GROUND WATER ATLAS
OF THE UNITED STATES

SEGMENT 6
Alabama
Florida
Georgia
South Carolina

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

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

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

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

Dallas L. Peck

Department of the Interior

Manuel Lujan, Jr., Secretary

U.S. Geological Survey

Dallas L. Peck, Director

conversion factors

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

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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 sets of both the United States and Canada, formerly called 'Sea Level Datum of 1929.'
GROUND WATER ATLAS OF THE UNITED STATES
SEGMENT 6
ALABAMA, FLORIDA, GEORGIA, AND SOUTH CAROLINA

By James A. Miller

CONTENTS

Regional summary
Surficial aquifer system
Sand and gravel aquifer
Biscayne aquifer
Intermediate aquifer system
Floridan aquifer system
Southeastern Coastal Plain aquifer system
Piedmont and Blue Ridge aquifers
Valley and Ridge aquifers
Appalachian Plateaus and Interior Low Plateaus aquifers
References
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, Aetobatta, and Savannah Rivers. These larger 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 and 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 in 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. 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 condensed and falls as precipitation when reaching the coastline.

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

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

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(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 Coastal Plain aquifer system, all of which contain mostly freshwater. In other places, such as the area 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 layers of 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, however, 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 four-State area. All the aquifers from the surficial aquifer system down through the Coastal Plain aquifer system are present in the Coastal Plain physiographic province.

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 48 in per year in parts of north-central Florida to about 50 inches per year in the mountains of northeastern Georgia.

Figure 3. The surficial 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(s).
Figure 3. The numerous aquifers in Segment 6 can be grouped into nine major aquifers or aquifer systems. The extent of eight of these major aquifers or aquifer systems at the land surface is mapped here. One aquifer, the intermediate aquifer system, is not exposed at the land surface.
Figure 5. A simplified geologic map (above) shows the extent of the major rock units in Segment 6. The parallel between the geologic units and the major aquifers is shown on the map to the right.

GEOLOGY

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

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

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

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

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

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

Figure 6. The Paleozoic rocks range from flatlying to nearly folded. They are separated from crystalline rocks of the Piedmont and Blue Ridge physiographic provinces by faults. The Coastal Plain strata that underlie other 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 southeastern 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 (Fig. 13). 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 where the aquifers are exposed at the surface, where they are mostly sand, and where the aquifers are less permeable in other places. The Floridan aquifer system, but is also shown in other places. The three uppermost aquifers in the Coastal Plain are shown in Figure 9. These aquifers, the surficial aquifer system and sand and gravel aquifer, and Biscayne aquifer are all the same geologic age (primarily Paleocene 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 thin, widespread layer or unconsolidated sand beds that commonly contains a few beds of shell and limestone. This aquifer system generally yields small volumes of water, and is primarily used for domestic supplies. The sand and gravel aquifer consists largely of interbedded layers of coarse sand and gravel that were deposited by streams. Thin clay beds in this aquifer locally create semi-confined conditions. The sand and gravel aquifer yields moderate volumes of water, and is an important source of water for several counties in southeastern-most panhandle Florida and southwestern Alabama. Westward, in Mississippi, the sand and gravel aquifer grades into the Coastal plain 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 are deposited in marine settings.

The intermediate aquifer system (Fig. 9) underlies the surficial aquifer system and overlies the Floridian aquifer system. The intermediate aquifer system is bounded above and below by clayey confining units. The system is not exposed atland surface and is recharged primarily by downward leakage from overlying aquifers. Bed 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 is primarily used for domestic supplies.

*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 aquifer system is characterized by three younger aquifers shown in Figure 8. These aquifers, the surficial aquifer system, sand and gravel aquifer, and Biscayne aquifer are all the same geologic age (primarily Paleocene 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 thin, widespread layer or unconsolidated sand beds that commonly contains a few beds of shell and limestone. This aquifer system generally yields small volumes of water, and is primarily used for domestic supplies. The sand and gravel aquifer consists largely of interbedded layers of coarse sand and gravel that were deposited by streams. Thin clay beds in this aquifer locally create semi-confined conditions. The sand and gravel aquifer yields moderate volumes of water, and is an important source of water for several counties in southeastern-most panhandle Florida and southwestern Alabama. Westward, in Mississippi, the sand and gravel aquifer grades into the Coastal plain 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 are deposited in marine settings.

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**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. Ground water is the principal source of water supply in some counties in Wisconsin, Illinois, and New Mexico, where most population centers are served by surface water, primarily by rivers and streams. In many other areas, ground water is used to supplement surface water supplies, and where surface water is not available, ground water is used for a variety of purposes, including irrigation, domestic, and industrial uses.

The withdrawal of ground water for all uses in Wisconsin, Illinois, and New Mexico, for the years 1980 and 1985, is shown in Figure 14. Withdrawals for all purposes in these three regions were similar during the two years. The withdrawal of ground water for all uses in Wisconsin, Illinois, and New Mexico, was about 1,000 million gallons per day, or about 1 million acre-feet per year. The withdrawal of ground water for all uses in Wisconsin, Illinois, and New Mexico, was about 1,000 million gallons per day, or about 1 million acre-feet per year. The withdrawal of ground water for all uses in Wisconsin, Illinois, and New Mexico, was about 1,000 million gallons per day, or about 1 million acre-feet per year. The withdrawal of ground water for all uses in Wisconsin, Illinois, and New Mexico, was about 1,000 million gallons per day, or about 1 million acre-feet per year.

About 3.181 million gallons per day was withdrawn from the Florida aquifer system, almost four times as much water as was withdrawn from the second most used aquifer, the Biscayne aquifer (786 million gallons per day), and almost twice as much water as was withdrawn from all other principal aquifers combined. Water was withdrawn from the Floridan aquifer although it only extends throughout a small area in the southeastern tip of Florida, than from either the Southeastern Coastal Plain aquifer system (374 million gallons per day) or the surficial aquifer system (301 million gallons per day) even though both have a much larger geographic extent. This is because the Biscayne is the source of supply for many large cities, including Miami, West Palm Beach, and Fort Lauderdale, along the southeastern coast of Florida. About 298 million gallons per day was withdrawn from the intergranular aquifer, 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 withdrawals, was obtained from the Piedmont and Blue Ridge aquifers because surface water was the primary source of supply in the area underlain by these aquifers.
INTRODUCTION

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

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

HYDROGEOLOGIC UNITS

The surficial aquifer system consists mostly of beds of unconsolidated sand, silt, clay, and shell. Locally, clay beds create confined or semiconfined aquifers, especially in outer coastal plain and along the present coastline. Groundwater in the surficial aquifer system is under pressure, and the water table of the surficial aquifer, leakage can occur in to a surface-water body or to the ocean.

