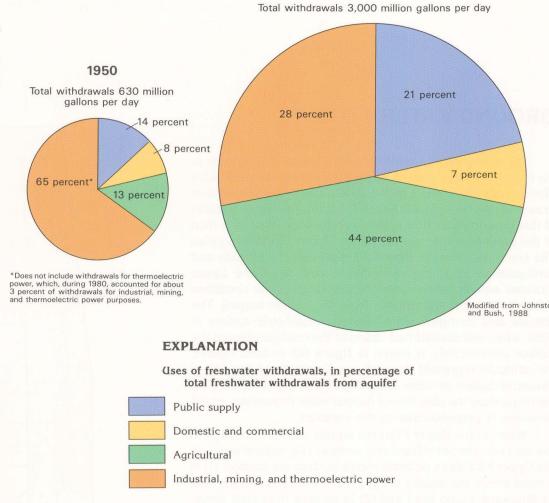
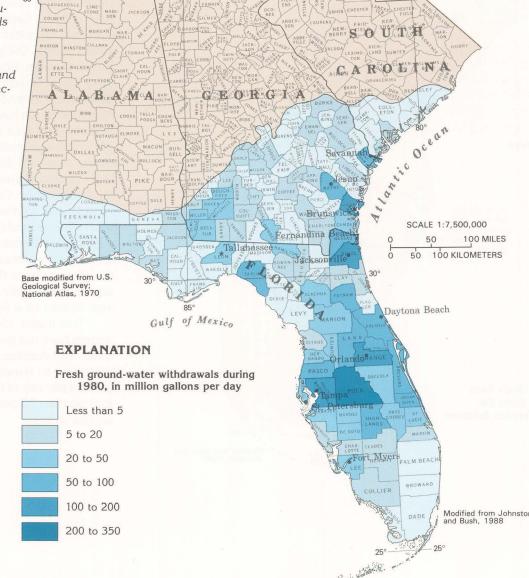


Figure 66. The distribution of freshwater withdrawals from the Floridan aquifer system mostly reflects the water needs of population centers. However, irrigation and phosphate-mining activities account for much of the freshwater withdrawals in central peninsular Florida.



The regional distribution of estimated withdrawals of freshwater from the Floridan aquifer system, by county, for all uses except domestic and commercial, is shown in figure 66. More water is withdrawn in central Florida than elsewhere, primarily for citrus irrigation and processing, and phosphatemining activities. Almost 30 percent of the total pumpage is withdrawn in a five-county area—Hillsborough, Orange, Pasco, Pinellas, and Polk Counties. Polk County uses the most ground water; about 310 million gallons per day was withdrawn during 1980. Orange County was second in ground-water use, with an estimated 200 million gallons per day being withdrawn. Pumpage is primarily for irrigation in most of those counties in central Florida where 20 to 100 million gallons per day are withdrawn (fig. 66). The large withdrawals (50 to 100 million gallons per day) in Taylor County in the easternmost part of panhandle Florida are primarily for industrial use (pulp and paper production).

Substantial volumes of fresh ground water are withdrawn in several coastal counties in northeastern Florida and coastal Georgia (fig. 66). During 1980, public supply and industrial pumpage accounted for about 160 million gallons per day in

the Duval-Nassau County, Fla., area (Jacksonville and Fernandina Beach); about 100 million gallons per day in Glynn County, Ga., (Brunswick); and about 75 million gallons per day in both Wayne County (Jesup) and Chatham County (Savannah), Ga. In Georgia, the greatest withdrawals for agricultural purposes, primarily irrigation, during 1980 were in a 15-county area known as the Dougherty Plain in southwestern Georgia, where a total of about 210 million gallons per day was withdrawn.

Uncontrolled flowing wells in many counties in central and southern Florida are a commonly overlooked but important source of discharge from the Floridan aquifer system. Where hydraulic heads are high, some of these wells discharge at land surface; others discharge into shallow zones in the Floridan or overlying aquifers through deteriorated well casings or open boreholes. In 1978, there were as many as 15,000 uncontrolled flowing wells in Florida that discharged an estimated 790 million gallons per day—almost one-third as much as was pumped from the aquifer system during 1980. Many of these wells were subsequently located and plugged under an ongoing program conducted by State and local governmental agencies.

INJECTION WELLS

Parts of the Lower Floridan aquifer that contain saltwater are locally used as receiving zones for industrial and municipal wastes disposed of through injection wells in Florida. The location of injection-well sites in Florida that were operating as of January 1988 is shown in **figure 67**. About 208 million gallons per day of wastes are injected into these wells; about 97 percent of this volume is municipal waste. Some of the wells, such as those in Polk County, Fla., are used to inject wastes into permeable rocks below the Floridan aquifer system because the entire Floridan contains freshwater in Polk County. The majority of injection wells, however, are completed in the deeper parts of the Floridan that contain saltwater.

In central Florida, particularly in the Orlando area (Orange County), drainage wells have been used since the early 1900's to dispose of storm runoff into the Upper Floridan aquifer (fig. 67). Public water-supply wells in the Orlando area, accordingly, are drilled into the Lower Floridan aquifer, which is separated from the Upper Floridan aquifer by a confining unit. There is no evidence to date that the drainage wells have contaminated the Lower Floridan aquifer to any great extent, even though they provide an estimated 30 to 50 million gallons per day of recharge to the system.

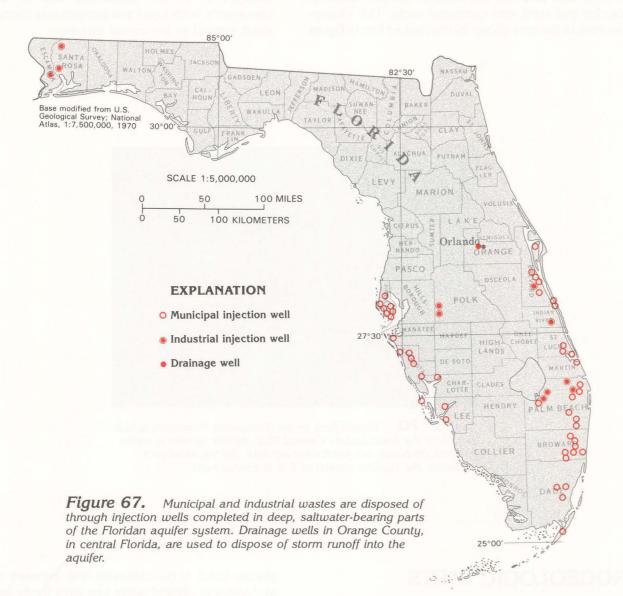
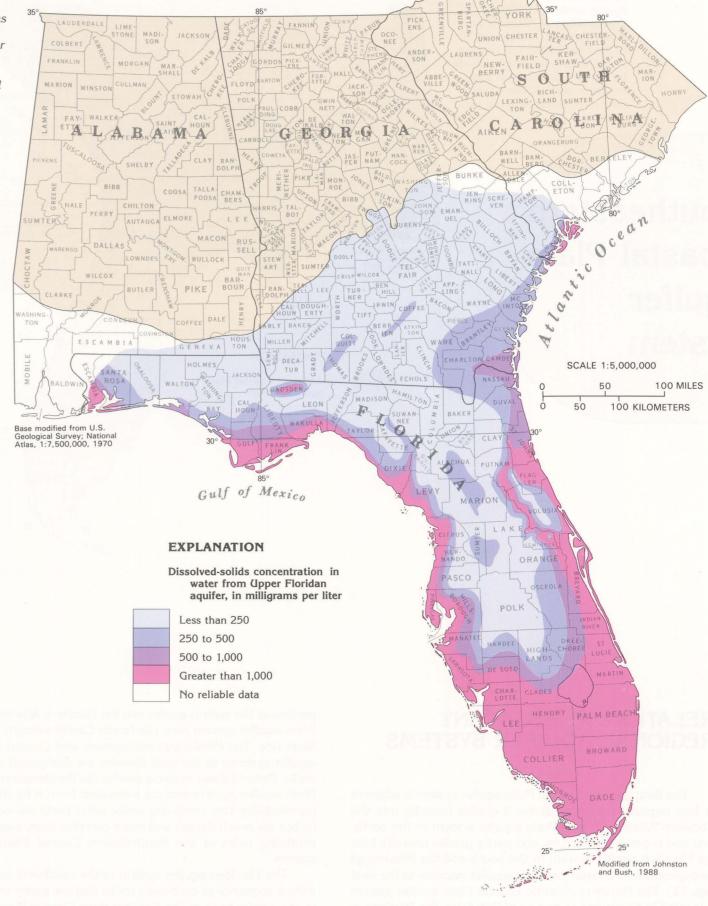


Figure 68. Concentrations of dissolved solids in water from the Upper Floridan aquifer increase coastward, primarily because of mixing with saltwater. In outcrop areas and where the upper confining unit is thin, flow is vigorous and dissolved-solids concentrations are generally less than 250 milligrams per liter.



GROUND-WATER QUALITY

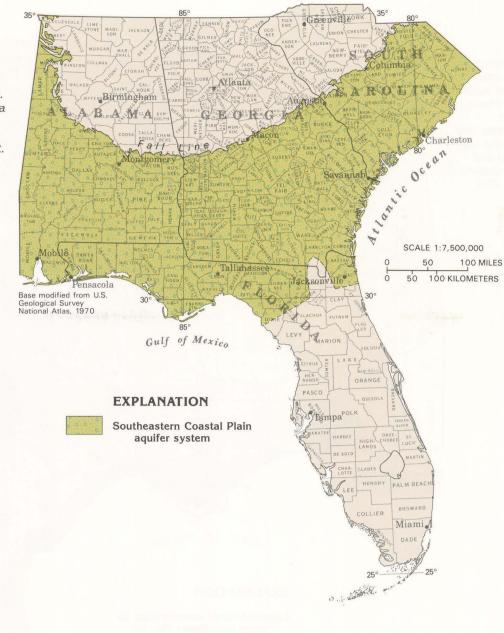
Dissolved-solids concentrations (the sum of all cations and anions in solution) of water in the Floridan aquifer system are related to: (1) the ground-water flow system, and (2) the proximity to saltwater. In places where the aquifer system is unconfined or thinly confined, ground-water flow is vigorous. Large volumes of water move quickly in and out of the aquifer system, and dissolved-solids concentrations are minimal. Water that travels down longer flowpaths, and, thus, dissolves more limestone and possibly sulfate minerals, such as gypsum, has greater dissolved-solids concentrations. Dissolved-solids concentrations in the Upper Floridan aquifer are shown in figure 68. Near the east and west coasts of Florida, and locally in eastern South Carolina and adjacent areas of coastal Georgia, large dissolved-solids concentrations are due to the mixing of fresh ground water with deeper saltwater that migrates into

the aquifer from the ocean. In western panhandle Florida and in the southern one-third of that State, large concentrations of dissolved solids result from the ground water mixing with residual saltwater that a sluggish flow system has left unflushed from the aquifer. The band of large dissolved-solids concentrations along the St. Johns River in east-central Florida likewise reflects unflushed, residual saltwater.

The most common cations in water from the Upper Floridan aquifer are calcium, magnesium, and sodium; the most common anions are bicarbonate, chloride, and sulfate. All of these ions are present either in the minerals of the aquifer or in unflushed saltwater within the aquifer. In general, water in the Lower Floridan aquifer is chemically similar to that of the Upper Floridan aquifer, except for dissolved-solids concentrations. There are more dissolved solids in the water in the Lower Floridan aquifer because this water has followed longer flowpaths and, accordingly, has had more time to dissolve aquifer minerals.

Figure 69. The Southeastern Coastal Plain aquifer system underlies the entire Coastal Plain of Alabama and South Carolina, and almost all of the Coastal Plain of Georgia. The system extends into Florida for a short distance and also underlies much of the Coastal Plain of Mississippi to the west.

Southeastern Coastal Plain aquifer system



RELATION TO ADJACENT REGIONAL AQUIFER SYSTEMS

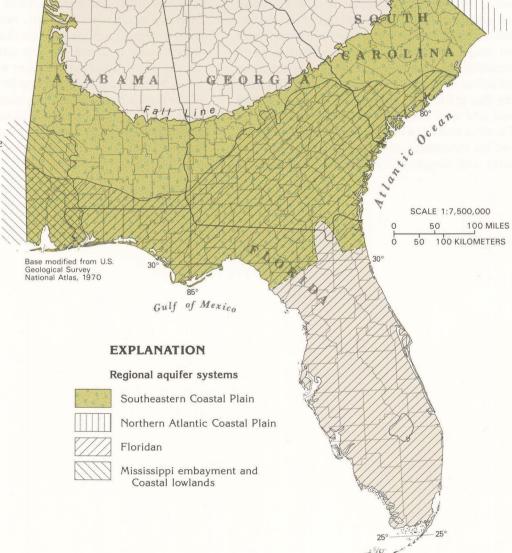
The Southeastern Coastal Plain aquifer system is adjacent to four regional aquifer systems. It grades laterally into the Northern Atlantic Coastal Plain aquifer system to the northeast and is partly overlain by, and partly grades laterally into, the Floridan aquifer system to the south and the Mississippi embayment and Coastal lowlands aquifer systems to the west (fig. 71). The Northern Atlantic Coastal Plain aquifer system is located in Segments 11 and 12 of this Atlas, the Mississippi embayment aquifer system is located in Segments 5 and 10, and the Coastal lowlands aquifer system is located in Segments 4 and 5.

The predominately clastic nature of the aquifers and confining units of the Southeastern Coastal Plain aquifer system

persists as the system grades into the Northern Atlantic Coastal Plain aquifer system near the North Carolina-South Carolina State line. The Mississippi embayment and Coastal lowlands aquifer systems to the west likewise are composed of clastic rocks. Parts of these systems overlie the Southeastern Coastal Plain aquifer system and are separated from it by thick, low-permeability clay confining units; other parts are equivalent to, but are much thicker and more complex than, aquifers and confining units of the Southeastern Coastal Plain aquifer system.

The Floridan aquifer system to the southeast consists of a thick sequence of carbonate rocks that are partly equivalent to the clastic beds of the Southeastern Coastal Plain aquifer system. In places, thick sequences of carbonate strata of the Floridan aquifer system overlie the clastic rocks. There is no confining unit separating the two aquifer systems, and the major difference between them is that the Floridan aquifer system tends to be more permeable.

