GROUND WATER ATLAS OF THE UNITED STATES

SEGMENT 10
Illinois Indiana Kentucky Ohio Tennessee

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

Reston, Virginia
1995
GROUND WATER ATLAS OF THE UNITED STATES
Hydrologic Investigations Atlas 730-K

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 or 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.

Gordon P. Eaton

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Gordon P. Eaton, 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-1929)—a geodetic datum derived from a general adjustment of the three-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

ATLAS ORGANIZATION

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

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INTRODUCTION

This report provides a summary of ground-water conditions and problems in Illinois, Indiana, Kentucky, Ohio, and Tennessee, which compose Segment 10 of the Ground Water Atlas of the United States, an area of about 217,000 square miles. The definition, distribution, this-known, water-yielding, and water-quality characteristics of the principal aquifers in the segment are the primary topics of this chapter. Ground-water source, occurrence, movement, use, and problems also are discussed where appropriate.

Segment 10 consists of parts of seven physiographic provinces (fig. 1)—the Coastal Plain, Blue Ridge, Valley and Ridge, Appalachian Plateaus, Interior Low Plateaus, Central Lowland, and Ozark Plateaus. The provinces have unique hydrogeologic characteristics that make it convenient to describe the principal aquifers in each province.

SOURCE OF GROUND WATER

The upper part of the rock mass that underlies Segment 10 generally contains fresh ground water, whereas the intermediate and lower parts generally contains saltwater. Freshwater is here defined as water that contains dissolved-solids concentrations of 1,000 milligrams per liter or less; the term "saltwater" is applied to water with dissolved-solids concentrations of greater than 1,000 milligrams per liter. For comparison, dissolved-solids concentrations in seawater are about 35,000 milligrams per liter. Water with concentrations of dissolved solids of greater than 35,000 milligrams per liter is called brine.

The source of the freshwater in Segment 10 is precipitation, primarily rain and snow. Long-term average annual precipitation in Segment 10 ranges from about 36 inches in the northern part of Illinois, Indiana, and Ohio to more than 80 inches in eastern Tennessee (fig. 2). Of the precipitation that falls on the five-State area, about 50 to 70 percent is returned to the atmosphere by evaporation from surface-water bodies and transpiration by plants. Much of the remainder constitutes runoff.

Long-term average annual runoff ranges from about 10 inches in some of the northern parts of the area to about 30 inches in some parts of central and southeastern Tennessee (fig. 3). Part of the runoff is direct surface runoff, and part is water that infiltrates the land surface, percolates to the ground-water system, and moves through aquifers to discharge into streams as base flow. Most of the precipitation that percolates downward and becomes ground-water recharge circulates through the shallow aquifers; only a small part enters the deep aquifers. Annual ground-water recharge is estimated to range from about 1 inch in parts of Illinois where precipitation is least and the permeability of the soil and rock at the land surface is low to as much as 13 inches in parts of Tennessee where precipitation is greatest and the permeability of materials at the land surface is high.

Saltwater is present at depths of 500 feet or less in much of Segment 10, particularly in aquifers in Paleozoic rocks. The source of the saltwater is assumed to be a combination of the fresh ground water and the seawater in which the rocks were deposited or by which they were later invaded. The dissolved-solids concentration in the saltwater increases with depth and reaches brine concentration in some parts of the segment. The brine might be derived from the solution of evaporite deposits or from ionic filtration by clay or shale beds during the process of sediment compaction or both.
Figure 4. Aquifers in unconsolidated sand and gravel deposits overlie aquifers in semiconsolidated and consolidated rocks in large parts of Segment 10. Most of the sand and gravel aquifers are north of Kentucky. The most productive aquifers in the unconsolidated deposits consist of coarse, well-sorted, stratified glacial deposits.