Locally, thin clay beds create confined or semiconfined surficial aquifer system to keep the saltwater from moving elsewhere. In northern Florida, thin, unnamed sand sequences of Pleistocene and younger age comprise the system, whereas offshore, the Floridan is lower than the hydraulic head of the surficial aquifer system through the clayey confining unit. The water-table configuration is generally subdued reflection of the topography of land surface. Steep gradients occur in broad, flat interstream areas and under topographically high areas. The arrows show the general direction of ground-water movement.

GROUND-WATER FLOW

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

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

In places, some water leaks upward from the underlying Floridan aquifer system through the clay confining unit separating the Floridan and surficial systems (fig. 17). In other places, 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, seawater can enter through the aquifer in coastal areas. Encroachment is more extensive during droughts because there is less freshwater available in the surficial aquifer system to keep the saltwater from moving inland.

The configuration of the long-term, average water table of the surficial aquifer system, where it has been mapped in the eastern and southern part of the Florida peninsula, is shown in figure 18. The water table generally is 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 topographically high areas. The arrows show the general direction of ground-water movement.

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 transectivity of the surficial aquifer system is extremely variable. Most reported values range from 1,000 to 30,000 feet squared per day; in places, values of 25,000 to 50,000 feet squared per day have been reported. The largest 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.

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). 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.
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. 29). The aquifer is presently (1990) called the Mollee-Pinconee aquifer in Alabama, in the past, it has been called the Citronelle or Citronelle-Mocone aquifer in that State by some authors. In any case, the sand and gravel aquifer grades laterally into part of the coastal plain aquifer system that extends westward into southern Texas. The sand and gravel aquifer is the primary source of water in Baldwin, Washington, and eastern Escambia Counties, Ala., and in Santa Rosa and Escambia Counties, Fla. The aquifer also supplies most of the water used on farms in the area. About 80 percent was withdrawn in 1985 from the sand and gravel aquifer for all uses during 1985. About 50 percent was withdrawn in Pinellas, Fla., and the majority of the remaining 20 percent was withdrawn in the State of Florida. 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 units. Wells in the aquifer is under nonconfined conditions, but near the land surface, clay beds are thin or are absent, and in artesian conditions, where such beds exist, movement of groundwater is generally coastal.

INTRODUCTION

The sand and gravel aquifer consists of rocks ranging in age from middle Miocene to Holocene that were mostly deposited in a deltaic environment in Alabama, Missouri, and Illinois. Rocks in the aquifer are all included in the unconfined Catahoula Sandstone, a thin, predominantly nonmarine sequence of sand and gravel beds. The Mesozoic units shown in figure 21 are overlain by the Citronelle Formation of Miocene 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 Cretaceous locally contains layers of sand, or cemented sand or gravel, that retard ground-water movement. The principal geologic units that comprise the aquifer in the westernmost part of the panhandle of Florida are shown in figure 21. The Alum Bluff Group and the Choctawatchee Formation, which have a marine environment, are most easily recognizable near the coast. Northward, these beds grade into unconfined coarse sand and gravel, which make up the main water-yielding unit of the upper part of the sand and gravel aquifer.

GEOLOGY

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THICKNESS

The sand and gravel aquifer is approximately wedge-shaped and thickens southeastward from a flatter edge in northeastern Alabama (fig. 23). Throughout the southern two-thirds of the area underlain by the aquifer, the confining unit forming the base of the aquifer consists of either the upper or lower clay members of the Pensacola Clay (fig. 23). Analysis of aquifer test data, supplemented by the results of laboratory testing of cores from the Pensacola Clay, indicates that the permeability of this confining unit is so small that practically no water passes across it. In 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 nonconfined conditions. This zone is recharged directly by precipitation, and ground-water discharge is in Mobile County. In southern Alabama, where the hardpan or clay beds are near the land surface, smaller volumes are discharged by wells. Most of the well discharges from this zone. This indicates that the aquifer is generally coastward.

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 well-field waters up to the Gulf of Mexico have been reported. Most of the well discharges from this zone. This indicates that the aquifer is generally coastward.

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, according to U.S. Geological Survey data, in the aquifer has concentrations of dissolved solids that ordinary are less than 50 milligrams per liter. Chloride concentrations also are ordinarily less than 50 milligrams per liter except in a few locations near the coast and adjacent to large bays and sounds where there is a transition zone of fresh water and seawater, and in the coastal plain portion of panhandle Florida, where greater than 1,000 milligrams per liter are reported in water from some wells. Water is fresh offshore, with a pH of about 6.0; locally, the water is more acidic (pH 4.5). Dissolved-iron concentrations may be objectionable; concentrations as large as 4.5 milligrams per liter have been reported. Iron is readily susceptible to contamination. Contamination of the groundwater system by some authors. In any case, the sand and gravel aquifer grades laterally into part of the coastal plain aquifer system that extends westward into southern Texas. The sand and gravel aquifer is the primary source of water in Baldwin, Washington, and eastern Escambia Counties, Ala., and in Santa Rosa and Escambia Counties, Fla. The aquifer also supplies most of the water used on farms in the area. About 80 percent was withdrawn in 1985 from the sand and gravel aquifer for all uses during 1985. About 50 percent was withdrawn in Pinellas, Fla., and the majority of the remaining 20 percent was withdrawn in the State of Florida. 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 units. Wells in the aquifer is under nonconfined conditions, but near the land surface, clay beds are thin or are absent, and in artesian conditions, where such beds exist, movement of groundwater is generally coastal.

FRESH GROUND-WATER WITHDRAWALS

Withdrawals of freshwater from the sand and gravel aquifer totaled 130 million gallons per day during 1985. About 44 percent, or about 60 million gallons per day, was withdrawn for public supply (fig. 29). 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.
Biscayne aquifer

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

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

Figure 28. The rocks that comprise the top of the Biscayne aquifer vary in character. They are mostly oolitic limestone that is present at the land surface throughout the top of the aquifer to the northeast.

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 pumped at present (1990) is somewhat greater. About 70 percent of the water was drawn for public supply. Major population centers that depend on the Biscayne aquifer for water supply include Boca Raton, Pembroke 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 contaminatable. The aquifer is the only source of drinking water for about 3 million people.

Water in the Biscayne aquifer is underconfined, or water table, conditions and the water table fluctuates in direct and rapid response to variations in precipitation. The aquifer extends beneath Biscayne Bay, where it is sea water, 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 in response to lowering of the water table. Groundwater is subject to contamination. The aquifer is the only source of drinking water for about 3 million people.

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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, Pleistocene rocks also are included in the aquifer (fig. 27).

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

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

The Biscayne aquifer grades northward and westward into sandy deposits that are part of the surficial aquifer system. Wells 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 shallow water in southeastern Florida, and is not hydraulically connected to the Biscayne aquifer.