Figure 71. The Southeastern Coastal Plain aquifer system grades into parts of four other regional aquifer systems. Three of these—the Northern Atlantic Coastal Plain, Mississippi embayment, and Coastal lowlands aquifer systems—consist of clastic rocks. The fourth, the Floridan aquifer system, consists of carbonate rocks.



INTRODUCTION

The Southeastern Coastal Plain aquifer system consists of four regional aquifers that are composed predominately of clastic rocks ranging in age from Cretaceous to late Tertiary. The aquifer system underlies an area of about 90,000 square miles in the Coastal Plain of Alabama, Georgia, and South Carolina and extends for a short distance into northern Florida (fig. 69). The system also extends westward throughout much of Mississippi, where it underlies an area of about 32,000 square miles. The upper part of the Southeastern Coastal Plain aquifer system grades into the Mississippi embayment aquifer system in western Alabama. The Mississippi part of the aquifer system is within Segment 5 of this Atlas.

The southern and southeastern limits of the aquifer system extend past the coastline in most places. That is, the rocks that comprise some of the water-yielding units of the aquifer system are permeable enough to maintain their character as aquifers for some distance offshore. However, the aquifers contain saltwater with dissolved-solids concentrations of 10,000 milligrams per liter or more near the coast in most areas. The limit of the aquifer system in peninsular Florida is the place at which the rocks of the lowermost regional aquifer change from a sand and clay sequence to low-permeability, calcareous clay and sand, and carbonate rocks. This change is approximately in the area shown by the dashed line in **figure**

69. West of Jacksonville, Fla., rocks of this lowermost aquifer are locally absent. Shallower regional aquifers in the system change to low-permeability rocks in southern Georgia. The northern limit of the aquifer system is its contact with crystalline rocks or consolidated sedimentary rocks of Paleozoic age at the Fall Line, which marks the updip extent of Coastal Plain sediments.

Rocks of the Southeastern Coastal Plain aquifer system were deposited in fluvial, deltaic and shallow-marine environments during a series of transgressions and regressions of the sea. Coarser grained, fluvial to deltaic sediments are located primarily near the updip extent of the aquifer system and consist primarily of coarse sand and gravel that form productive aquifers (fig.70). Most of the aquifers in the system, however, consist chiefly of fine to coarse sand.

Confining units within the system are mostly silt and clay, except for a thick sequence of chalk in Alabama and Mississippi. All these fine-grained materials form effective confining units that retard the vertical movement of ground water, especially where they are thick. The proportion of clay in the aquifer system generally increases in the direction of the coastline; thus, even though the system thickens in this direction, its overall transmissivity is much less toward the coastline.

The interbedding of coarse- and fine-grained sediments is complex because of fluctuating sea level and resulting changes in energy conditions and in depositional environments. Rock types and textures may change greatly within short vertical or horizontal distances.



Figure 70. Gravel beds in the Tuscaloosa Formation, which is part of the Southeastern Coastal Plain aquifer system in northwestern Alabama, are productive aquifers. For the most part, however, the aquifers consist of fine to coarse sand.

HYDROGEOLOGIC UNITS

There are many geologic formations in the complexly interbedded rocks that comprise the Southeastern Coastal Plain aquifer system. Likewise, there are many aquifers and confining units of local extent. Sequences of local aquifers may be grouped together and treated as a single, regionally extensive aquifer. One way to establish that local aquifers function as a single aquifer is to show that their hydraulic heads fluctuate in the same manner and at about the same time. Likewise, sequences of local confining units can be grouped as a single regional confining unit that impedes the vertical ground-water flow between regional aquifers.

The sediments of the Southeastern Coastal Plain aquifer system have been grouped into seven regional hydrogeologic units—four regional aquifers separated by three regional confining units. The geologic formations comprising the four regional aquifers and the three regional confining units that separate them are shown in **figure 72**. Also shown in **figure 72** are the Floridan aquifer system and the surficial aquifer system, which is generally thin and is not present everywhere. The Floridan aquifer system is hydraulically connected in different places to three of the regional aquifers of the Southeastern Coastal Plain aquifer system (**fig. 72**). In most

places, there is no confining unit between the two aquifer systems and ground water can pass freely between them.

Several geologic formations are included in each of the geohydrologic units shown in figure 72. In some places, the boundaries of the formations coincide with those of the hydrogeologic units; in other places, they do not. For example, the top of the Gosport Sand in Alabama is the same as the top of a regional aquifer. In contrast, the Cape Fear Formation in South Carolina is partly an aquifer and partly a confining unit. The regional hydrogeologic units differentiated are primarily units of similar permeability that hydraulically function in the same way. The regional aquifers are mostly sand with minor gravel and limestone beds, but they locally may contain clay beds. The regional confining units are primarily clay, silt, or chalk, but locally may contain sand beds.

Each of the regional aquifers of the Southeastern Coastal Plain aquifer system has been named for a major river that crosses the outcrop belt of the aquifer and, thus, exposes the aquifer. From youngest to oldest, the four regional aquifers differentiated in the system are the Chickasawhay River aquifer, the Pearl River aquifer, the Chattahoochee River aquifer, and the Black Warrior River aquifer. The regional confining units separating these aquifers bear the same name of the aquifer they overlie. For example, the Pearl River regional confining unit lies above the Pearl River regional aquifer and beneath the Chickasawhay River regional aquifer; and so on (fig. 72).

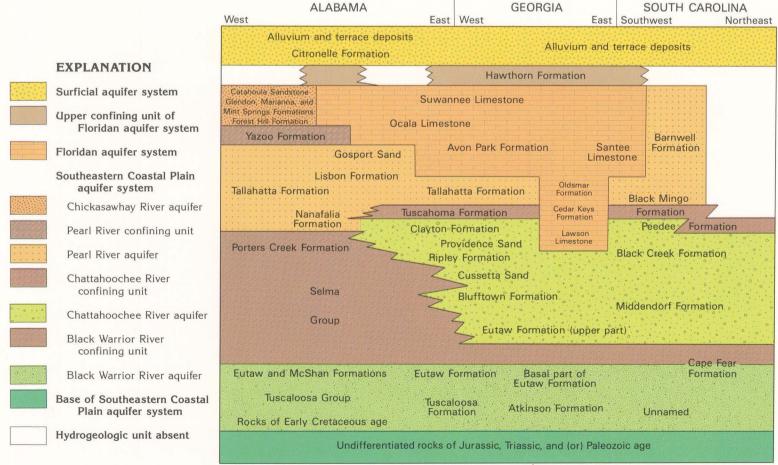


Figure 72. The large number of geologic formations that comprise the Southeastern Coastal Plain aquifer system can be grouped into four regional aquifers, which are named after major rivers that cross their outcrop areas. Three regional confining units separate the aquifers. This chart is not intended to show exact correlations of the geologic units.

Modified from Miller and Renken, 1988

TOP OF THE AQUIFER SYSTEM

The rocks grouped into the four regional aquifers and the intervening three regional confining units of the Southeastern Coastal Plain aquifer system are exposed at the land surface, approximately as a series of arcuate bands (fig. 73). In Alabama, the rocks comprising the oldest geohydrologic unit, the Black Warrior River aquifer, are exposed farthest north, with successively younger rocks cropping out toward the Gulf Coast. In eastern Georgia and western South Carolina, the younger rocks that comprise the Pearl River aquifer are exposed at the land surface. These rocks completely cover the older rocks that comprise the Chattahoochee River and Black Warrior River aquifers and their intervening confining units.

In south-central Alabama, the clastic rocks that comprise the Chickasawhay River aquifer grade into carbonate rocks that comprise the upper part of the Floridan aquifer system (fig. 73); the Chickasawhay River aquifer does not extend east of this area. The sandy beds of the Chattahoochee River aquifer grade westward into clayey confining units in western Alabama, and the aquifer does not exist beyond that area. Carbonate rocks of the Floridan aquifer system overlap the clastic rocks of the Pearl River aguifer. No clayey confining unit separates these rocks except locally in western Alabama.

Rocks comprising the regional confining units of the Southeastern Coastal Plain aguifer system are not exposed at the land surface except in Alabama. Accordingly, permeable beds of some of the regional aquifers lie directly on top of each other in their outcrop areas in Georgia and South Carolina. However, the low-permeability rocks comprising the regional confining units are present in the subsurface in these two States.

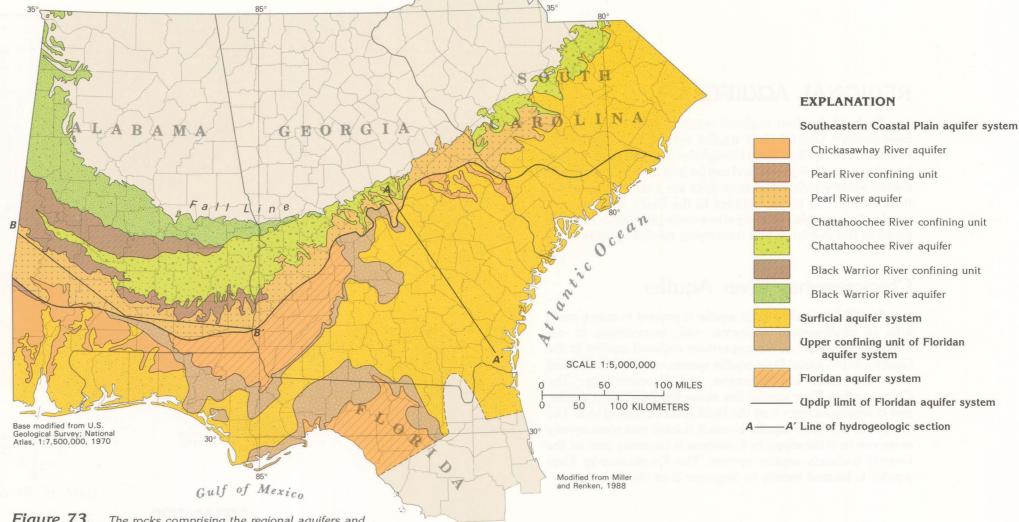


Figure 73. The rocks comprising the regional aquifers and confining units of the Southeastern Coastal Plain aquifer system are exposed at the land surface as a series of arcuate bands. In Georgia, South Carolina, and southwestern Alabama, the aquifer system is overlain by other aguifers.

Figure 74. An idealized hydrogeologic section in southeastern Georgia shows how two of the regional clastic aguifers of the southeastern Coastal Plain aquifer system grade into carbonate rocks of the Floridan aquifer system. The line of the section is shown in figure 73.

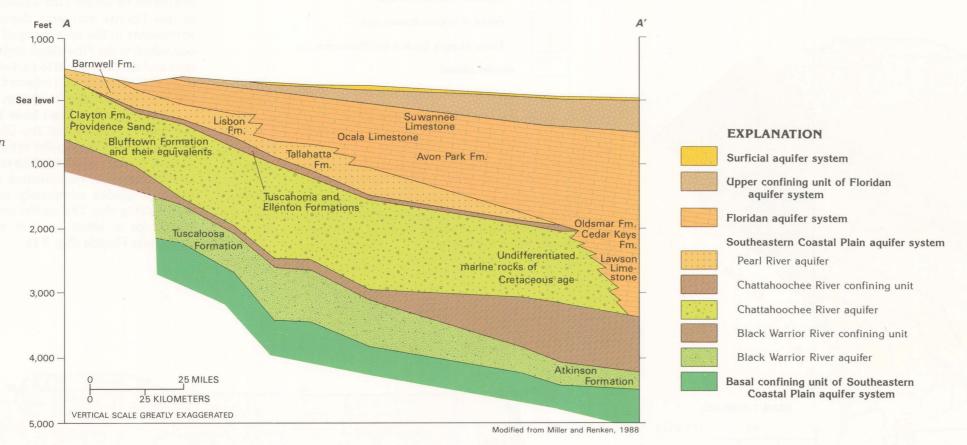
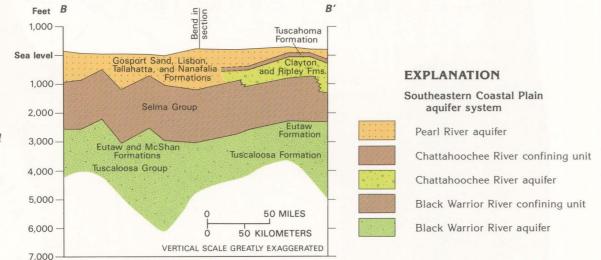


Figure 75. An idealized hydrogeologic section trending eastward across Alabama shows that some regional aguifers of the Southeastern Coastal Plain aquifer system are thick and continuous, whereas others pinch out as their rocks become fine-grained enough to be considered confining units. The line of the section is shown in figure 73.



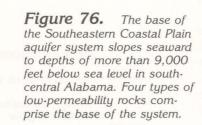
Hydrogeologic section B-B' (**fig. 75**) in southern Alabama shows the Pearl River aquifer is at the land surface. The Chattahoochee River aquifer and its overlying Chattahoochee River confining unit are present only in the eastern one-third of the section. They both merge to the west into the Pearl River aquifer and are included as part of it. The Black Warrior River confining unit is everywhere thicker than 1,000 feet along the line of the section. None of the data used to construct this section are from wells deep enough to completely penetrate the Black Warrior River aguifer, which contains mostly saltwater in the area of the section; the two shallower aguifers contain freshwater.

BASE OF THE AQUIFER SYSTEM

Modified from Miller and Renken, 1988

The base of the Southeastern Coastal Plain aquifer system consists of rocks of several types, all of which have extremely low permeability. The base of the system slopes gently from its inner margin toward the Atlantic Ocean and more steeply toward the Gulf of Mexico (fig. 76). Near the Georgia-Florida State line, the rocks that comprise the base of the aquifer system are warped into two deep basins separated by a high area that is a northwestward extension of the Peninsular arch in Florida. The base of the system is about 4,500 feet below sea level in the Southeast Georgia embayment and is about 10,000 feet below sea level in south-central Alabama. Westward, in Mississippi, the base of the aquifer system trends more northward due to the effect of downwarping in the Mississippi

The low-permeability rocks comprising the base of the aquifer system can be grouped into four categories (fig. 76). From oldest to youngest, these are: predominantly Precambrian crystalline rocks, including igneous and metamorphic rocks that are buried extensions of the Piedmont; Paleozoic sedimentary rocks that are mostly sandstone and shale in western Alabama, and black shale and white quartzite elsewhere; early Mesozoic rocks that are predominately coarsegrained redbeds intruded by diabase; and Jurassic sedimentary rocks that are mostly varicolored sandstone interbedded with shale.