EXPLANATION

Surficial aquifer system

- Sand and gravel aquifers at or near land surface, and alluvium along streams and rivers
- Patterned area shows Mississippi River Valley alluvial aquifer

- Sand and gravel aquifers buried beneath fine-grained material

- Surficial deposits generally less than 100 feet thick, and the occurrence of sand and gravel aquifers difficult to locate

- Southern limit of glaciation

PRINCIPAL AQUIFERS

The rocks that underlie Segment 10 are divided into the different hydrogeologic units (aquifers and confining units) shown in Figures 4 and 5. These aquifers and confining units are grouped according to the physiographic provinces shown in Figure 1, and are described in general accordance with these physiographic provinces.

Throughout Segment 10, the rocks that compose aquifers and confining units generally are divided into three types according to their degree of consolidation— the Precambrian and Paleozoic rocks are consolidated, the Cretaceous and Tertiary rocks generally are semiconsolidated, and the Quaternary deposits generally are unconsolidated. Exceptions are where carbonate cements have been dissolved from Paleozoic sandstone beds, which leaves them partly unconsolidated and friable, and where the younger unconsolidated deposits have been partly cemented or lithified. The consolidated rocks generally are covered with younger unconsolidated deposits or unconsolidated regolith derived from weathering of the consolidated rocks.

Unconsolidated, coarse-grained deposits of Quaternary age (primarily of glacial origin) compose principal aquifers that overlie the Paleozoic rocks throughout most of the Central Lowland and the northern parts of the Interior Low Plateaus and Appalachian Plateaus Physiographic Provinces (figs. 1 and 4). Coarse-grained alluvium that has been derived from glacial material and deposited along present or buried major stream channels constitutes aquifers in the same areas. A band of alluvium parallel to the Mississippi River in westernmost Kentucky and Tennessee also composes an aquifer. Where the glacial deposits consist of coarse, well-sorted sand and gravel, they constitute some of the most productive aquifers in Segment 10. These unconsolidated deposits are collectively called the surficial aquifer system.

Semiconsolidated rocks of Cretaceous and Tertiary age compose principal aquifers in the Mississippi Embayment section of the Coastal Plain Province (figs. 1 and 5). Consolidated rocks of Paleozoic age compose principal aquifers in the Central Lowland, the Interior Low Plateaus, the Appalachian Plateaus, the Valley and Ridge, and the Ozark Plateaus Provinces. Consolidated rocks of Precambrian age compose principal aquifers of the Blue Ridge Province.
The numerous aquifers mapped in Segment 10 vary in their hydrologic character in different physiographic provinces. Most aquifers of the Mississippi embayment aquifer system are in semi-consolidated rocks.

Figure 5. The numerous aquifers mapped in Segment 10 vary in their hydrologic character in different physiographic provinces. Most aquifers of the Mississippi embayment aquifer system are in semi-consolidated rocks.

Figure 6. The arches, domes, and structural basins in Precambrian rocks and in the overlying Paleozoic sedimentary rocks of Segment 10 were created by tectonic forces. Aquifers in the Paleozoic sedimentary rocks are near the land surface over the arches and domes and are deeply buried in the structural basins.

GEOLOGIC SETTING

To a large extent, the geology of the area controls the occurrence, movement, availability, and quality of the groundwater resources. Thus, a basic understanding of the geology is necessary to understand the groundwater hydrology.

Precambrian igneous, metamorphic, and sedimentary rocks are at the land surface in the Blue Ridge Province in eastern Tennessee. Elsewhere in Segment 10, Precambrian igneous and metamorphic rocks are buried beneath younger rocks. The top of the Precambrian rocks is about 1,000 feet below sea level in northern Illinois and is about 15,000 feet below sea level at the junction of Illinois, Indiana, and Kentucky.

A thick sequence of consolidated sedimentary rocks of Paleozoic age overlies the Precambrian rocks. These sedimentary rocks are primarily siltstone, shale, sandstone, limestone, and dolomite. Tectonic forces warped the deeply buried Precambrian rocks and created arches, domes, structural basins, and fracture systems in the overlying Paleozoic rocks (Fig. 6).