Base and Thickness

The base of the Biscayne aquifer in Dade County and southern Broward County is a low-permeability sandy silt that is part of the Tamiami Formation. Farther north, the base is not as distinct; rather, it consists of a transition zone that changes from a mixture of moderately permeable calcareous sand, shell, and silt, which are probably 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, thicknesses 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 300 feet near the coast.

Salinity water 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.

Hydrogeologic System

Groundwater 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 seaward 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 seaward during the wet season, when as much as 90 percent of the area, 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 slugs 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 standing basin for streams, such as the St. Johns 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.

Surface water from lakes and streams also enters the Biscayne aquifer. Historically, this water is released to maintain canal flow. Natural land-surface sheetflow and levee heights are such that the overall movement of impounded water is from Lake Okeechobee to Conservation Areas 1 and 2, and thence, sequentially to Conservation Area 3, where the water released from Conservation Area 3 sustains the flow of freshwater into the Everglades National Park.

Canals and water-control structures that comprise the canal system, and three water-control areas are illustrated in figure 30. Canals have been used extensively in southern Florida for drainage and flood control. Levees were also constructed, first to prevent flooding from Lake Okeechobee, and subsequently to impound excess water in three large water-conservation areas for later release. These alterations to the natural hydrologic system have culminated in a regional water system: major features of this system are shown in figure 30. The South Florida Water Management District utilizes a system of canals, levees, control structures, pumping stations, and water conservation (storage) areas (Conservation Areas 1 through 3) 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. Swageup from the canals into the Biscayne aquifer during such periods helps maintain the water level in the aquifer. A network of major pumping stations provides flood protection by pumping excess stormwater from canals into the conservation areas. When floodwater is released from these impoundments, this water is released to maintain canal flow. Natural land-surface sheetflow and levee heights are such that the overall movement of impounded water is from Lake Okeechobee to Conservation Areas 1 and 2, and thence, sequentially to Conservation Area 3, where the water released from Conservation Area 3 sustains the flow of freshwater into the Everglades National Park.

Canals and water-control structures on the canals are used to store stormwater and control floods. When it is later needed.
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 pumping. 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, associated with such extreme water-level fluctuations as those shown in figure 33, thus the lowering of the water table, saltwater encroachment in canals, and the ocean; by evaporation; and by transpiration by plants.

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. Near Miami and Fort Lauderdale areas, the water table 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 controlled canals on the water table are shown by the irregular patterns of the contours, particularly where they point upward 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 pumping 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 shallow part of the aquifer such as the foraminiferal limestone. These areas are shown by the irregular patterns of the contours 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.

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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 aquifer adjacent to the canal. These canal-aquifer water-level relations are shown schematically in Figure 36. The arrows show the direction that water moves when the water level of the canal is lower (fig. 36A) and higher (fig. 36B) than the water table in the aquifer. The degree of connection decreases as fine sediment settles out of the canal water and lines the canal bottom. Accordingly, the degree of connection may change from time to time because of either accumulation of these sediments or their removal during runoff from intense storms.

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

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 4-foot column of freshwater is necessary to balance a 4-foot column of saltwater. This means that, for each 1 foot of freshwater above sea level, there is approximately a 4-foot column of freshwater below sea level. According to lowering of freshwater levels by drainage canals or by intensive pumping creates an imbalance that causes the inland movement of saltwater. How saltwater can encroach coastal areas as a result of development is shown diagrammatically in Figure 38. In the natural, balanced condition shown in Figure 38A, saltwater is present only near the shoreline and is balanced by a thick inland column of freshwater. Construction of a drainage canal, however (fig. 38B), lowers freshwater levels and allows landward movement of saltwater in the canal and aquifer. In addition, the canal becomes a tidal channel that conveys saltwater inland and, through laterally into the Biscayne Aquifer. Where municipal well fields draw 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 are the same, artifically raising water levels in both the canal and the adjacent aquifer. Thus, further saltwater encroachment is prevented and, in some instances, has even been reversed.

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

The sequence of maps in Figure 40 shows the inland movement of saltwater in the Biscayne aquifer in response to development. The colored area on all the maps shows the inland extent of saltwater at the base of the aquifer. Under natural conditions, as shown by the 1904 map, saltwater was limited to a narrow band along the coastline and to short tidal reaches of natural water courses. Urban and agricultural development and the resulting drainage of the land had not yet begun. Before 1946, canal flow was virtually uncontrolled and ground-water levels were greatly lowered because of extensive pumping. The threat of contamination of inland municipal well fields spurred remedial action. Salinity-control structures were constructed in coastal reaches of the major canals and tidal or reversed saltwater encroachment, particularly adjacent to the canals (compare the 1953 and 1959 maps of fig. 40). By 1977, additional control structures and effective water-management practices had reduced the area of saltwater contamination considerably from its maximum extent in 1953.

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 and leachates, 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 dispose of storm runoff or industrial waste. Most disposal wells are completed in aquifers containing saltwater that underlie

The freshwater-saltwater interface was raised when canals were built. An unvegetated canal that extends into an area of heavy pumping can convey saltwater inland.

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 37. Dam con­
trol structures, such as this one, have been constructed in response to encroachment of saltwater.

Figure 39. Saltwater in­
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Figure 40. Saltwater encroachment in the Biscayne Aquifer, mainly adjacent to canals, occurred in approximately the larger areas from 1904 until 1953. After the employment of control structures on major canals and the installation of additional control structures, encroachment of saltwater was markedly slowed and even reversed in places.

Figure 41. Most of the freshwater withdrawn from the Biscayne Aquifer during 1953 was used for public supply and agricultural purposes.
Collectively, aquifers in south-central Florida that lie between the surficial aquifer system and the Floridan aquifer system are called the intermediate aquifer system in this Atlas. The approximate extent of the intermediate aquifer system is shown in Figure 42. This aquifer system contains water under confined, or artesian, conditions, but does not yield as much water as the underlying Floridan aquifer system. Accordingly, the intermediate aquifer system is not extensively used, and its characteristics are not well known, especially where the Floridan is near the land surface and contains freshwater. The intermediate aquifer system is the main source of water supply in Sarasota, Charlotte, and Lee Counties, Fla., where the underlying Floridan aquifer system is deeply buried and contains brackish or saltwater.

The intermediate aquifer system consists of sand beds and limestone lenses that are parts of the Tampa Limestones and Hawthorn Formation of Miocene age and sand, limestone, and shell beds of the Tamiami Formation of Pliocene age (fig. 43). Clay confining units isolate the aquifers in the system from the Floridan and surficial aquifer systems. Where the rocks of the intermediate aquifer system grade into slightly yielding or nonyielding clayey beds, they become part of the upper confining unit of the Floridan aquifer system. Locally, in Clay, Gadsen, and Indian River Counties, Fla., the Hawthorn Formation yields water, but its water-yielding beds are not continuous. In Glades County, Fla., 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.