EXPLANATION

feet. Datum is sea level

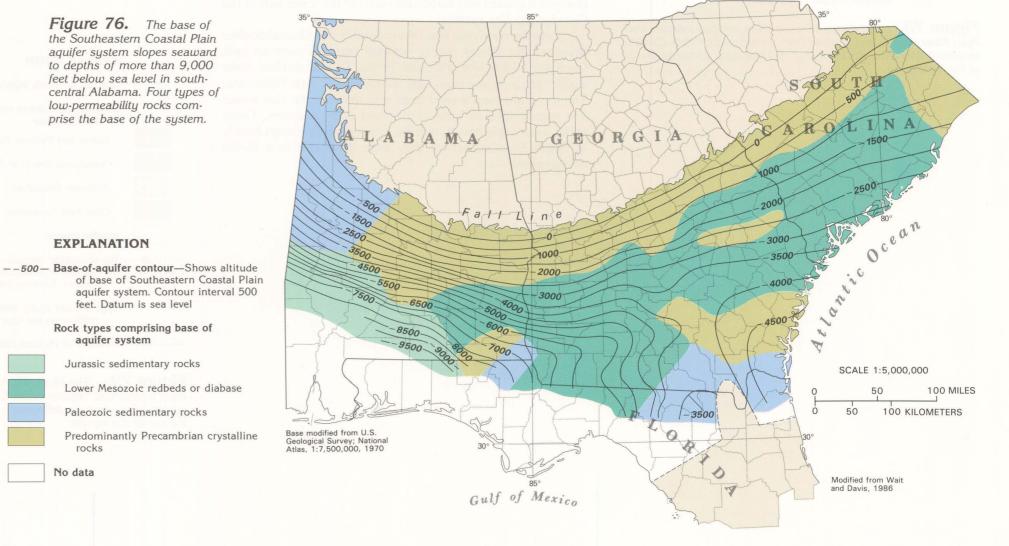
Rock types comprising base of

Jurassic sedimentary rocks

Paleozoic sedimentary rocks

aquifer system

No data



VARIATIONS WITHIN THE

The different regional aquifers and confining units of the

Southeastern Coastal Plain aquifer system thicken and thin in

the subsurface, and in places are absent, as their permeability

characteristics grade from those of an aquifer to those of a con-

fining unit or vice versa. These gradational differences are

shown on two hydrogeologic sections; one perpendicular and

(fig. 74) shows that there are three regional aquifers that com-

prise the aquifer system there. The different geologic forma-

tions that comprise each aquifer are identified on the section.

All the aquifers dip toward the southeast from the outcrop area.

The thickness of each individual aquifer, and the aquifer system

as a whole, is greatest near the middle of the section. The Black

Warrior River aquifer extends farther to the southeast than do

the two shallower aquifers. The Pearl River and Chattahoochee

River aquifers, and the Chattahoochee River confining unit be-

tween them, all end near the coast. In the coastal area, the sandy aquifer material and the clayey confining-unit material

of the Southeastern Coastal Plain aquifer system grade into

carbonate rocks of the Floridan aquifer system. Near the north-

west side of the section, the Pearl River and Chattahoochee

River aquifers are in direct hydraulic contact.

Hydrogeologic section A-A' in southeastern Georgia

one parallel to the outcrop area of the aquifer system.

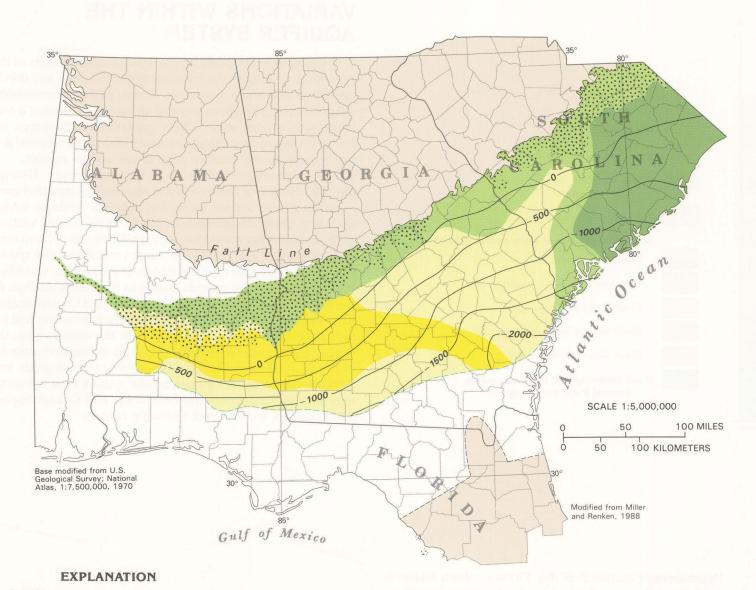
AQUIFER SYSTEM

REGIONAL AQUIFERS

Each of the four regional aquifers that comprise the Southeastern Coastal Plain aquifer system includes several smaller-scale aquifers. Even though the regional aquifers contain clayey confining units and can be locally subdivided, their overall water-yielding characteristics are similar throughout their extent. The rocks included in the Black Warrior River aquifer, for example, are everywhere more permeable than the rocks of the overlying and underlying confining units.

Chickasawhay River Aquifer

The Chickasawhay River aquifer is present in only a small area in southwestern Alabama, and, accordingly, is not mapped. This aquifer, the uppermost regional aquifer in the Southeastern Coastal Plain aquifer system, consists of sand and limestone beds of Oligocene and Miocene age. The Chickasawhay River aquifer lies above the Pearl River aquifer and is separated from it by the Pearl River confining unit. The Chickasawhay River aquifer is much thicker and more areally extensive in Mississippi; in Louisiana it becomes part of the Coastal lowlands aquifer system. The Chickasawhay River aquifer is located mostly in Segment 5 of this Atlas.



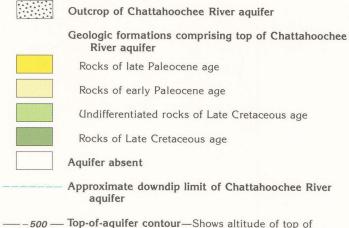


Figure 78. The Chattahoochee River aquifer underlies the Pearl River aquifer and extends from southeastern North Carolina to central Alabama. Rocks of four different ages comprise the top of the aquifer.

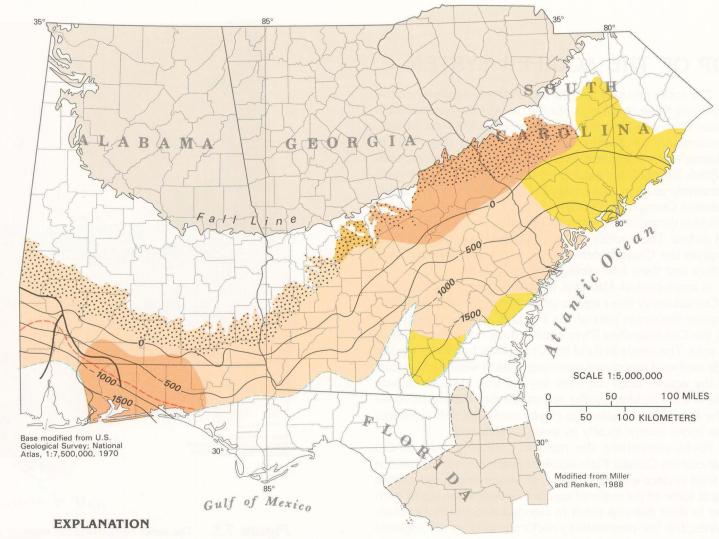
500 feet. Datum is sea level

Chattahoochee River aguifer. Contour interval

Chattahoochee River Aquifer

The Chattahoochee River aquifer lies above the Black Warrior River aquifer and the two are separated by the Black Warrior River confining unit. The Chattahoochee River aquifer is separated from the overlying Pearl River aquifer by the Chattahoochee River confining unit. The Chattahoochee River aquifer extends from southeastern North Carolina westward into central Alabama (fig. 78), where the lower part of the aquifer changes from sand to clay and chalk, and the clay confining unit over it pinches out (fig. 75). West of this area, equivalent permeable rocks are grouped with those of the Pearl River aquifer, and the fine-grained rocks in the lower parts of the aquifer are included in the Black Warrior River confining unit. The southern limit of the Chattahoochee River aquifer is where it grades into carbonate rocks of the lower part of the Floridan aquifer system.

Like the overlying Pearl River aquifer, the Chattahoochee River aquifer slopes gently seaward from its outcrop belt. Geologic formations included in the Chattahoochee River aquifer range in age from Late Cretaceous to Late Paleocene. The rocks are mostly sand beds with thin, lignitic clay lenses and locally include glauconitic sand and limestone. These rocks were deposited in marine environments except locally in South Carolina, where they were deposited in a fluvial environment.



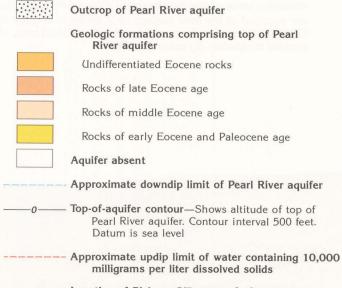
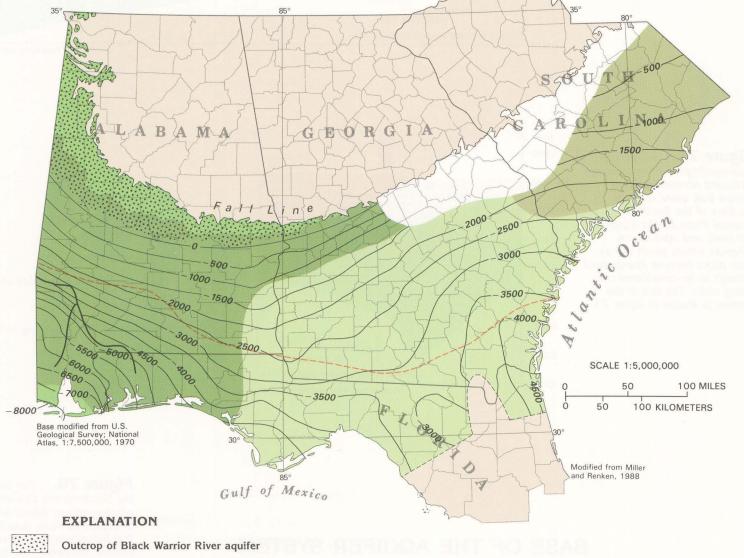


Figure 77. The top of the Pearl River aquifer is about 1,500 feet below sea level in places. Rocks of four different ages comprise the top of the aquifer.

Pearl River Aquifer

The Pearl River aquifer is a thick sequence of sand with minor sandstone and gravel, and a few limestone beds. The sediments comprising the aquifer range in age from Paleocene to late Eocene and were deposited mostly in marine environments in the area mapped in **figure 77**. The aquifer is equivalent to the Mississippi embayment aquifer system to the west and southwest and to part of the Floridan aquifer system in southern Georgia and adjacent areas. The Pearl River aquifer and the Floridan aquifer system are hydraulically connected.

The top of the Pearl River aquifer slopes gently toward the Atlantic Ocean and the Gulf of Mexico (fig. 77). The seaward limit of the aquifer in Florida and Georgia is the area where it grades completely into carbonate rocks of the Floridan aquifer system. In southwestern Alabama, its limit is the area where it grades completely from sandy strata into low-permeability clay. The aquifer contains freshwater everywhere except for a small area in southwestern Alabama and panhandle Florida (fig. 77).



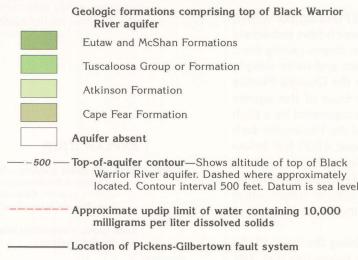
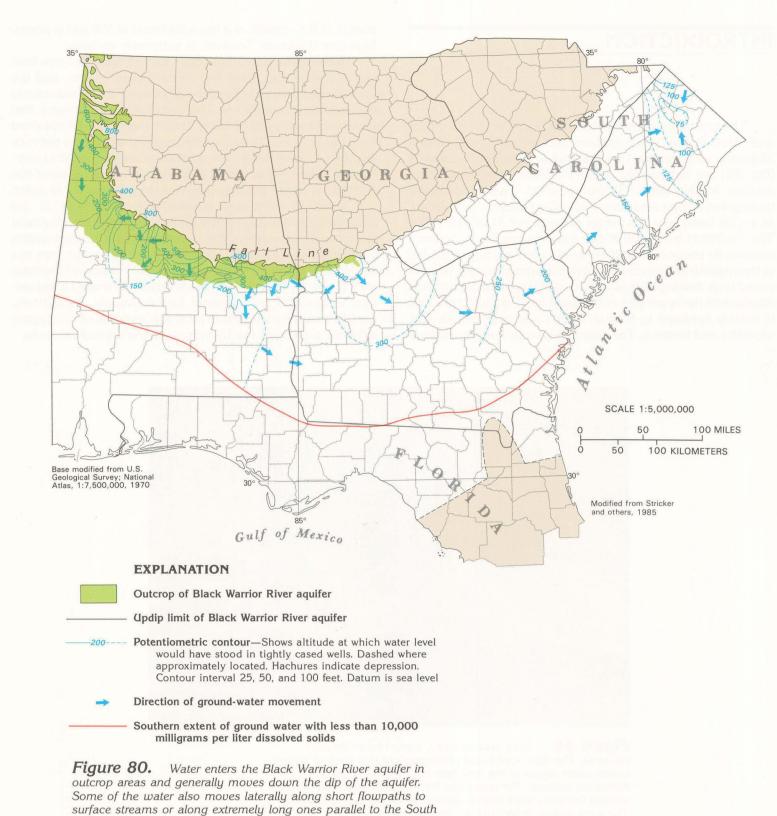


Figure 79. The Black Warrior River aquifer is the basal, and most widespread, aquifer in the Southeastern Coastal Plain aquifer system. Four geologic formations, all of Cretaceous age, comprise the top of the aquifer.