On the crests and flanks of the arches and domes, freshwater can be obtained from water-yielding rocks that are either exposed at the land surface or buried at shallow depths. The same water-yielding rocks are deeply buried in the structural basins and mostly contain saltwater or brine.
The distribution of the Paleozoic rocks in the area is controlled by the position of the arches, domes, structural basins, and associated faults. The oldest Paleozoic rocks (Cambrian) are at the land surface between southeast trending thrust faults in the Blue Ridge and the Valley and Ridge Provinces in eastern Tennessee. Cambrian strata also outcrop below Quaternary deposits and locally crop out in a small area south of a normal fault in eastern Illinois (fig. 7). Ordovician rocks either are at the land surface or subcrop over the arches and domes, where rocks younger than Ordovician were either eroded or never deposited. The youngest Paleozoic rocks (Pennsylvanian and Permian) are present in the areas coincident with the structural basins (figs. 6 and 7). Pennsylvanian strata are present in the Illinois Basin in central and southern Illinois, southwestern Indiana, and northeastern Kentucky. Pennsylvanian and Permian strata are present in the Appalachian Basin in southeastern Ohio, whereas only Pennsylvanian strata are present in the same basin in eastern Kentucky and central Tennessee.

The Paleozoic rocks are covered by sedimentary rocks of late Mesozoic and Cenozoic age in the Mississippi Embayment section of the Coastal Plain Province in the western parts of Kentucky and Tennessee and in southern Illinois (figs. 1 and 7). These Coastal Plain deposits thicken from less than 100 feet near their northern and eastern limits to about 3,000 feet at the southwestern tip of Tennessee. The deposits are primarily semiconsolidated layers of clay, silt, and sand.

In the northern part of Segment 10, the Paleozoic rocks are covered by Quaternary deposits, which consist of different combinations of clay, silt, sand, and gravel. Most of these materials were deposited by the ice of continental glaciers that covered large parts of North America during the Pleistocene Epoch by meltwater from the ice. The southern limit of glaciation (fig. 7) marks the general southern extent of these deposits in Segment 10, but meltwater deposits are present south of this limit along the Ohio River and many of its tributaries.

The distribution of the different geologic units at depth is shown by the geologic sections in figure 8. From this perspective, the effects of arches, domes, structural basins, and associated faults on the distribution of the rocks in Segment 10 are more apparent.

**Figure 7.** A simplified geologic map shows the extent of the major rock units in Segment 10. The younger rocks are associated with structural basins, older rocks are associated with a fault in northern Illinois and the area of arches or domes in the clinal part of the area. The oldest rocks are exposed in the central part of Illinois.
The aquifers of the Central Lowland Physiographic Province consist of unconsolidated sand and gravel deposits of Quaternary age (fig. 11) and consolidated sandstone, limestone, and dolomite of Paleozoic age (fig. 12). The principal aquifers in Paleozoic rocks primarily are sandstone and dolomite of Mississippian age, dolomite and limestone of Devonian and Silurian age, and sandstone and dolomite of Ordovician and Cambrian age (fig. 13).

The geologic and hydrologic nomenclature used in this chapter differs from State to State because of independent geologic interpretations and varied distribution and lithology of rock units. A fairly consistent set of nomenclature, however, can be derived from the most commonly used rock and aquifer names. Therefore, the nomenclature used in this report is essentially a synthesis of that of the U.S. Geological Survey, the Illinois State Geological Survey, the Illinois State Water Survey, the Indiana Geological Survey, the Kentucky Geological Survey, the Ohio Geological Survey, and the Tennessee Department of Conservation, Division of Geology. Individual sources for nomenclature are listed with each correlation chart in this chapter.

The Central Lowland Province in Segment 10 is characterized by a low-relief surface formed by glacial till, outwash plains, and glacial-lake plains. A fairly consistent set of nomenclature, however, can be derived from the most commonly used rock and aquifer names. Therefore, the nomenclature used in this report is essentially a synthesis of that of the U.S. Geological Survey, the Illinois State Geological Survey, the Illinois State Water Survey, the Indiana Geological Survey, the Kentucky Geological Survey, the Ohio Geological Survey, and the Tennessee Department of Conservation, Division of Geology. Individual sources for nomenclature are listed with each correlation chart in this chapter.