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 thins as the lower Hawthorn-upper Tampa aquifer thickens southward from its thickest area in Pinellas County, Fla. (fig. 45). Further southwest 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.

GROUNDFLOW 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.

FRESH GROUNDWATER WITHDRAWALS

Withdrawals of freshwater from the intermediate aquifer system totaled about 240 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.
The Floridan aquifer system is one of the most productive aquifers in the world. This aquifer system underlies an area of about 100,000 square miles in southern Alabama, southeastern Georgia, southern South Carolina, and all of Florida. Draining into 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 pumping is concentrated or the yield from the system is minimal.

The Floridan is a multi-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 seawage and industrial wastes are injected into it. Near Orlando, Fla., drainage wells are used to divert surface runoff into the Floridan for all purposes. Withdrawals during 1988 were about 3 billion gallons per day. In addition, the aquifer system provides water for numerous industrial wastes are injected into it. Near Orlando, Fla., drainage wells are used to divert surface runoff into the Floridan for all purposes. Withdrawals during 1988 were about 3 billion gallons per day. In addition, the aquifer system provides water for industries and irrigate 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 pumping is concentrated or the yield from the system is minimal.

The Floridan is a multi-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 seawage and industrial wastes are injected into it. Near Orlando, Fla., drainage wells are used to divert surface runoff into the Floridan for all purposes. Withdrawals during 1988 were about 3 billion gallons per day. In addition, the aquifer system provides water for industries and irrigate 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 pumping is concentrated or the yield from the system is minimal.

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 Aven 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 more linearly 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 Aven Park Formation, the Oldsmar Formation of early Eocene age, and the upper part of the Cedar Keys Formation of Pliocene 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 Palaeocene 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 a confining unit and ultimately reach the Upper Floridan aquifer.;

The geologic characteristics 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 Aven Park Formation. Where the Tampa Limestone is highly permeable, it also is included in the Upper Floridan. In most places, the Upper Floridan aquifer yields sufficient water 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 well sites, the confining unit consists of clay, if at others, it is a very fine-grained (micritic) limestone, at still other places, it is a dolostone with the pore spaces filled with anhydrite. Regardless of rock type, whether the middle confining unit is present, it restricts the movement of ground water between the Upper and Lower Floridan aquifers.

The geologic and hydraulic properties of the Upper Floridan aquifer are not as well known as those of the Lower 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 Aven Park Formation and the Oldsmar Limestone, and the upper part of the Cedar Keys Formation. Much of the Lower Floridan aquifer contains seawater. In some important, high-altitude areas, as well as in areas of 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 confining 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 zone is named to the zone not because it consists of boulders, but because it is difficult to drill into, having the same rough, abaking, abrasive effect on the drill stem and drilling rig as boulders would. The Boulder Zone contains anhydrite and is used as the receiving zone for treated sewage and other wastes disposed through injection wells in the Miami Port 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 created by the vigorous circulation of ground water through the carbonate rocks in the geologic past, and this does not result from the present groundwater flow system.

The thickness of the Floridan aquifer system generally thins 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 South Georgia embayments, respectively. In north-central peninsular Florida, the limestone units that comprise the aquifer system are thin over the upwarped Peninsula arch. A series of small faults bounds downdropped, trough-like coastal blocks (grabens) in southern Georgia and southwestern Alabama (fig. 51). Within these grabens, particularly near the Gulf of Mexico, 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.
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 toward the southeast. The left side of the figure, representing conditions in south-central Georgia, shows that the Floridan is 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 breaks 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 claysy 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 saline water and used as a receiving zone for injected wastes, is shown near the right side of Figure 52. This zone is about 1,000 feet thick in this area.

The Boulder Zone is overlain by the Biscayne aquifer, which is separated from the Floridan aquifer system by a claysy confining unit that is about a half-mile thick in this area. The Boulder Zone is one of these vertical solution tubes rather than a large cavern. The Boulder Zone is overlain by the Biscayne aquifer, which is separated from the Floridan aquifer system by a claysy confining unit that is about a half-mile thick in this area. The Boulder Zone is one of these vertical solution tubes rather than a large cavern. The Boulder Zone is overlain by the Biscayne aquifer, which is separated from the Floridan aquifer system by a claysy confining unit that is about a half-mile thick in this area. The Boulder Zone is one of these vertical solution tubes rather than a large cavern. The Boulder Zone is overlain by the Biscayne aquifer, which is separated from the Floridan aquifer system by a claysy confining unit that is about a half-mile thick in this area. The Boulder Zone is one of these vertical solution tubes rather than a large cavern. The Boulder Zone is overlain by the Biscayne aquifer, which is separated from the Floridan aquifer system by a claysy confining unit that is about a half-mile thick in this area. The Boulder Zone is one of these vertical solution tubes rather than a large cavern. The Boulder Zone is overlain by the Biscayne aquifer, which is separated from the Floridan aquifer system by a claysy confining unit that is about a half-mile thick in this area. The Boulder Zone is one of these vertical solution tubes rather than a large cavern. The Boulder Zone is overlain by the Biscayne aquifer, which is separated from the Floridan aquifer system by a claysy confining unit that is about a half-mile thick in this area. The Boulder Zone is one of these vertical solution tubes rather than a large cavern. The Boulder Zone is overlain by the Biscayne aquifer, which is separated from the Floridan aquifer system by a claysy confining unit that is about a half-mile thick in this area. The Boulder Zone is one of these vertical solution tubes rather than a large cavern. The Boulder Zone is overlain by the Biscayne aquifer, which is separated from the Floridan aquifer system by a claysy confining unit that is about a half-mile thick in this area.