Black Warrior River Aquifer

The basal aquifer of the Southeastern Coastal Plain aquifer system is the Black Warrior River aquifer. Although this regional aquifer crops out only in Alabama, Mississippi, and a small part of westernmost Georgia, it is extensive in the subsurface (fig. 79) and is the most widespread of the regional aquifers in the system. In North Carolina, the aquifer grades laterally into the basal aquifers of the Northern Atlantic Coastal Plain aquifer system. The top of the aquifer, as shown by the contours in figure 79, ranges from a few hundred feet above sea level in its outcrop area to about 7,000 feet below sea level in southwestern Alabama. The aquifer is absent in a wide band adjacent to the inner Coastal Plain margin in South Carolina and eastern Georgia. There, the Chattahoochee River aquifer lies directly on the low-permeability rocks of the base of the aquifer system.

The Black Warrior River aquifer consists mostly of Upper Cretaceous sand and clay that were deposited in fluvial, deltaic, and marine environments. Locally, sands of Early Cretaceous age are included in the aquifer in Alabama. The aquifer is displaced by faults in southwestern Alabama that have offset its top by as much as 500 feet. These faults do not affect the ground-water flow system, however, because they occur where the aquifer contains stagnant saltwater. About one-third of the aquifer contains water with dissolved-solids concentrations greater than 10,000 milligrams per liter, as shown in figure 79.



GROUND-WATER FLOW

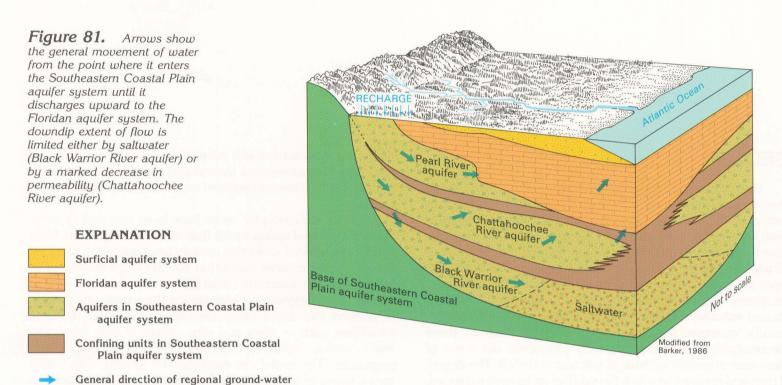
Recharge enters the Southeastern Coastal Plain aquifer system from precipitation on the outcrop areas of the aquifers. When reaching the water table, most of this water moves laterally to discharge at small streams in the outcrop area, evaporates, or is transpired by plants. Only a small part of the water percolates downward into the deeper parts of the aquifer system. In the outcrop areas, movement of the water is downward along generally short flowpaths until it reaches the area where the aguifers are confined. From this area, most of the movement is horizontal, along generally long flowpaths, until the water approaches discharge points, where its movement becomes again predominately vertical—but here, it moves upward, either toward a surface-water body or a shallower aquifer, either of which is a discharge area.

A map of the potentiometric surface (fig. 80) of the Black Warrior River aguifer shows that in outcrop areas, where water in the aquifer is under unconfined (water-table) conditions, it stands at high altitudes. These areas are primarily in Alabama, and the potentiometric surface is irregular because the aquifer is eroded by streams of various sizes that locally divert groundwater flow. As the aquifer becomes confined, its potentiometric surface is smoother and the contours representing that surface are more evenly spaced. Most of the water in the aquifer flows coastward and down the dip of the beds. However, an important component of flow is parallel to the Atlantic Ocean (perpendicular to dip), particularly in South Carolina where the water moves slowly northeastward along long flowpaths. The Chattahoochee River and Pearl River aquifers do not have this

coast-parallel direction of flow. Most of the water in these two shallower aquifers moves down the dip of the aquifers.

In southeastern Georgia, water moves readily between the Southeastern Coastal Plain and Floridan aquifer systems. Idealized conditions and the general direction of ground-water movement from the inner margin of the Coastal Plain to the Atlantic Ocean are shown in figure 81. In southeastern Georgia, only the Pearl River aquifer (of the three Southeastern Coastal Plain regional aquifers shown) extends to the land surface and receives direct recharge from precipitation. However, the Chattahoochee River confining unit that underlies the Pearl River aquifer pinches out updip, allowing water to leak freely downward from the Pearl River aquifer to the underlying Chattahoochee River aquifer. The Black Warrior River aquifer that lies still deeper is recharged in this area only by downward leakage across the confining unit that completely covers the

Where the aquifers become confined, the flow arrows show that the predominant movement of the water is lateral and down the dip of the aquifers. Near the coast, the arrows turn upward as flow is blocked either by saltwater or by the aquifer becoming so fine-grained that its permeability is greatly decreased. Flow is then primarily vertical to shallower aquifers or surface-water bodies, such as the ocean. Some water leaks either downward from or upward to the Floridan aquifer system from the Southeastern Coastal Plain aquifer system, depending on which aquifer system has the higher hydraulic head at a given place. The saltwater shown in the coastal area of the Black Warrior River aquifer is stagnant. The horizontal flow arrow, shown near the right side of the figure, in this aguifer represents the coastal-parallel component of ground-water flow that is unique to the aquifer.



GROUND-WATER QUALITY

Carolina coast.

Water in each of the regional aquifers of the Southeastern Coastal Plain aquifer system undergoes similar chemical changes as it moves from outcrop areas down the hydraulic gradient into deeper, confined parts of the aquifers. Initial changes are gradual and result from chemical interactions between the water and the minerals comprising the rocks. In deep parts of the aquifers, changes result from the mixing of freshwater with saltwater.

The principal water-quality constituents that are used to characterize the ground water in the Southeastern Coastal Plain aquifer system are dissolved solids, dissolved iron, and dissolved chloride. Dissolved-solids concentrations are generally less than 50 milligrams per liter in outcrop recharge areas but increase as the water moves downgradient and dissolves some of the aquifer minerals. Concentrations greater than 500 milligrams per liter generally occur only where there is mixing of freshwater and saltwater. This mixing has produced dissolved-solids concentrations as large as 10,000 milligrams per liter in places.

Dissolved-iron concentrations generally are less than 100 micrograms per liter in recharge areas but increase markedly downgradient where concentrations ranging from 1,000 to 10,000 micrograms per liter are present in bands parallel to outcrop areas. Farther downgradient, dissolved-iron concentrations decrease as the iron precipitates. Still farther downgradient, iron concentrations again increase in the freshwatersaltwater mixing zone.

Dissolved-chloride concentrations have the same pattern as dissolved-solids concentrations; both relate in large part to the degree to which freshwater has flushed saltwater, entrapped during deposition of the sediments, from the aquifers. The distribution of dissolved-chloride concentrations in water from the middle part of the Black Warrior River aquifer is shown in figure 82 and represents the general distribution of chloride concentrations for all the aquiters. Concentrations increase downgradient, locally exceeding 3,000 milligrams per liter in west-central Alabama and 20,000 milligrams per liter in southern Georgia. The downgradient increase in concentrations is gradual to about 1,000 milligrams per liter, where there is a marked increase as the freshwater mixes with saltwater.

Classification of waters based on their dominant cations and anions are called hydrochemical facies. The distribution of these hydrochemical facies (fig. 83) shows the progressive change in the chemical character of the water as it moves through the aquifer. To demonstrate the classification used, a calcium bicarbonate water is one in which calcium ions account for more than 50 percent of the total cations in the water and bicarbonate ions account for more than 50 percent of the total anions. Where no ion exceeds 50 percent, the water is said to have "no dominant" hydrochemical facies. In outcrop areas, the ground water is a calcium bicarbonate type. As water moves deeper into the aquifer, it becomes a sodium bicarbonate type. Finally, in the deeper parts of the aquifer, the water becomes a sodium chloride type. The water mapped in the figure as a sodium chloride type is not everywhere saltwater; some of the water is usable or even potable in many places, but its dominant ions in this area are sodium and chloride. The distribution of hydrochemical facies shown in figure 83 is representative of water in all the aquifers of the Southeastern Coastal Plain aquifer system.

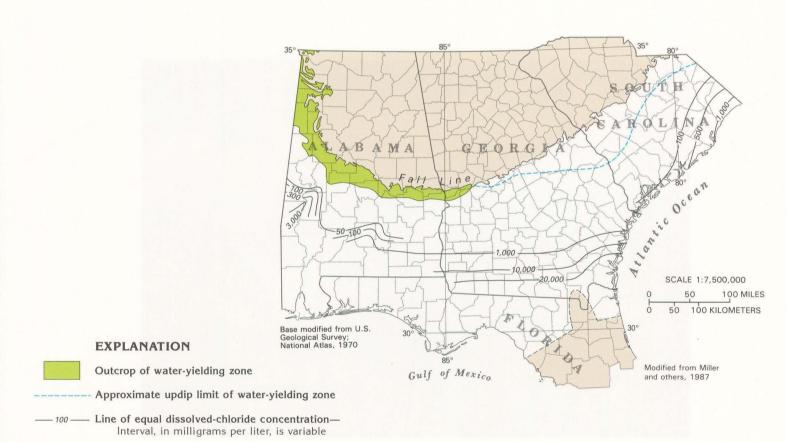


Figure 82. Concentrations of dissolved chloride in water from the middle water-yielding zone of the Black Warrior River aquifer increase downgradient.

---- Freshwater-saltwater interface

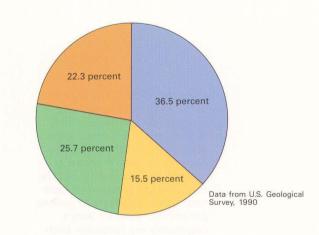


Figure 83. The chemistry of the water in the middle water-yielding zone of the Black Warrior River aquifer changes downgradient in a predictable fashion. The waterchemistry types, or hydrochemical facies, generally vary from calcium bicarbonate in aquifer outcrop areas to sodium chloride at great depths.

water-vielding zone



FRESH GROUND-WATER **WITHDRAWALS**

An estimated 574 million gallons per day of freshwater was withdrawn from the Southeastern Coastal Plain aquifer system during 1985. About 210 million gallons per day was withdrawn for public supply, the principal use (fig. 84). About 89 million gallons per day was withdrawn for domestic and commercial uses. About 150 million gallons per day was withdrawn for agricultural purposes, and about 125 million gallons per day was withdrawn for industrial, mining, and thermoelectric-power uses.

EXPLANATION

Use of fresh ground-water withdrawals during 1985, in percent—Total fresh ground-water withdrawals during 1985 were 361 million gallons per day



Domestic and commercial

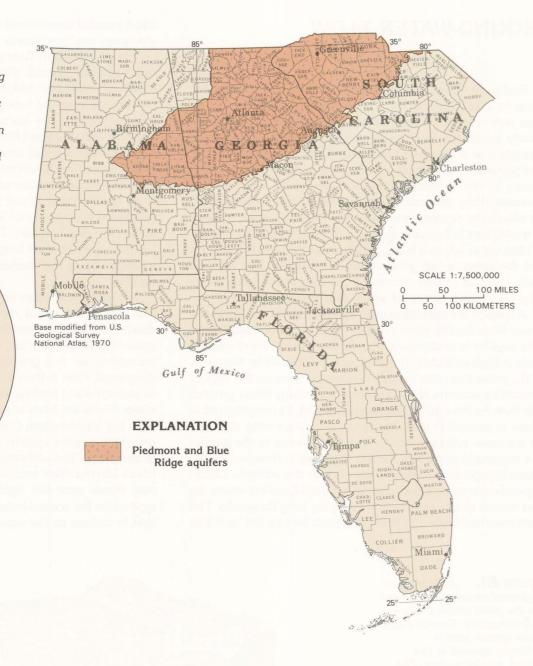


Industrial, mining, and thermoelectric power

Figure 84. About one-half of the freshwater withdrawn from the Southeastern Coastal Plain aquifer system during 1985 was used for public supply and domestic and commercial purposes.

Figure 85. Crystalline-rock aquifers underlie the rolling hills of the Piedmont physiographic province and the rugged mountains of the Blue Ridge physiographic province in a band that extends from east-central Alabama northeastward through western South Carolina.

Piedmont and Blue Ridge aquifers



GEOLOGY

Bedrock underlying the Piedmont and Blue Ridge physiographic provinces consists of many different types of metamorphic and igneous rocks that are complexly related. Rock type varies markedly from place to place. For example, Blue Ridge and Piedmont rocks are divided into more than 90 units on the 1976 geologic map of Georgia. The main rock types are gneiss and schist of various compositions; however, extremely fine-grained rocks, such as phyllite and metamorphosed volcanic tuff, ash, and flows are common in places. Locally, quartzite and marble are present. Most of these metamorphic rocks were originally sediments, but some of them were originally igneous or volcanic materials. The degree of heat and pressure to which the original rocks were subjected, coupled with the degree of structural deformation (principally folding and shearing) that they have undergone, has deter-

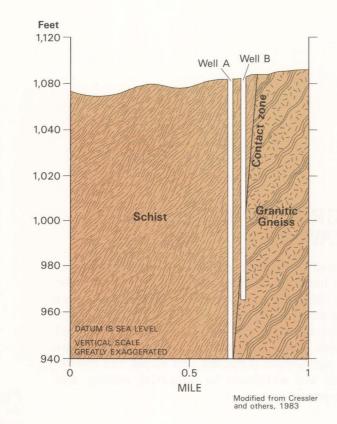
mined the final texture and mineralogy of the rocks. Most of the rocks have undergone several periods of metamorphism. Locally, they contain mineralized zones, some of which are ore bearing.

All the metamorphic rocks have been intruded by large to small bodies of igneous rock that varies in composition from felsic (light-colored rocks that contain large quantities of silica) to mafic (dark-colored rocks that contain large quantities of ferromagnesian minerals). Large igneous intrusions consist of granite, quartz monzonite, and gabbro; these rocks are present in plutons that cover many tens of square miles. Smaller intrusions, such as dikes and sills, consist of both felsic and mafic rocks, including syenite, andesite, diabase, and pegmatite. The rocks are displaced by several major fault zones, some of which extend for hundreds of miles. Locally, shearing along large fracture zones has produced siliceous, intensely fractured rocks, such as mylonite or phyllonite.



Figure **87.** The rugged, densely forested mountains of the Blue Ridge physiographic province have formed on hard, crystalline rocks.

Figure 88. The difference in the yield of different rock types is substantial in places. Well A, which is completed in schist, yielded about 1 gallon per minute; well B, which is open to granitic gneiss and the contact zone between the two rock types, yielded 100 gallons per minute. Contact zones commonly are favorable locations for yielding large volumes of water.



INTRODUCTION

The crystalline-rock aquifers that underlie the Piedmont and Blue Ridge physiographic provinces in east-central Alabama, northwestern Georgia, and western South Carolina (fig. 85) are collectively called Piedmont and Blue Ridge aquifers in this Atlas. Similar aquifers extend northward throughout a large area from North Carolina into New Jersey, in a wide band near the center of Segment 11 of this Atlas. The Piedmont and Blue Ridge aquifers consist of bedrock overlain by unconsolidated material called regolith. Included in the regolith are: saprolite, which is a layer of earthy, decomposed rock developed by weathering of the bedrock; soil that develops on the upper part of the saprolite; and alluvium, which is mainly confined to stream valleys and may overlie soil, saprolite, and bedrock. The saprolite is by far the largest com-

ponent of the regolith, and has a thickness of 150 feet in places. Saprolite thickness, however, is extremely variable.

Because the crystalline rocks formed under intense heat and pressure, they have few primary pore spaces, and the porosity and permeability of the unweathered and unfractured bedrock are extremely low. This does not mean, however, that these rocks will yield no water. Ground water can be obtained from two sources: (1) the regolith, and (2) fractures in the rock (fig. 86). Locally, where the crystalline rocks consist of marble, the dissolving action of slightly acidic ground water has created solution openings that yield large volumes of water.

Although there are considerable differences in the mineralogy and texture of the rocks comprising the Piedmont and Blue Ridge aquifers, the overall hydraulic characteristics of the aquifers are similar. Locally, however, the occurrence and availability of ground water varies greatly because of the complex variability in rock type. Such variability makes it impractical to describe ground-water flow regionally. Accordingly, specific examples taken from local studies are used to illustrate different aspects of the hydrology of the crystalline rocks.

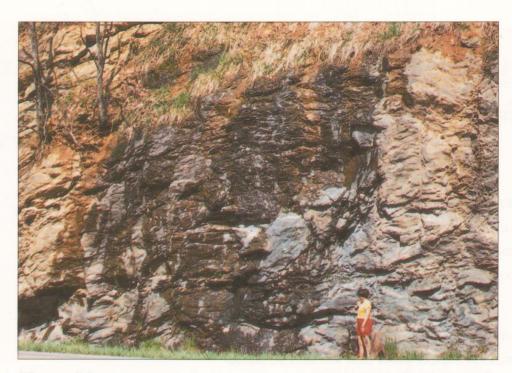


Figure 86. In crystalline rocks, water moves through fractures. The dark spot in the photograph of this roadcut shows where water issues at the rock face from part of a nearly horizontal fracture. The water has first moved downward through vertical fractures, then moves laterally to its point of discharge. The surrounding, lighter colored rock is dry.

RELATION OF ROCK TYPE AND WELL YIELD

Although some wells completed in the Piedmont and Blue Ridge aquifers yield almost 500 gallons per minute, the average reported well yield is much less and generally is in the range of about 15 to 20 gallons per minute. Yields of largediameter wells drilled for public water supply average about 30 gallons per minute. Part of the variation in yield depends upon the type of rock in which the well is completed. Wellyield data for Greenwood County, S.C., which is in the Piedmont physiographic province, are summarized in table 1. Wellyield data from a study conducted along the Blue Ridge Parkway in western North Carolina are summarized in table 2, and are considered to be representative of rocks of the Blue Ridge physiographic province shown in figure 86; typical topography of the province is shown in figure 87. Data in both tables indicate that granite gneiss can be expected to yield more water than mica schist and mica gneiss. Quartzite, where present, yields almost as much water as does granite gneiss. The yield of granite is directly dependent on the degree to which the granite has been fractured. Surprisingly, the fine-

 Table 1.
 Yields of wells vary with metamorphic and igneous

Metamorphic belt or pluton	Median well yield (gallons per minute)	Ranges of yield (gallons per minute)	Number of wells
Carolina slate belt (phyllite, metavolcanic rocks)	28	2-100	22
Charlotte belt (granite gneiss, granite)	17	0-100	91
Kings Mountain belt (mica schist, mica gneiss)	15	0-150	51
Mulberry Creek pluton (granite)	22	0- 50	9
Coronaca pluton (granite, syenite)	15	0- 35	20
Greenwood pluton (gabbro, diorite)	17	6-100	12
Verdery pluton (gabbro)	6	_	1

rock type in Greenwood County, South Carolina (Piedmont

physiographic province)

textured rocks of the Carolina slate belt (table 1) locally yield large volumes of water. This is because these rocks are intensely fractured in the areas where the well data were collected; similar rocks in North Carolina, where they are less fractured, have less than average yields.

Solution openings commonly have been developed by the dissolving action of slightly acidic ground water in marble that is locally present in the Piedmont and Blue Ridge physiographic provinces. These openings first develop as enlargements of joints and foliation planes, and some of them enlarge until they form large conduits. Wells penetrating such solution openings will yield large volumes of water.

Contact zones between crystalline-rock types are favorable places for the location of wells yielding large volumes of water. Two wells in Carroll County, in western Georgia, are shown schematically in **figure 88**. Well A missed the contact zone between granitic gneiss and schist and was completed in the schist. This well yielded only about 1 gallon per minute. Well B penetrated the contact zone between the two rock types and bottomed in the granitic gneiss. This well yielded 100 gallons per minute. Although not all contact zones have such a great contrast in well yield, they are generally favorable places to locate wells.

Table 2. Yields of wells vary with metamorphic and igneous rock type in the Blue Ridge physiographic province of western North Carolina

Rock type	Average well yield (gallons per minute)	Number of wells
Granite	17	40
Mica gneiss	19	397
Mica schist	21	213
Quartzite and metasandstone	22	30
Granite gneiss	23	455

RELATION OF FRACTURING AND WELL YIELD

Fractures in the crystalline rocks of the Piedmont and Blue Ridge physiographic provinces traditionally have been described as steeply inclined, intersecting openings that are generally more numerous at shallower depths. This is because the fractures tend to be sealed as lithostatic pressure increases with depth. Bedrock ranges from unfractured to intensely fractured in those places where two or more fracture sets intersect.

Wells that penetrate no fractures will yield little or no water. Wells that penetrate only a few small, shallow fractures initially may have an adequate yield; however, after the fractures are drained, well yield can suddenly decrease and the sustained yield may be small. Wells that penetrate only one large fracture have similar yield characteristics. Wells that penetrate several small fractures as well as one large one probably will have a large sustained yield. Wells that penetrate intensely fractured rock will be the most dependable in terms of sustained yield.

Steeply inclined fractures are commonly expressed at the land surface as lineaments (straight-line orientations of topographic or geologic features or both); these lineaments generally are about 1 mile, or more long. Lineaments may be expressed as straight ridge lines or stream reaches, extensions of rock contacts or igneous dikes, the axes of folded rocks,

shear zones, and so forth. Lineaments can be identified from satellite imagery, aerial photographs, and topographic maps. Wells drilled along such lineaments or along known fracture traces, consistently yield more water than randomly located wells (table 3).

Some wells yielding large volumes of water that were recently drilled in the Piedmont and Blue Ridge physiographic provinces of Georgia and South Carolina penetrated horizontal or nearly horizontal fractures that are 1 to 8 inches high at depths that range from about 30 to 1,650 feet. Artesian pressure in some of these horizontal fractures indicates that they are connected to recharge areas at higher altitudes by vertical or steeply inclined fractures. These nearly horizontal fractures are thought to be stress-relief fractures that are formed in the manner shown schematically in figure 89. Pre-existing stress (fig. 89A) in the rock column, shown by the arrows, is relieved as erosion removes some of the overlying rock (fig. 89B), allowing hairline fractures to form. Continued erosion (fig. 89C) results in a slightly arched, somewhat lens-shaped fracture that has the greatest vertical separation under a topographically low area, such as a stream valley where more overburden has been removed. These types of fractures are most common in coarse crystalline rocks, such as monzonite, granite gneiss, biotite gneiss, amphibolite, and interlayered gneiss and schist. The areal extent of these features is not known, but sparse well data indicate that the fractures extend from about 100 feet to more than 1,000 feet from the wells.

Table 3. Yields of wells located along lineaments or the traces of known fractures in the Piedmont physiographic province of South Carolina consistently are greater than those of wells not located along such features

[Modified from Snipes and others, 1984]							
	Median yield (gallons per minute)						
Linear or nonlinear features	Greenwood County	Abbeville County	Oconee, Anderson and Pickens Counties				
Lineaments and fracture traces	25	35	20				
Nonlinear features	12	5	4				

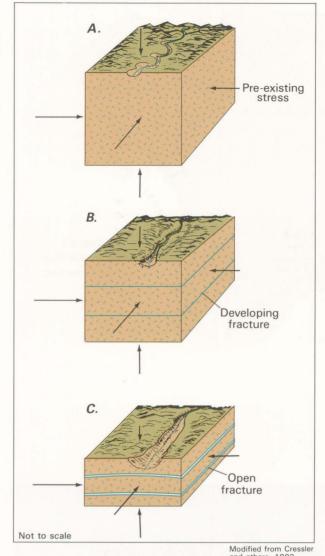


Figure 89. Nearly horizontal fractures in crystalline rocks have recently been penetrated by several deep wells. These fractures probably form by expansion of the rock as overlying material is removed by erosion. Where present, these horizontal fractures produce large volumes of water.

RELATION OF REGOLITH THICKNESS AND TOPOGRAPHY

The thickness of the regolith can be estimated from the topographic setting of a particular location. Usually, only a thin cover of regolith underlies ridges, hill tops, steep draws, and steep slopes (fig. 91) because of the combination of less fracturing and more erosion on the topographically high and steep areas. Narrow valleys, most upland flats, and gentle slopes have moderate regolith thicknesses. The greatest thicknesses of regolith, in places as much as about 100 feet, are under broad draws, broad valleys, and a few upland flats. Wells yielding 50 gallons per minute or more in the Piedmont and Blue Ridge physiographic provinces are most common in broad draws and valleys where regolith thickness exceeds 50 feet. Wells located on slopes and hills will generally yield only small volumes of water (table 4).

Table 4. Yields of wells located in valleys in the Piedmont physiographic province in South Carolina are as much as 25 times more than those of similar wells located on hills. The anomalously large yields of wells located on ridges reflect the fact that the rock under many ridges is sheared

[Modified from Snipes and others, 1984]							
and the same of th	Median yi	Median yield (gallons per minute)					
Topographic feature	Greenwood County	Abbeville County	Oconee, Anderson and Pickens Counties				
Valley	35	25	15				
Ridge	17	35	12				
Slope	17	7	5				
Hill	12	1	4				
Number of wells	206	111	237				

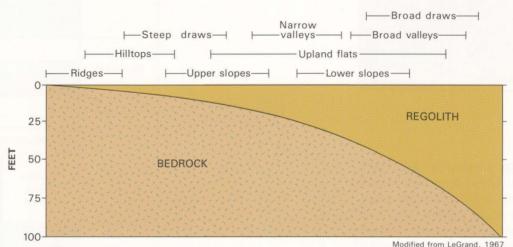


Figure 91. The regolith generally is thin beneath ridges and hilltops and is thickest in broad draws and valleys. This is due to the greater degree of bedrock fracturing under the topographically low areas.

GROUND-WATER FLOW

Water in the rocks of the Piedmont and Blue Ridge aquifers generally is unconfined. Locally, artesian conditions exist when wells penetrate deeply buried fractures that are hydraulically connected to recharge areas at higher altitudes or in places where the regolith is clayey and forms a confining unit. A generalized sketch showing ground-water movement in the unsaturated and saturated zones of the Piedmont and Blue Ridge aquifers is shown in figure 92. Water enters the ground in recharge areas, which generally include all the land surface except the lower parts of valleys, and percolates vertically downward through the unsaturated zone. Once the water reaches the saturated zone, or water table, it moves laterally to points of discharge. The water discharges as springs, seeps, baseflow to streams, and as seepage to lakes. The water table is a subdued replica of surface topography; thus, the depth to the water table varies, depending largely on topography and to a lesser extent on rainfall. On hills and steep ridges, the water table lies tens to hundreds of feet below land surface; the water table is at or near the land surface in valleys and adjacent to lakes, ponds, and wetlands. The dashed arrows in figure 92 show how water moves through the soil-and-alluvium and saprolite parts of the regolith. Water movement in the bedrock is restricted entirely to flow through fractures.

GROUND-WATER QUALITY

The quality of water from the Piedmont and Blue Ridge aquifers generally is suitable for drinking and other uses practically everywhere. Concentrations of dissolved constituents except for fluoride, iron, manganese, and, locally, sulfate seldom exceed State and Federal drinking-water standards. Wells yielding water containing large concentrations of these constituents possibly penetrate mineralized zones, although large iron concentrations may be due to the action of iron-fixing bacteria. Oxidation and filtration usually will alleviate problems of large iron and manganese concentrations, and render the water potable. Rarely, radioactive minerals occur in concentrations sufficient to create water-quality problems.

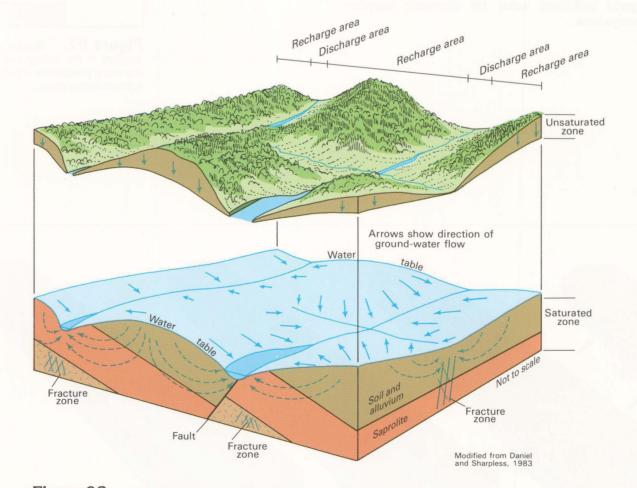


Figure 92. Ground water percolates downward through the unsaturated zone (shown lifted up) to the water table, then moves laterally to discharge points. In the bedrock, the water is channeled through fractures.