BOULDER ZONE

The deeply buried zone of cavernous permeability, called the Boulder Zone, developed in dolomite in the Lower Floridan aquifer, underlies a 13-county area in southern Florida (Figure 54). The Boulder Zone is not a single, simple, almost flat-lying feature 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 3,600 feet below sea level. The zone is thought to represent caverns developed at several different levels and connected by vertical "pipes" of solution tubes similar to a modern cave system. A 90-foot high cave reported in the subsurface in southern Florida probably is one of these vertical solution tubes rather than a large cavern. 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 20 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 several 100 to 1,060 feet of low-permeability limestone and dolomite, which retard the upward movement of injected fluids to shallower parts of the Floridan aquifer system that contain fresher although still brackish water.
EFFEC TS ON CONFINEMENT

Effects 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 dissolves some carbon dioxide from the atmosphere as the precipitation falls and the more carbon dioxide from organic matter in soil as the precipitation percolates downward through the soil, thus forming weak carbonic acid. This acid 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 acid water moves through the aquifer, 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 Rete Palace 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 ground water solution 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 at or near the land surface, or is overlain by a thin layer of soil or by a clayey, and other types of openings caused by dissolution, and by few surface streams. Dissolution of carbonate rocks is greatest where ground water solution 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 at or near the land surface, or is overlain by a thin layer of soil or by a clayey, residual soil. In adjacent areas, the Floridan is confined, but the upper confining unit is less than 100 feet thick (fig. 53). 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 unbroken (fig. 55), there has been little dissolution of the aquifer system except in deeply buried zones of paleokarst, such as the Hernando permeable zone of southwestern Georgia and northeastern Florida, and the Boulder Zone of southern Florida. However, these deeply buried zones chiefly formed in the geologic past, where 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 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 aquifer, the best-known part of the Floridan aquifer 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 aquifer 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 aquifer 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).

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 (aquiclude 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 land 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 spring issues. 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 caves channel the ground water to the point where they are exposed at land surface and become the orifices of major springs (fig. 58).
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 is generally perpendicular to the contours.

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 counterclockwise 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 one-half 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 (estimated 1 to 3 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 confined 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 unconfined freshwater heads went 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 down-dropped 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 southern Florida 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 zones of depression at Sawnos, Jessup, and Brunswick, Ga., and at Fernandina Beach and Fort Walton Beach, Fl. 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. Asa 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. Predewater potentiometric gradients have been locally reversed in some coastal areas, creating the potential for encroachment of saltwater from the Gulf of Mexico 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 predewaterflow 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 accounted 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 cavities. 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 enters pre-existing openings ranging from pores spaces between limestone particles to fractures in the rocks. 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. Laken commonly occur as 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 streamed. Where they are not plugged, sinkholes form a direct connection from the land surface to the Upper Floridan aquifer, allowing surface runoff to move more directly and quickly into the aquifer.

By 1950, withdrawals of freshwater from the Floridan for all purposes totaled about 260 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 agricultural, 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 purposes, 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.

The regional distribution of estimated withdrawals of freshwater from the Floridan aquifer system mostly reflects the water needs of population centers. The highest freshwater withdrawals occur in the central peninsula Florida.

The Florida Division of Water Resources has been conducting water quality testing and monitoring in the Floridan aquifer. The results of these studies indicate that the water quality of the Floridan aquifer system is good. However, the Floridan aquifer is subjected to a variety of water quality problems, including nutrient enrichment, salinity intrusion, and contamination from land-based sources. These problems can affect water quality and accessible water supplies in the region.
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.

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, and dissolved solids concentrations are minimal. Water that travels down longer flowpaths, and, thus, dissolves more limestone and possibly sulfide 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 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.
**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 northwest and is partly overlain by, and partly grades laterally into, the Floridan aquifer system to the southeast consist of clastic rocks. The aquifer system grades into the Floridan aquifer system underlies much of the Coastal Plain of southeastern Alabama, Georgia, and South Carolina. The Floridan aquifer system consists of carbonate rocks. The 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. The system extends westward throughout much of the Coastal Plain; the Mississippi part of the aquifer system is within Segment 5 of this Atlas. The system extends westward throughout much of the Coastal Plain; the Mississippi part of the aquifer system is within Segment 5 of this Atlas.

**HYDROGEOLOGIC UNITS**

There are many geologic formations in the complex 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 regional confining units consist of the regional confining unit, the regional confining unit, and the regional confining unit, which are generally thick and are 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.

**Figure 69.** The southeastern coastal plain aquifer system underlies the entire Coastal Plain of Alabama and South Carolina, and extends off the Coastal Plain of Georgia, eastern North Carolina, and southward for a short distance and extends westward much of the Coastal Plain of Mississippi in the west.

**Figure 70.** Closed beds in the Brunswick formation, which is part of the southeastern coastal plain aquifer system in northeastern Georgia, are productive aquifers. For the most part, the upwell sand in Alabama is the same as the top of the 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 Chicotawhee 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 name of the aquifers they overlie. For example, the Pearl River confining unit lies above the Pearl River regional aquifer and beneath the Chicotawhee River regional aquifer, and so on (fig. 72).
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 southern Alabama, the clastic rocks that comprise the Chickasawhay River aquifer grade into carbonate rocks that comprise the base of the aquifer system. The sandy beds of the Chattahoochee River aquifer grade into carbonate rocks except locally in western Alabama. The sandy beds of the Chattahoochee River aquifer grade into carbonate rocks of the Floridan aquifer system. Near the Georgia–South Carolina line, the rocks comprising the oldest geohydrologic unit, the Pearl River aquifer, are exposed at the land surface. These rocks completely cover the older rocks that comprise the Pearl River aquifer system. The line of the section shown on these two hydrogeologic sections lines up with the line of the section shown in figure 74. All the aquifers dip toward the southeast from the outcrop area.

Hydrogeologic section B–B’ (fig. 75) in southern Alabama shows the Pearl River aquifer 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. Both merge to the west into the Pearl River aquifer and are included as part of it. 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 between 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 Florida aquifer system. Near the north‐west side of the section, the Pearl River and Chattahoochee River aquifers are in direct hydraulic contact.

Figure 74. An idealized hydrogeologic section trending eastward across Alabama. Clastic rocks constitute the Black Warrior River aquifer system. Carbonate rocks of the Pearl River 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.

Figure 75. An idealized hydrogeologic section trending eastward across Alabama. Carbonate rocks 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.

Figure 76. 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 Pennsylvanian arch in Florida. The base of the system is about 4,000 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 embayment. 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 predominantly coarse‐grained midsandblends include black shale; and Jurassic sedimentary rocks that are mostly varicolored sandstone interbedded with shale.

The three regional aquifers and the three regional confining units of the Southeastern Coastal Plain aquifer system are exposed at the land surface as a series of arcuate bands. To Georgia, South Carolina, and southeastern Alabama, the aquifer system is overlain by other aquifers.
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, secondarily, in northwestern Florida. This aquifer, the uppermost regional aquifer in the Southeastern Coastal Plain aquifer system, consists of sand and gravel 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 is more extensively developed 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.

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 a thick sequence of sand and gravel beds of Late Cretaceous age, 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, calcilastic sand 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.

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 78. 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 Florida and adjacent areas. The Pearl River aquifer and the Floridan aquifer system are hydrologically 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 southeastern Alabama, it is limited to 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).