RELATION OF REGOLITH THICKNESS AND WELL YIELD

The regolith that forms a nearly continuous layer over the bedrock in the Piedmont and Blue Ridge physiographic provinces consists of saprolite, soil, and alluvium. The saprolite is ordinarily the thickest component of the regolith and its character varies greatly depending on bedrock type. Material in the regolith varies from clay and rock fragments (mostly in the saprolite) to sand and boulders in stream alluvium. Accordingly, the porosity of the regolith varies greatly, but it is everywhere more porous than the underlying, unweathered bedrock. At any given place, the porosity of the regolith usually decreases with depth as the degree of weathering of the saprolite decreases. Water within the bedrock primarily is present in fractures that decrease in number and tend to be sealed at depth. The relation of the regolith and the fractured bedrock is shown schematically in figure 90.

Because the porosity of the regolith is much greater than that of the bedrock, the regolith has the capacity to store a much larger volume of water. The cylinder-and-cone sketch at the right side of **figure 90** illustrates this diagramatically. Most of the stored ground water is in the cylinder, which represents the regolith. The smaller, tapering, cone-shaped area below represents water stored in fractures in the bedrock. The volume of the cone decreases with depth proportionately as the number of fractures decreases.

The regolith and bedrock fractures are directly connected to form an integrated ground-water flow system in which the regolith functions as a reservoir, providing water to the interconnecting fractures in the bedrock. Even though wells in crystalline-rock areas are ordinarily cased through the regolith, the fracture-regolith interconnection allows water stored in the regolith to move vertically into the fractured rock and then through the fractures to the well.

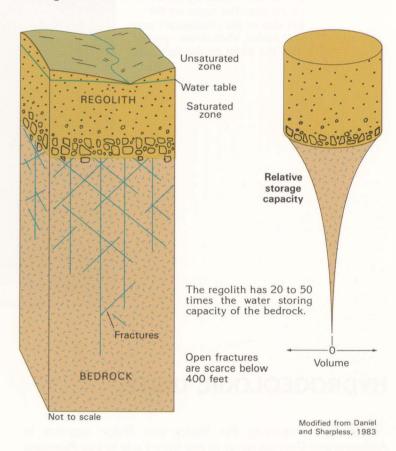
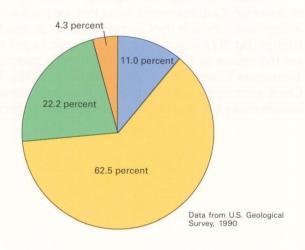


Figure 90. The regolith, or layer of weathered rock material, soil, and alluvium overlies fractured crystalline bedrock. The majority of the water is stored in the more porous regolith and percolates downward into the interconnected fractures. Therefore, wells can obtain some of this stored water even though they are cased entirely through the regolith.



EXPLANATION

Use of fresh ground-water withdrawals during 1985, in percent—Total fresh ground-water withdrawals during 1985 were 100 million gallons per day

during 1985 were 100 million gallon

11.0 Public supply

62.5 Domestic and commercial

22.2 Agricultural

Figure 93. Most of the freshwater withdrawn from the Piedmont and Blue Ridge aquifers during 1985 was used for domestic and commercial supplies, and for agricultural purposes.

4.3 Industrial, mining, and thermoelectric power

FRESH GROUND-WATER WITHDRAWALS

Total freshwater withdrawals from the Piedmont and Blue Ridge aquifers were estimated to be about 100 million gallons per day during 1985. About 11 million gallons per day was withdrawn for public supply (fig. 93). Most of the water pumped for public supply is withdrawn by small communities; larger cities and towns in the Piedmont and Blue Ridge physiographic provinces are supplied by surface water. About 63 million gallons per day was pumped for domestic and commercial uses, the principal uses. About 22 million gallons per day was withdrawn for agricultural purposes. About 4 million gallons per day was withdrawn for industrial, mining, and thermoelectric-power uses.

Figure 94. Valley and Ridge aquifers underlie a broad band that trends northeast through eastern Alabama and the northwestern corner of Georgia. The narrow, parallel band in northeastern Alabama is the Sequatchie Valley.

Valley and Ridge aquifers

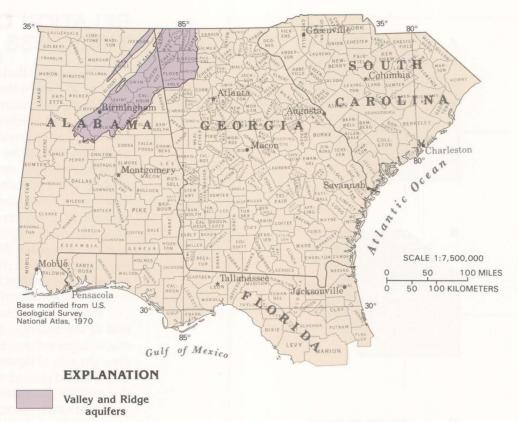


Figure 96. In places, rocks of the Valley and Ridge physiographic province are displaced by thrust faults, such as the one shown by the inclined line. The rocks on the left side of the photograph were first folded, then thrust upward over the rocks on the right side.



HYDROGEOLOGIC UNITS

Rocks comprising the Valley and Ridge aquifers in Alabama and Georgia range in age from early to late Paleozoic (fig. 97). Many of the geologic formations are continuous from Alabama into Georgia. Other geologic formations change character between the two States, or even within a State. The changes are primarily facies variations, such as a transition from sandstone to limestone, or limestone to shale, and are accompanied by corresponding changes in permeability. The boundaries of aquifers and rock units are generally considered to be the same throughout the Valley and Ridge physiographic province. Because of this parallelism, aquifers are not given names; rather, the hydrologic characteristics of individual geologic formations are discussed, a practice that is followed for the Valley and Ridge aquifers in this Atlas.

Most of the Valley and Ridge aquifers consist of limestone or dolomite. Carbonate-rock units that are productive aquifers in Segment 6 include the Chickamauga, Knox, and Conasauga Groups (fig. 97), which yield 10 to 50 gallons per minute and are the source of numerous springs. Wells completed in the Tuscumbia Limestone, in combination with the Fort Payne Chert, commonly yield 20 to 30 gallons per minute. The carbonate rocks are productive aquifers primarily because of the

ease with which solution openings develop in the easily dissolved limestone and dolomite. These openings, which originate as bedding planes and joints in the carbonate rocks, are enlarged by percolating, slightly acidic ground water, and become linked as a series of conduits that transmit large volumes of ground water rapidly through the carbonate rocks. Wells penetrating solution openings commonly yield 100 gallons per minute or more. Secondly, the easily eroded carbonate rocks form wide valley floors, which are favorable areas for recharge.

Geologic formations consisting of sandstone also are aquifers, but yield less water than the carbonate rocks. Much of the water from sandstone is obtained from fractures. Wells completed in the Frog Mountain Sandstone, and in sandstone beds in the Red Mountain and Rome Formations, commonly yield 10 gallons per minute.

The Fort Payne Chert also is a productive aquifer; it consists of thin-bedded, intensely fractured (thus highly permeable) chert in which the original carbonate matrix has been completely dissolved in most places. Locally, where the Floyd Shale and Weisner Quartzite are fractured, they yield sufficient water for domestic supplies. The regolith (weathered bedrock combined with soil and alluvium) developed on the Paleozoic rocks will yield sufficient water for domestic supplies practically everywhere.

INTRODUCTION

Aquifers in the Valley and Ridge physiographic province consist of permeable geologic formations within folded and faulted Paleozoic sedimentary rocks. The extent of the Valley and Ridge aquifers in Segment 6 is shown in figure 94. These aquifers are much more areally extensive in Segment 11 of this Atlas, and, accordingly, are not discussed in great detail here. The Valley and Ridge physiographic province is so named because it consists of a series of parallel valleys separated by steep to well-rounded ridges that rise from about 100 to 700 feet above the valley floors. The valleys are underlain by easily eroded rocks, and the ridges by more resistant rocks. Major streams flow down the axes of many of the valleys, and tributary streams commonly join the major streams at nearly right angles.

Sedimentary rocks of the Valley and Ridge physiographic province are mostly limestone, sandstone, and shale, with lesser dolomite, siltstone, conglomerate, coal, chert, and a few beds of hematite (iron ore). Of these, the most productive aquifers are in limestone and dolomite, which yield water from solution openings. Sandstone and chert beds also yield considerable water to wells in places. Many springs issue from both limestone and sandstone; some of the springs issuing from limestone flow at a rate of several thousand gallons per minute and are used for municipal water supplies.

Folding in the rocks of the Valley and Ridge physiographic province varies from tightly compressed folds (**fig. 95**) to broad, open folds; in general, folding is tighter in the northwestern part of the province. In some places, lateral compressional forces that caused the folding exceeded the shear strength of the rock and thrust faults formed (**fig. 96**). Some of these thrust faults displaced the Paleozoic strata laterally as much as 5 to 10 miles. Surface traces of the larger faults extend for many miles. The folding and faulting has resulted in geologic and topographic complexity, reflected by many local ground-water flow systems.



Figure 95. Rocks in the Valley and Ridge physiographic province are characterized by intense folding, such as the syncline shown here.

System	NW Ala	bama _{SE}	NW	Geo	orgia _{SE}	Lithology
		Bangor Limestone		WELL THE FIRST CO.		
Mississippian	Monteagle Limestone		Monteagle equivalent		Floyd Shale	Thick-bedded, dark-colored lime- stones. Floyd is silty shale with
Mississippian	Tuscumbi	a Limestone	Tuscum	200000000000000000000000000000000000000		limestone beds and lenses
		Fort Payne Chert				Thin to thick-bedded chert, original in limestone matrix
aracine 1		Chattanooga S	Shale			Fissile black shale
Devonian	Frog N	Frog Mountain Sandstone Ar			Armuchee Chert	Frog Mtn : coarse-grained sandston Armuchee : thin bedded chert
Silurian	rian Red Mountain Formation				Shale, sandstone, siltstone. Red iro ore in part of Alabama	
	Sequatch	ie Formation	Sequatchie Limestone			Thick-bedded argillaceous limestor
	Stones	Chickamauga Limestone	Chick		mauga	Dark-colored limestone and shale.
Ordovician	River Group	Lenoir Limestone		Group		Mudstone, siltstone in upper par in Georgia
Ordovician	Newala Limestone			L	Newala imestone	Thick-bedded limestone
	Longview Limestone					
	Chepultepec Dolomite	Knox Group		Lower Knox undifferentiated		Cherty limestone and dolomite
	Copper Ridge Dolomite					Constant
		Bibb Dolomite				
	Ketona Dolomite	Ketona Dolomite	Com	Conasauga Group		Alternating shale and limestone. Dolomite in upper part in Alabam
Cambrian		Briersfield Dolomite	Cons			
	Conasaug	a Formation				
		Rome Formation	n			Shale, siltstone, sandstone
		Sha	dy Dolom	ite		Thick-bedded dolomite
		Weis	ner Quartz	zite		Quartzite with much shale

Figure 97. Several geologic formations, shown in color, are aquifers in the Valley and Ridge physiographic province. Most of the more productive aquifers are limestone. The gray area represents missing rocks.

Modified from Miller, 1974

Northeast Sandstone Shale Limestone C. D. E. Northeast

Figure 98. These blocks show steps in the formation of the Sequatchie Valley. Unfolded rocks (A) were subsequently warped and displaced by a thrust fault (B). A stream first eroded through the sandstone "cap" (C) and later into underlying limestone (D). Presently, a wide stream valley containing numerous sinkholes has developed on the limestone exposed along the axis of the folded rocks (E).

GEOLOGIC STRUCTURE

Folding has markedly affected the topography of the Valley and Ridge physiographic province and also affects the hydrologic characteristics of the rocks. The Sequatchie Valley, an isolated northeast-trending anticline that appears as the separate "finger" of Valley and Ridge aquifers in **figure 94**, illustrates the effect of folding. The series of schematic block diagrams shown in **figure 98** illustrate the development of the Sequatchie Valley. The blocks are drawn as they would appear if viewed looking northeastward into Tennessee from a point near the Alabama-Tennessee State line.

Originally, the flatlying Paleozoic sedimentary rocks consisted of a limestone sequence overlain by shale and sandstone (fig. 98A). Folding and thrust-faulting took place as a result of compression from the southeast (fig. 98B). Most of the deformation occurred at or near the end of Paleozoic time. The Mississippian limestone sequence and the Pennsylvanian sandstone that caps it were both fractured by the folding. The fracturing increased the susceptibility of the sandstone to erosion, and a stream network soon developed along the crest of the upfolded strata (fig. 98C).

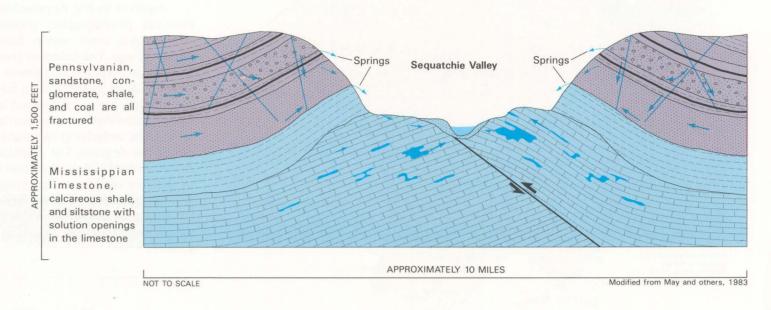
As the stream continued to erode headward and laterally, a flat plain was developed on an area of increasingly exposed carbonate rocks (fig. 98D). Continued erosion both widened and lengthened the valley into its present configuration (fig. 98E). Once the limestone was exposed, dissolution accelerated the valley-forming process. Sinkholes first developed near the headwaters of the stream (fig. 98D) and subsequently formed along the floodplain (fig. 98E). The tributary streams that join the trunk stream at almost right angles are partially controlled by fractures developed perpendicular to those trending along the center of the fold.