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 west-central Georgia, it is extensive in the sub-surface (fig. 79) and is the most widespread of the regional aquifers in the system. In North Carolina, the aquifer grades laterally into the basal aquifer 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 southeastern 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 upgradient areas of the aquifers. When reaching the water table, most of this water moves laterally to discharge at small streams in the outcrop area, or is transpired by plants. Only a small part of the water percolates down and moves more slowly through the unsaturated zone. Movement in the deeper parts of the aquifer is approximately vertical downgradient.

GROUND-WATER QUALITY

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. In both the coastal and outcrop areas, the water is a calcium bicarbonate type, where calcium and bicarbonate ions account for more than 90 percent of the total calcium and bicarbonate ions in solution.

Classified waters based on their dominant cations in figure 83 and represents the general distribution of chloride concentrations in the Black Warrior River aquifer. 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.
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. This is mainly confined to stream valleys and may overlie soil, saprolite, and bedrock. The saprolite is by far the largest component 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. Although there are considerable differences in the mineralogy and texture of the rocks comprising the Piedmont and Blue Ridge aquifers, the 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.

GEOLa

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 obsidian 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, have determined 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 gabbros; 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 xilinious, intensely fractured rocks, such as mylonite or phyllonite.

RELATION OF ROCK TYPE TO 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 large diameter 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. Well yield data for Greenwood County, S.C., which is in the Piedmont physiographic province, are summarized in table 1. Well yield 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. 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 diorite granite gneiss. The yield of granite is directly dependent on the degree to which the granite has been fractured. Surprisingly, the fine-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.

Table 1. Yields of wells vary with metamorphic and igneous rock type in Greenwood County, South Carolina (Piedmont physiographic province)

<table>
<thead>
<tr>
<th>Rock type</th>
<th>Average well yield (gallons per minute)</th>
<th>Number of wells</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphic belt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carolina slate belt</td>
<td>2-150</td>
<td>22</td>
</tr>
<tr>
<td>Cherty sandstone</td>
<td>15-100</td>
<td>61</td>
</tr>
<tr>
<td>Cherty sandstone</td>
<td>5-100</td>
<td>14</td>
</tr>
<tr>
<td>Granite gneiss</td>
<td>10-200</td>
<td>22</td>
</tr>
<tr>
<td>Granite gneiss</td>
<td>5-100</td>
<td>14</td>
</tr>
<tr>
<td>Granite gneiss</td>
<td>2-100</td>
<td>22</td>
</tr>
<tr>
<td>Granite gneiss</td>
<td>0-100</td>
<td>14</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Rock type</th>
<th>Average well yield (gallons per minute)</th>
<th>Number of wells</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphic belt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carolina slate belt</td>
<td>2-150</td>
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</tr>
<tr>
<td>Cherty sandstone</td>
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</tr>
<tr>
<td>Granite gneiss</td>
<td>10-200</td>
<td>22</td>
</tr>
<tr>
<td>Granite gneiss</td>
<td>5-100</td>
<td>14</td>
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<tr>
<td>Granite gneiss</td>
<td>2-100</td>
<td>22</td>
</tr>
<tr>
<td>Granite gneiss</td>
<td>0-100</td>
<td>14</td>
</tr>
</tbody>
</table>
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, while wells that penetrate only a few small, shallow fractures generally 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) both these lineaments generally are about 1 mile, or more long. Lineaments may be expressed as straight fracture lines or stream reaches, extensions of rock contacts or igneous dikes, the axes of folded rocks, or rock contacts or igneous dikes, the axes of folded rocks, and steep slopes (fig. 91) because of the combination of less 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 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 and the valleys of linear features in the Piedmont physiographic province of South Carolina (from Le Grand, 1967). Yields are converted to 50 feet from the wells.

<table>
<thead>
<tr>
<th>Linear or non-linear feature</th>
<th>Median yield (gallons per minute)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large fracture</td>
<td>20</td>
</tr>
<tr>
<td>Small fracture</td>
<td>15</td>
</tr>
<tr>
<td>Ridge</td>
<td>10</td>
</tr>
<tr>
<td>Valley</td>
<td>5</td>
</tr>
<tr>
<td>Ridge</td>
<td>5</td>
</tr>
<tr>
<td>Valley</td>
<td>1</td>
</tr>
<tr>
<td>Number of wells</td>
<td>20</td>
</tr>
</tbody>
</table>

**GROUND-WATER FLOW**

Water in the rocks of the Piedmont and Blue Ridge aquifers generally is unconfined. Locally, water conditions exist where wells penetrate deeply burried fractures that are hydrodynamically connected to recharge areas at higher altitudes or, in places where the regolith is clays and forms a confining unit. A generalized sketch showing ground-water movement in the unconfined 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 unconfined zone where the water reaches the saturated zone, or water table. It moves laterally to points of discharge. The water discharge springs, weeps, basements to streams, and as seepage to lakes. The water table is a subadultria surface of topography and, 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 is near the ground, while in broad draws where the land surface is flat, 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 percolates into the ground. 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 components 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.

**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 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 more than 50 gallons per minute or more in the Piedmont and Blue Ridge physiographic provinces are 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.

**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 components 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.
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 area-wide 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 range from about 100 to 170 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

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 shale 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. Filling the rocks of the Valley and Ridge physiographic province vary 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.

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 from 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-rocks 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 Weiser Quartzite are fractured, they yield sufficient water for domestic supplies. The relicts (weathered bedrock combined with soil and alluvium) developed on the Paleozoic rocks will yield sufficient water for domestic supplies practically everywhere.

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 illustrates 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 folding of 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 cap it were both fractured by the folding. The fracturing increased the susceptibility of the sandstone to erosion, and a stream network was developed along the crest of the uplifted strata (fig. 98C). As the stream continued to erode headward and laterally, a flat plain was developed on an area of intensively 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. Stinkhole 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 these trend along the center of the fold.

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

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

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.

Figure 98. These block diagrams show steps in the formation of the Sequatchie Valley. Overfolded rocks (A) were subsequently upturned and displaced by a thrust fault (B). A stream that eroded through the sandstone "cap" (C) and later into underlying limestone (D). Presently, a wide stream valley containing numerous tributaries has developed on the limestone exposed along the axis of the folded rocks (E).
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 sides of the valley, exposing a wide band of Mississippian limestone that is dissected 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 short water in ridge faces where it emerges as springs. Most of the water in the limestone moves through large solution openings.

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, 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 solute concentrations.

Water in the Valley and Ridge aquifers is mostly a calcium bicarbonate type (fig. 100A). Slight differences exist between sandstone from 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. 100B), and the ratio of calcium to magnesium values is less 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 100. Rock type is a major factor determining aquifer yield in the Valley and Ridge physiographic province. The most productive aquifers are predominantly limestone.

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.