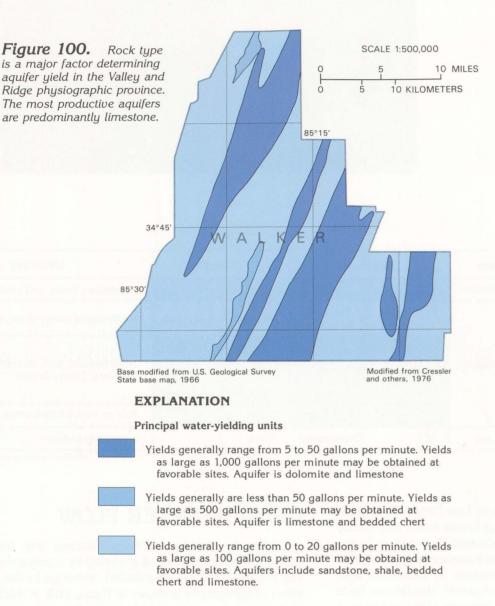
GROUND-WATER FLOW

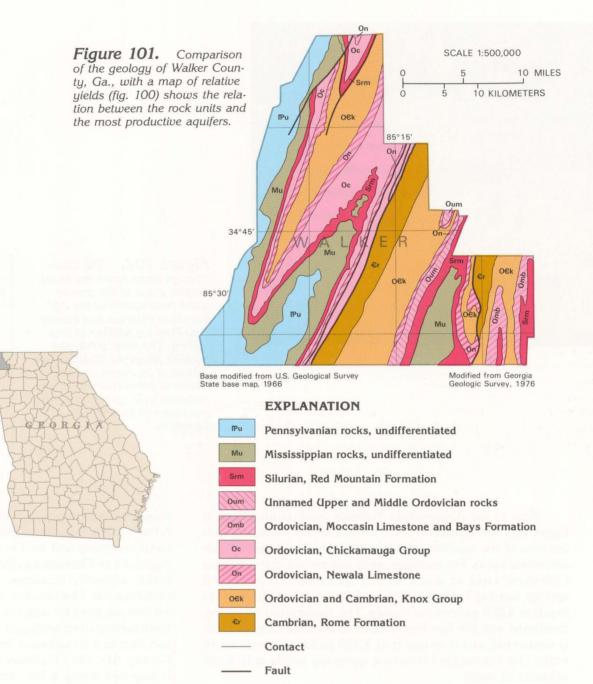
The general flow pattern in folded rocks is typified by that of the Sequatchie valley (fig. 99). The cap of Pennsylvanian clastic rocks and coal beds has been completely eroded from the axis of the valley, exposing a wide band of Mississippian limestone that is displaced by a thrust fault.

The Valley and Ridge aquifers are recharged by precipitation falling on outcrop areas. The precipitation percolates downward through the Pennsylvanian rocks primarily as flow along steeply inclined fractures. Shale beds retard the vertical flow and cause much of the water to move laterally through beds of sandstone and conglomerate until it emerges as springs along the face of steep slopes. A small proportion of the water leaks downward across shale beds and into the Mississippian limestone, where it is joined by ground water that originated as precipitation that fell directly on the limestone exposed along the valley floor. Water in the limestone moves mostly along solution conduits developed by dissolution of the rock along joints and bedding planes. Eventually, the water from the limestone discharges into surface streams as baseflow.

Figure 99. The arrows show the movement of water in the folded and faulted rocks of the Valley and Ridge physiographic province. Shale confining beds divert water to ridge faces where it emerges as springs. Most of the water in the limestone moves through large solution openings.







RELATION OF ROCK TYPE AND WELL YIELD

Most of the water in the aquifers of the Valley and Ridge physiographic province flows through fractures or solution openings, rather than through pore spaces within the rock. The number and size of fractures and solution openings, coupled with their degree of interconnection, determines hydraulic properties and controls well yield. The interconnection of these large-scale openings, which are most common at depths of less than 350 feet, varies directly with the type of rock. The relation of well yield and rock type is illustrated by **figures 100** and **101**.

The relative yield of the principal water-yielding units in Walker County, Ga., is shown in figure 100 by bands of color that trend northeast. The geology of Walker County is shown in figure 101. The areas of maximum well yields in figure 100 coincide with limestone and dolomite units of the Knox Group and the Newala Limestone in figure 101. Areas of maximum well yields in figure 100 generally are coincident with rocks of the Chickamauga Group and Silurian and younger rocks in figure 101. Intermediate yields are obtained from the Fort Payne Chert (fig. 101), but only where the topography developed on it is nearly level. Like other productive aquifers, the Fort Payne Chert does not yield as much water where it is exposed as thin bands in steep valley walls, because the recharge area of the aquifer is small in such a topographic setting.

GROUND-WATER QUALITY

The quality of the water in the Valley and Ridge aquifers is somewhat variable, but generally is satisfactory for municipal supplies and other purposes. Most of the water in the upper parts of the aquifers is not greatly mineralized and is suitable for most uses without treatment. Dissolved-solids concentrations average about 140 milligrams per liter, and chloride concentrations average about 4 milligrams per liter. Iron, however, commonly is present in large concentrations, in some places exceeding the limit of 300 micrograms per liter recommended for drinking water. Iron concentrations of as much as 20,000 micrograms per liter have been measured in water from some wells completed in Valley and Ridge aquifers. Locally, the water contains large sulfate concentrations.

Water in the Valley and Ridge aquifers is mostly a calcium bicarbonate type (fig. 102A). Slight differences exist between water from sandstone of the Pottsville Formation of Pennsylvanian age, which supplies a few domestic wells along scattered ridge tops in the area, and water from the pre-Pennsylvanian, predominantly carbonate-rock, aquifers from which most of the water is obtained. Magnesium concentrations are greater in water from the pre-Pennsylvanian rocks (fig. 102B) because of the presence of dolomite in many of the aquifers. Concentrations of sodium and potassium are greater in water from the Pottsville Formation due to the presence of feldspar and mica in that unit.

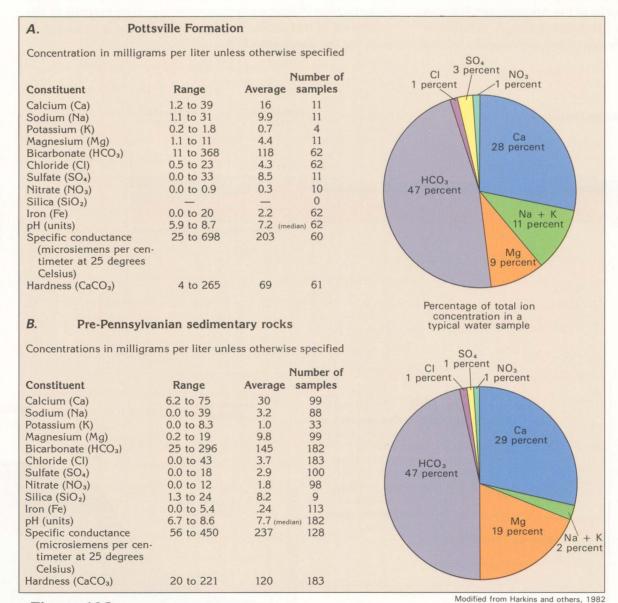
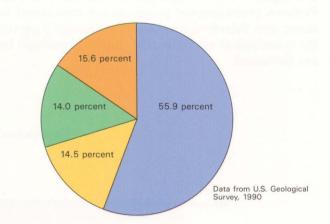


Figure 102. Water in sandstone aquifers, such as in the Pottsville Formation, is a calcium bicarbonate type (A), with feldspar and mica contributing some sodium and potassium. In aquifers that consist mostly of carbonate rocks (B), magnesium (from dolomite) is an important constituent in ground water.



EXPLANATION

Use of fresh ground-water withdrawals during 1985, in percent—Total fresh ground-water withdrawals

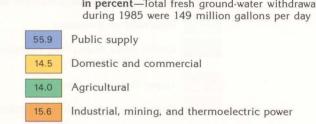


Figure 103. Most of the freshwater withdrawn from the combined Valley and Ridge, Appalachian Plateaus, and Interior Low Plateaus aquifers during 1985 was pumped from limestone aquifers and used for public supply.

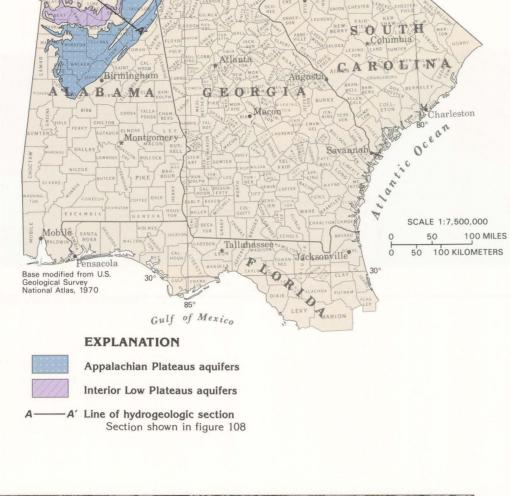
FRESH GROUND-WATER WITHDRAWALS

Total withdrawals of freshwater from the combined Valley and Ridge, Appalachian Plateaus, and Interior Low Plateaus aquifers during 1985 were about 149 million gallons per day. Withdrawals are not categorized by rock type, but most of the pumpage was from limestone aquifers. About 83 million gallons per day was withdrawn for public supply use, primarily by small communities (fig. 103). The remaining pumpage was almost equally divided among domestic and commercial (about 22 million gallons per day); agricultural (about 21 million gallons per day); and industrial, mining, and thermoelectric-power uses (about 23 million gallons per day).

Figure 104. Flatlying Paleozoic sedimentary rocks that comprise the Appalachian Plateaus and Interior Low Plateaus aquifers underlie much of northern Alabama. The straight line shows the location of the hydrogeologic section in

Appalachian Plateaus and **Interior Low Plateaus** aquifers

Figure 106. Thin bedded rocks, such as the Fort Payne Chert shown here, are productive aquifers in places.

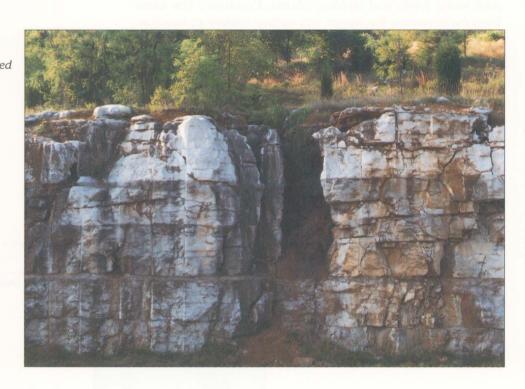




INTRODUCTION

Aquifers in the Appalachian Plateaus and Interior Low Plateaus physiographic provinces consist of permeable stratigraphic units within flatlying sedimentary rocks of Paleozoic age. The extent of these aquifers, which are treated together in Segment 6, is shown in figure 104. These aquifers underlie most of the area in Segment 10 of this Atlas, and, accordingly, are not discussed in great detail here. Both the Appalachian Plateaus and Interior Low Plateaus are extensive tablelands; underlying rocks are either flat or dip at angles of only a few degrees. The Appalachian Plateaus are flat areas of undissected plateau that lie at high altitudes and are capped by resistant sandstone. These high areas resemble large mesas and are bounded by steep-faced slopes. In the Interior Low Plateaus province, erosion has removed part or all of the resistant sandstone cap, exposing underlying limestone at the

> Figure 105. Vertical joints in the horizontally bedded rocks, such as the massive limestone shown here, have locally been enlarged by dissolution of the rock, and have subsequently filled with sediment. Unfilled joints are effective conduits for ground



it can transmit.

The major aquifers in both physiographic provinces are

in limestone units of Mississippian age that are exposed in wide

valley floors in the Interior Low Plateaus province and are

covered, in the Appalachian Plateau areas, by clastic rocks of

Pennsylvanian age. Where they are uneroded, Pennsylvanian

sandstone units supply sufficient water for domestic use. Most

of the water in both limestone and sandstone is present in frac-

tures. In the limestone, the circulation of slightly acidic ground

water has enlarged these fractures by dissolution of the car-

bonate rock. Where vertical fractures extend to the land sur-

face, the enlarged solution conduits may become completely

or partially filled with sediment transported into them by sur-

face streams (fig. 105). Where they are unfilled, solution

openings convey large volumes of water. Thin-bedded, siliceous

limestone and chert of the Fort Payne Chert of Mississippian

age (fig. 106) also constitutes a productive aquifer in the Ap-

palachian Plateaus physiographic province. The Fort Payne has

been intensely fractured, thus increasing the volume of water

Figure 107. The Chattanooga Shale forms the basal confining unit of the groundwater flow system of the Appalachian Plateaus and Interior Low Plateaus aquifers in Segment 6. The most productive aquifers above the Chattanooga consist of limestone and are shown in color. However, many domestic wells yield water from sandstone of the Pottsville Formation.

System	NW Alabama SE Pottsville		Georgia	Lithology Sandstone, shale, and coal	
Pennsylvanian			Formation		
	Pennington Formation	Parkwood Formation	Pennington Formation	Multicolored minor shale, sandstone	
	Bangor		Limestone	Thick-bedded, dark-colored lime- stones. Cherty in part	
Mississippian	Monteagle Limestone		Monteagle equivalent		
	Tuscumbia Limestone		Tuscumbia equivalent		
		Fort Payne	Chert	Thin to thick-bedded chert	
Devonian		Chattanooga	Shale	Fissile black shale	

GROUND-WATER FLOW

underlying limestone aquifer.

Flow in the Appalachian Plateaus and Interior Low

Plateaus aquifers is affected primarily by topography, structure,

and the development of solution openings in the rocks. The

effect of topography is shown in figure 109. A thick sequence

of shale, sandstone, and coal overlies Mississippian limestone.

Recharge to the aquifers is by precipitation on the flat, mesa-

like plateau tops. The water then percolates downward through

the interbedded Pennsylvanian rocks, primarily along steeply inclined joints and fractures. In places, shale beds retard the

vertical flow and some of the water is shunted laterally along

bedding planes, mostly in sandstone and conglomerate beds,

until it emerges as springflow along steep valley walls, such

as the Cumberland escarpment. Some of the water is able to

leak downward across the thick shale confining unit into the

palachian plateaus is not as vigorous as that in places where

erosion has exposed the carbonate rocks in the Interior Low Plateaus. As shown in figure 109, solution openings in limestone under the Appalachian plateaus are developed primarily along the bases of the escarpments and do not extend far under the shale and sandstone. Water-quality data,

however, indicate that circulation has been sufficient to allow

Circulation of water in the limestone underlying the Ap-

Modified from Patchen and others, 1985

HYDROGEOLOGIC UNITS

Rocks comprising the Appalachian Plateaus and Interior Low Plateaus aquifers in Alabama and Georgia are mostly limestone, sandstone, and shale, but also include beds of siltstone, conglomerate, dolomite, and chert. They range in age from Devonian to Pennsylvanian (fig. 107). Most of the formations are continuous from Alabama into extreme northwestern Georgia. Many of these formations extend into the Valley and Ridge physiographic province, where they are folded. The rocks have little variation in lithology throughout northern Alabama and northwestern Georgia, and the permeability characteristics of the rocks are, accordingly, uniform. Like the Valley and Ridge aquifers, boundaries of geologic formations and aquifers in the Appalachian Plateaus and Interior Low Plateaus physiographic provinces are considered to be the same, and, therefore, no aquifers are formally named; rather, the hydrologic characteristics of individual geologic formations are discussed.