Figure 101. Comparison of the geology of Walker County, Ga., with a map of relative yields of fresh ground water. Differences in the principal area coincide with limestone and dolomite units of the Knox Group and the Newala Limestone in figure 101. Magnesium and calcium in the Knox Group and the Newala Limestone are essential to set up a chemical equilibrium for water in the Knox Group and the Newala Limestone.

A. Pottsville Formation

Concentration in milligrams per liter unless otherwise specified

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Range</th>
<th>Average</th>
<th>Number of samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium (Ca)</td>
<td>1.2 to 11</td>
<td>3.6</td>
<td>7</td>
</tr>
<tr>
<td>Sodium (Na)</td>
<td>1.1 to 11</td>
<td>3.0</td>
<td>8</td>
</tr>
<tr>
<td>Potassium (K)</td>
<td>0.2 to 19</td>
<td>4.4</td>
<td>18</td>
</tr>
<tr>
<td>Magnesium (Mg)</td>
<td>0.2 to 19</td>
<td>4.4</td>
<td>18</td>
</tr>
<tr>
<td>Chloride (Cl)</td>
<td>0.2 to 19</td>
<td>4.4</td>
<td>18</td>
</tr>
<tr>
<td>Sulfate (SO₄)</td>
<td>0.2 to 19</td>
<td>4.4</td>
<td>18</td>
</tr>
<tr>
<td>Bicarbonate (HCO₃)</td>
<td>0.2 to 19</td>
<td>4.4</td>
<td>18</td>
</tr>
</tbody>
</table>

B. Pre-Pennsylvanian sedimentary rocks

Concentrations in milligrams per liter unless otherwise specified

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Range</th>
<th>Average</th>
<th>Number of samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium (Ca)</td>
<td>6.2 to 75</td>
<td>30</td>
<td>99</td>
</tr>
<tr>
<td>Sodium (Na)</td>
<td>0.0 to 31</td>
<td>1.2</td>
<td>86</td>
</tr>
<tr>
<td>Potassium (K)</td>
<td>0.0 to 31</td>
<td>1.2</td>
<td>86</td>
</tr>
<tr>
<td>Magnesium (Mg)</td>
<td>0.2 to 19</td>
<td>4.4</td>
<td>18</td>
</tr>
<tr>
<td>Sulfate (SO₄)</td>
<td>0.2 to 19</td>
<td>4.4</td>
<td>18</td>
</tr>
<tr>
<td>Bicarbonate (HCO₃)</td>
<td>0.2 to 19</td>
<td>4.4</td>
<td>18</td>
</tr>
<tr>
<td>Chloride (Cl)</td>
<td>0.2 to 19</td>
<td>4.4</td>
<td>18</td>
</tr>
<tr>
<td>Iron (Fe)</td>
<td>0.2 to 19</td>
<td>4.4</td>
<td>18</td>
</tr>
<tr>
<td>Sulfate (SO₄)</td>
<td>0.2 to 19</td>
<td>4.4</td>
<td>18</td>
</tr>
<tr>
<td>Bicarbonate (HCO₃)</td>
<td>0.2 to 19</td>
<td>4.4</td>
<td>18</td>
</tr>
<tr>
<td>Specific conductance (µS/cm at 25°C)</td>
<td>25 to 182</td>
<td>60</td>
<td>60</td>
</tr>
</tbody>
</table>

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.

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

Rocks comprising the Appalachian Plateau and Interior Low Plateau 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 eroded. 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 Plateau and Interior Low Plateau physiographic provinces are considered to be the same, and, therefore, no aquifers are formalized other than the hydrogeologic characteristics of individual geologic formations are discussed.

Most of the Appalachian Plateau 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 have reported flows of 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 Tuscaloosa Limestone, combined with the Fort Payne Chert that it is hydrologically connected with, yields as much as 2,200 gallons per minute to wells. The Monticello 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 plateau. Sandstones of the Parkwood Formation yield water to only a few scattered domestic wells. Water in the sandstone is obtained primarily from fractures.

Erosion of the flat lying rocks of the Appalachian Plateau physiographic province has produced isolated, sandstone-capped hills that rise several hundred feet above easily eroded limestone beds exposed in the Interior Low Plateau provinces. A thick black shale (the Chattanooga Shale) forms an effective basal confining unit for the ground-water flow system in the Appalachian Plateau aquifers. A thick sequence of permeable rocks, primarily limestone of Devonian to Cambrian age, underlies the Chattanooga Shale. However, the deeper beds of Ordovician limestone 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 Chattanooga 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 ground-water flow system.

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 flat lying rocks of the Appalachian Plateau 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

Flow in the Appalachian Plateau and Interior Low Plateau 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 on the precipitation on the flat, mesalike plateau tops. The water then percolates downward through the interbedded Pennsylvanian rocks, primarily along steeply inclined joints and fractures. In places, shale beds yield 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 in able to leak downward across the shale confining unit into the underlying limestone aquifers.

Circulation of water in the limestone underlying the Appalachian plateau is not as vigorous as that in places where erosion has exposed the carbonate rocks in the Interior Low Plateau. As shown in figure 109, solution openings in limestone under the Appalachian plateau 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 freshwater to displace saltwater from the limestone in most places.

Where erosion has removed the cherty Pennsylvanian and Upper Mississippian rocks, the flow pattern is different. Limestones underlying wide stream valleys in broad areas of the Interior Low Plateau are overlain only by a mantle of residuum. Recharge is principally from precipitation 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.

Introduction

Aquifers in the Appalachian Plateau and Interior Low Plateau physiographic provinces consist of permeable stratigraphic units within flat lying 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 Plateau and Interior Low Plateau are extensive tabular units; underlying rocks are either flat or dip at angles of only a few degrees. The Appalachian Plateau are flat areas of undisected plateau that lie at high altitudes and are capped by resistant sandstones. These high areas resemble large mesas and are bounded by steep-faced slopes. In the Interior Low Plateau provinces, erosion has removed part or all of the resistant sandstone cap exposing underlying limestones at the surface.

The major aquifers in both physiographic provinces are in limestone units of Ordovician to Mississippian age that are exposed in wide valley floors in the Interior Low Plateau provinces and are covered, in the Appalachian Plateaus, by clastic rocks of Pennsylvanian age. Where they are exposed, Pennsylvanian sandstone units supply sufficient water for domestic use. Most of the water in both limestone and sandstone is held in solution openings and fractures. In the limestone, the circulation of slightly acidic ground water has enlarged these fractures by dissolution of the carbonate rock. Where vertical fractures extend to the land surface, the enlarged solution conduits may become completely or partially filled with sediment transported into them by surface streams (fig. 105). Where they are unfilled, solution openings convey large volumes of water. Thin-bedded, siliciclastic limestones and cherts such as the Fort Payne of Mississippian age (fig. 106) also constitutes a productive aquifer in the Appalachian Plateau physiographic province. The Fort Payne has been intensely fractured, thus increasing the volume of water it can transmit.

Figure 104. Flat lying sedimentary rocks that comprise the Appalachian Plateau and Interior Low Plateau aquifers underlie much of northwestern Alabama and southeastern Tennessee. The straight line shows the location of the hydrogeologic section in figure 108.

Figure 105. Vertical section in the Appalachian Plateau showing location of aquifers in the Appalachian Plateau and Interior Low Plateau physiographic provinces. A number of these formations extend into the Appalachian Plateau and Interior Low Plateau physiographic provinces. A number of these formations extend into the Appalachian Plateau physiographic province. The Fort Payne has been intensely fractured, thus increasing the volume of water it can transmit.

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

Figure 107. The Chattanooga Shale forms the basal confining unit of the ground-water flow system in the Appalachian Plateau aquifers. A thick sequence of permeable rocks, primarily limestone of Devonian to Cambrian age, underlies the Chattanooga Shale. However, the deeper beds of Ordovician limestone 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 Chattanooga 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 ground-water flow system.

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 flat lying rocks of the Appalachian Plateau physiographic province extends to the southeast of this valley. The axis of the valley is occupied, in part, by the Tennessee River.

Hydrogeologic Sections

Most of the Appalachian Plateau 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 have reported flows of 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 Tuscaloosa Limestone, combined with the Fort Payne Chert that it is hydrologically connected with, yields as much as 2,200 gallons per minute to wells. The Monticello Limestone generally yields only small volumes of water.

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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 Plateau and Interior Low Plateau 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 Plateau 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 flanks of 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

<table>
<thead>
<tr>
<th>Availability of water</th>
<th>Adequacy</th>
<th>Topographic situation</th>
<th>Formation</th>
<th>Occurrence</th>
<th>Maximum thickness (feet)</th>
<th>Yield</th>
<th>Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upland</td>
<td></td>
<td></td>
<td>Pottsville Formation (sandstone)</td>
<td>Where the formation is more than 100 feet thick</td>
<td>200-470 gallons per minute per linear foot</td>
<td>Moderately hard</td>
<td>Clean and free of excess iron, odor; moderately soft; commonly corrosive</td>
</tr>
<tr>
<td>Upland</td>
<td></td>
<td></td>
<td>Boulder Limestone, Monticello Limestone, Calhoun Chert</td>
<td>Where the formation is more than 100 feet thick</td>
<td>200 gallons per minute per linear foot</td>
<td>Moderately hard</td>
<td>Clean and free of excess iron, odor; moderately soft; commonly corrosive</td>
</tr>
<tr>
<td>Upland</td>
<td></td>
<td></td>
<td>Fort Payne Chert</td>
<td>Where the formation is more than 100 feet thick</td>
<td>150 gallons per minute per linear foot</td>
<td>Moderately hard</td>
<td>Clean and free of excess iron, odor; moderately soft; commonly corrosive</td>
</tr>
<tr>
<td>Ground</td>
<td></td>
<td></td>
<td>Pottsville Formation (sandstone)</td>
<td>Where the formation is more than 100 feet thick</td>
<td>90 gallons per minute per linear foot</td>
<td>Moderately hard</td>
<td>Clean and free of excess iron, odor; moderately soft; commonly corrosive</td>
</tr>
</tbody>
</table>

Figure 110. Topography and rock type combine to affect the yield of Appalachian Plateau 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 Plateau and Interior Low Plateau 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, impart a "rotten-egg" 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, till, and mica content, than in the water from the limestone. Iron concentrations generally are greater in water from the sandstone whereas sulfate and chloride concentrations generally are greater in water from the limestone. Chloride concentrations, generally less than 200 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. Till, shale, 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.

Table 1. Water in the sandstone of the Pottsville Formation (A) and older beds of limestone (B) is chemically similar. Till, shale, 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.

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Range</th>
<th>Average</th>
<th>Number of samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium (Ca)</td>
<td>0.6 to 18</td>
<td>14</td>
<td>77</td>
</tr>
<tr>
<td>Sodium (Na)</td>
<td>0.6 to 18</td>
<td>14</td>
<td>77</td>
</tr>
<tr>
<td>Potassium (K)</td>
<td>0.1 to 58</td>
<td>14</td>
<td>77</td>
</tr>
<tr>
<td>Magnesium (Mg)</td>
<td>0.6 to 77</td>
<td>14</td>
<td>77</td>
</tr>
<tr>
<td>Chloride (Cl)</td>
<td>0.6 to 40</td>
<td>14</td>
<td>77</td>
</tr>
<tr>
<td>Sulfate (SO₄)</td>
<td>0.1 to 11</td>
<td>14</td>
<td>77</td>
</tr>
<tr>
<td>Nitrate (NO₃)</td>
<td>0.1 to 11</td>
<td>14</td>
<td>77</td>
</tr>
<tr>
<td>pH</td>
<td>6.4 to 8.2</td>
<td>14</td>
<td>77</td>
</tr>
<tr>
<td>Dissolved solids (mg/l)</td>
<td>6 to 272</td>
<td>14</td>
<td>77</td>
</tr>
</tbody>
</table>

Gypsum: occurs at 25 degrees Celsius.

Table 2. Water in the sandstone of the Pottsville Formation (A) and older beds of limestone (B) is chemically similar. Till, shale, 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.

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Range</th>
<th>Average</th>
<th>Number of samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium (Ca)</td>
<td>0.6 to 43</td>
<td>19</td>
<td>49</td>
</tr>
<tr>
<td>Sodium (Na)</td>
<td>0.6 to 43</td>
<td>19</td>
<td>49</td>
</tr>
<tr>
<td>Potassium (K)</td>
<td>0.1 to 58</td>
<td>19</td>
<td>49</td>
</tr>
<tr>
<td>Magnesium (Mg)</td>
<td>0.6 to 77</td>
<td>19</td>
<td>49</td>
</tr>
<tr>
<td>Chloride (Cl)</td>
<td>0.6 to 40</td>
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<td>49</td>
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<tr>
<td>Sulfate (SO₄)</td>
<td>0.1 to 11</td>
<td>19</td>
<td>49</td>
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<tr>
<td>Nitrate (NO₃)</td>
<td>0.1 to 11</td>
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<tr>
<td>pH</td>
<td>6.4 to 8.2</td>
<td>19</td>
<td>49</td>
</tr>
<tr>
<td>Dissolved solids (mg/l)</td>
<td>6 to 272</td>
<td>19</td>
<td>49</td>
</tr>
</tbody>
</table>

Figure 112. Water in the sandstone of the Pottsville Formation (A) and older beds of limestone (B) is chemically similar. Till, shale, 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.