Most of the Appalachian Plateaus aquifers identified in figure 107 are limestone units, which are productive aquifers because of the solution openings that develop in the soluble carbonate rocks. For example, wells completed in the Bangor Limestone yield as much as 200 gallons per minute, and springs issuing from the Bangor have reported flows of as much as 4,000 gallons per minute. The Tuscumbia Limestone, combined with the Fort Payne Chert to which it is hydraulically connected, yields as much as 2,300 gallons per minute to wells. The Monteagle Limestone generally yields only small volumes of water.

Sandstone beds of the Pottsville Formation yield small volumes of water, but the Pottsville supplies water to a large number of domestic wells because it caps thousands of square miles of upland plateaus. Sandstone of the Parkwood Formation yields water to only a few scattered domestic wells. Water in the sandstone is obtained primarily from fractures.

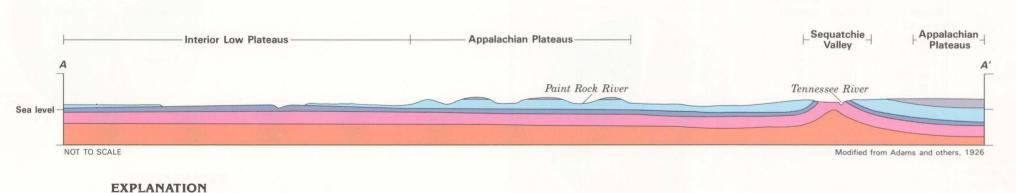
Erosion of the flatlying rocks of the Appalachian Plateaus physiographic province has produced isolated, sandstonecapped hills that rise several hundred feet above easily eroded

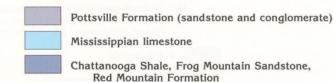
limestone beds exposed in the Interior Low Plateaus province. A thick black shale (the Chattanooga Shale) forms an effective basal confining unit for the ground-water flow system in the Appalachian Plateaus aquifers. A thick sequence of permeable rocks, primarily limestone of Devonian to Cambrian age, underlies the Chattanooga Shale. However, the deeper beds seldom are used for water supplies because of the expense of constructing deep wells and because many of these beds contain brackish or saltwater. In the northern part of Limestone County, Ala., the Chickamauga Limestone of Ordovician age is exposed along a few stream valleys and yields water to domestic wells. Except for this localized situation, the Chattanooga Shale can be considered to represent the base of the

The folded area near the right end of figure 108 is the Sequatchie Valley that is part of the Valley and Ridge physiographic province. Another area of flatlying rocks of the Appalachian Plateaus physiographic province extends to the southeast of this valley. The axis of the valley is occupied, in part, by the Tennessee River.

ground-water flow system.

freshwater to displace saltwater from the limestone in most places. Where erosion has removed the clastic Pennsylvanian and Upper Mississippian rocks, the flow pattern is different. Limestone underlying wide stream valleys in lowland areas of the Interior Low Plateaus is overlain only by a mantle of residuum. Recharge is principally from precipitation on the valley floor, and the water percolates quickly downward through the residuum into the underlying limestone. Karst topography commonly develops on the valley floors, especially where the cover of residuum is thin. Ground water does not usually circulate to great depths in this type of geologic setting.



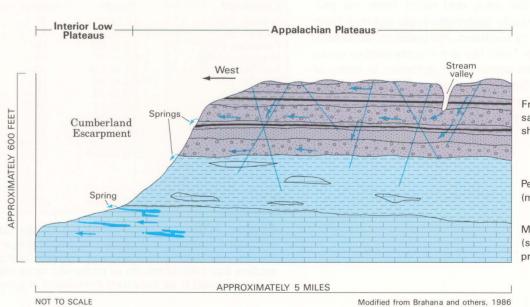


Upper Ordovician limestone Ordovician and Cambrian limestone

Contact

Figure 108. A southeast-trending hydrogeologic section shows that the rocks of the Appalachian Plateaus and Interior Low Plateaus are almost flat. Rivers have eroded through sandstone into underlying limestone. The folded area near the Tennessee River represents the Sequatchie Valley, which is part of the Valley and Ridge physiographic province. Location of the section is shown in figure 104.

Figure 109. Under the high, flat-topped Appalachian Plateaus, a "cap" of Pennsylvanian clastic rocks overlies limestone. Water moves along fractures in the clastic rocks (arrows), then along bedding planes, and then emerges as springs. In the limestone, water moves through solution openings.



Fractured Pennsylvanian sandstone, conglomerate, shale and coal

Pennington Formation (mostly shale)

Mississippian limestone (solution openings are

GROUND-WATER AVAILABILITY

The lithology of the rocks comprising the aquifers and the topography developed on them are the two major factors that determine the yield of Appalachian Plateaus and Interior Low Plateaus aquifers. The availability of ground water in Marshall County, Ala., is shown in **figure 110**. The southeastern one-third and the northwestern one-half of Marshall County are underlain by flat rocks that comprise part of the Appalachian Plateaus aquifers.

Areas where aquifers yield large, moderate, and small volumes of water are shown in **figure 110**. Volumes of water sufficient for some municipal and industrial supplies can be obtained readily from limestone formations and the Fort Payne Chert where these formations are exposed in broad lowlands. Domestic supplies can be obtained from limestone formations in any lowland area. Some limestone formations, where they crop out on the faces of steep ridges, yield little water. Sandstone of the Pottsville Formation varies greatly in its water-producing capabilities. Yield of the Pottsville is affected more by thickness, extent of fracturing, and depth of weathering than by topographic position, because the Pottsville is always a plateau-capping formation in upland areas.

Data in the table adjacent to **figure 110** indicate that most of the water in both limestone and sandstone units is present in fractures and solution openings. A small volume of water can be obtained from the intergranular pore spaces in the sandstone, but these spaces mostly are filled with cement of iron oxide, silica, or clayey material. In Marshall County, springs issue only from the limestone formations.

EXPLANATION

Availability of water	Adequacy	Topographic situation	Formation	Occurrence	Maximum well depth (feet)	Yield	Quality
Good	Municipal and industrial supply	Upland	Pottsville Formation (where the formation is more than 250 feet thick)	Sandstone frac- tures and pore spaces	250-470	Yields 150 gallons per minute on Brindley Mountain and 450 gallons per minute on Sand Mountain	Water contains excessive iron; soft to hard; commonly cor- rosive
		Lowland	Bangor Limestone, Monteagle Limestone, and Tuscumbia Limestone	Limestone solution openings and fractures	200	Yields up to 3,100 gallons per minute to springs. Yields up to several hundred gallons per minute can be expected from wells.	Moderately hard to hard
			Fort Payne Chert	Chert gravel	150	Yields 240 gallons per minute to wells	Soft
			Hartselle Sandstone, Monteagle Limestone	Broken and fractured rocks	300	Yields 700 gallons per minute to wells	Moderately hard
Fair	Domestic supply	Upland	Pottsville Formation (where the formation ranges from 100 to 250 feet in thickness)	Sandstone frac- tures and pore spaces	100-250	Yields 10 to 60 gallons per minute to wells	Water contains excessive iron; soft; commonly corrosive
		Lowland	Monteagle Limestone, Chickamauga Lime- stone	Limestone frac- tures and solution openings	200	Yields less than 70 gallons per minute to springs. Yields 10 to 150 gallons per minute to wells	Water from 20-25 percent of the wells has a hydrogen sulfide odor; moderately hard to hard
Poor	Intermittent or seasonal supply	Upland	Pottsville Formation (near the bluffs or where the formation is less than 100 feet thick)	Sandstone frac- tures and pore spaces	100	Yields less than 5 gallons per minute to wells	Water contains excessive iron; soft; commonly corrosive
		Steep ridges and rugged mountain slopes	Pennington Formation, Bangor Limestone, Red Mountain Formation, Chickamauga Lime- stone	Limestone frac- tures and solution openings, and sandstone fractures and pore spaces	200	Yields less than 5 gallons per minute to wells. Springs are intermittent. Seasonal yields range from a few to several hundred gallons per minute	Moderately hard to hard

Valley and Ridge physiographic province underlain by folded rocks

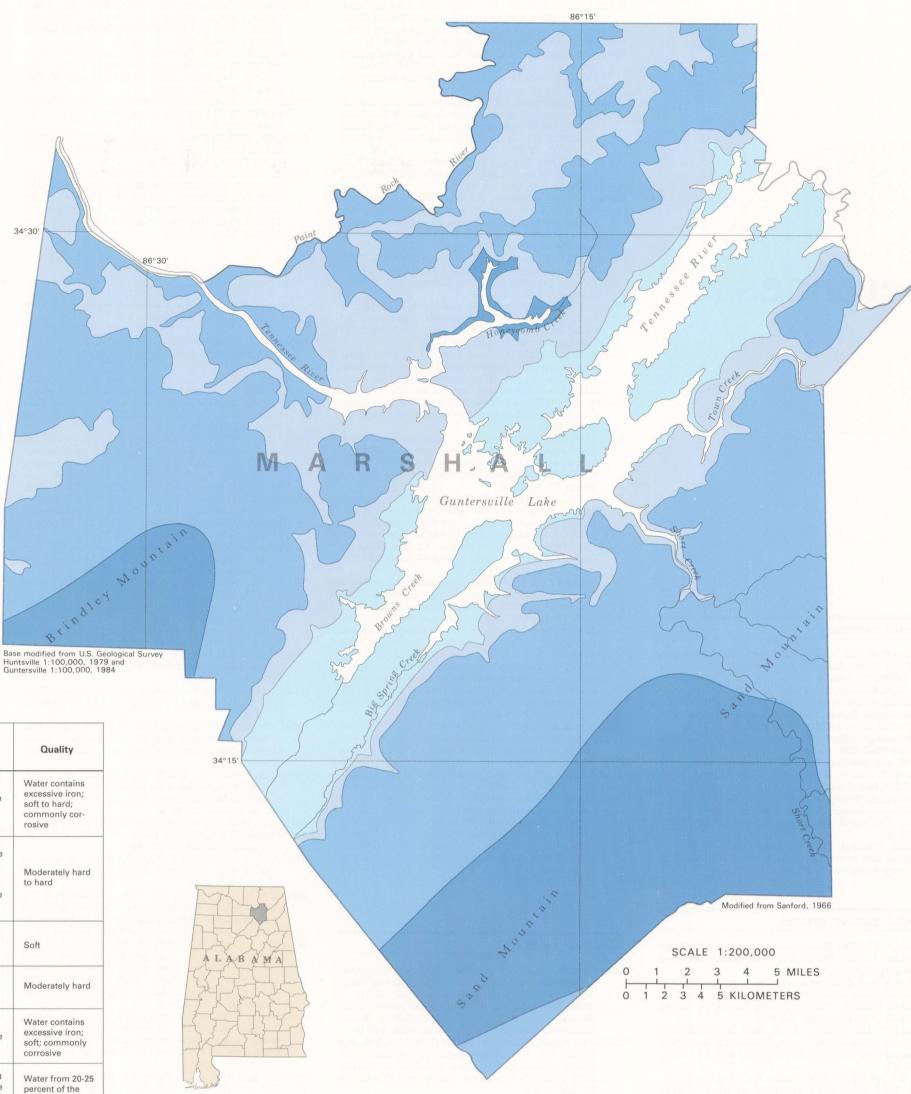


Figure 110. Topography and rock type combine to affect the yield of Appalachian Plateaus aquifers. Sandstone of the Pottsville Formation yields little water; limestone formations are productive aquifers except in areas of steep topography.

GROUND-WATER QUALITY

The quality of the water in the Appalachian Plateaus and Interior Low Plateaus aquifers is variable, but most of the water is suitable for most uses, although concentrations of sulfate and iron are objectionable in places. Large concentrations of hydrogen sulfide, derived from sulfate, can impart a "rottenegg" odor to the water. Large concentrations of iron cause staining of plumbing fixtures. The quality of the water generally deteriorates with depth as it becomes more mineralized. In places, dissolved-solids concentrations at depths of 300 feet or more in limestone aquifers are as large as 1,000 milligrams per liter.

Water in the sandstone of the Pottsville Formation and the underlying Mississippian limestone aquifers is chemically similar (fig. 111). Water from the Pottsville is a calcium magnesium bicarbonate type and water from the Mississippian limestone aquifers is a calcium bicarbonate type. Sodium and potassium concentrations are greater in water from the sandstone because of its shale, feldspar, and mica content, than in the water from the limestone. Iron concentrations generally are greater in water from the limestone whereas sulfate and chloride concentrations generally are greater in water from the limestone. Chloride concentrations, generally less than 250 milligrams per liter, vary from formation to formation.

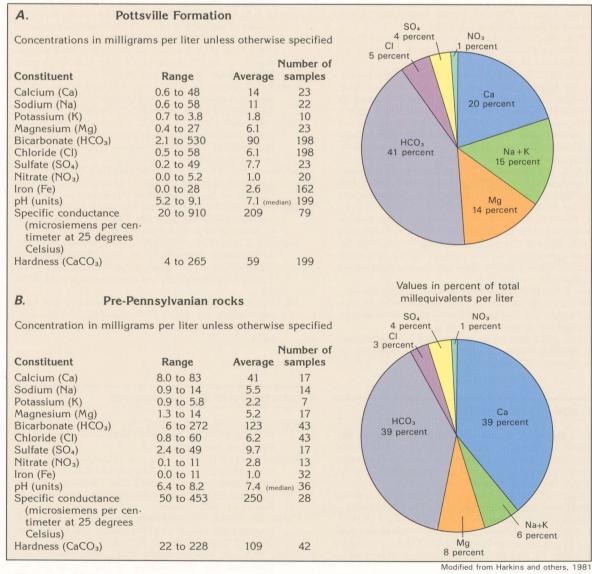


Figure 111. Water in the sandstone of the Pottsville Formation (A) and older beds of limestone (B) is chemically similar. Feldspar and mica in the Pottsville impart more sodium and potassium to the water, and the large concentration of calcium in water from pre-Pottsville rocks reflects a limestone source.

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