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Hydrogeologic Setting

The lateral extent, thickness, and hydraulic characteristics of each of the numerous sand and gravel aquifers and clay and silt confining units that make up the surficial aquifer system are difficult to map at a regional scale because the distribution of the sediments is extremely complex. Consequently, examples from different areas within the Central Lowland Province in Segment 10 are used to illustrate the similarities and differences in the hydrogeology of these deposits.

The sand and gravel aquifers of the surficial aquifer system are present in different hydrogeologic settings. Aquifers that consist of glacial deposits are in buried river valleys, such as the Mahomet Valley in central Illinois (fig. 15); glacial outwash plains, such as the one in northern Lagrange County, Ind. (fig. 16); and ancient river valleys, such as the one along the Great Miami River in Butler County, Ohio (fig. 17). The thick Quaternary sand and gravel deposits along the Mississippi River near East St. Louis, St. Clair County, Ill. (fig. 18), represent alluvium deposited by the ancestral Mississippi River. Much of this alluvium consists of eroded and reworked glacial deposits.

The occurrence and movement of the ground water is somewhat different in the four hydrogeologic settings shown in figures 15 through 18. In the buried bedrock valley setting (fig. 15), the shallow sand and gravel aquifers are isolated from direct recharge and discharge by overlying clay and silt deposits that compose local confining units. Under natural conditions, most of the water that recharges these shallow aquifers moves along short flow paths and discharges to local streams. The remainder of the water circulates into the deeper sand and gravel aquifers, but the long-term yield of the wells is less than 1 to about 300 feet per year. In the surficial aquifer systems of each of the numerous sand and gravel aquifers and clay and silt confining layers, a large volume of recharge to move toward nearby pumping wells. The recharge is obtained partly by induced infiltration of water from the river. The deeper buried sand and gravel aquifers shown in figure 17 are isolated from direct recharge and discharge by overlying clay and silt confining layers, a situation similar to that shown in figure 15. The sand and gravel deposits in the Mississippi River Valley (fig. 18) are somewhat isolated from direct recharge but have a direct hydraulic connection to the river. Under natural conditions, recharge percolates downward through clay and silt confining units and then mostly moves through the sand and gravel deposits to discharge at the river. Wells near the river capture some of the flow and also obtain some water by induced infiltration of water from the river.

Published reports on the sand and gravel deposits of the surficial aquifer system indicate that individual units range from less than 1 to about 300 feet in thickness. The thickest aquifers shown in this chapter are in the land surface and receive recharge directly from precipitation. Under natural conditions, water in the upper part of the glacial deposits discharges to local streams, lakes, or wetlands; however, water in the deeper parts of the sand and gravel deposits flows beneath local streamlines and lakes and discharges to larger streams that are regional drains. Large yields are possible from wells completed in the glacial outwash plains, particularly where the aquifers have a direct hydraulic connection to streams and lakes and the wells are located near these surface-water bodies. Parts of the hydrogeologic setting in figure 17 are similar to the settings illustrated by figures 15 and 16. The upper sand and gravel aquifer in figure 17A is recharged directly by precipitation and has a direct hydraulic connection to the Great Miami River, similar to the aquifer-lake connection shown in figure 16. This direct connection increases the potential for large volumes of recharge to move toward nearby pumping wells. The recharge is obtained partly by induced infiltration of water from the river. The deeper buried sand and gravel aquifers shown in figure 17B are isolated from direct recharge and discharge by overlying clay and silt confining layers, a situation similar to that shown in figure 15.

Generalized Ground-Water Movement

Although ground water in the surficial aquifer system is under water table, or unconfined, conditions in many places, artesian, or confined, conditions exist in places where interbedded clay or silt compose local confining units. Together, water table and artesian water levels compose the potentiometric surface of an aquifer. The difference in the altitude of the potentiometric surface above a horizontal distance is called the hydraulic gradient. Ground water moves through an aquifer in a direction generally parallel to the hydraulic gradient. The movement generally is perpendicular to the local gradient of the potentiometric surface.

A local example of the configuration of the potentiometric surface of the surficial aquifer system and its relation to stream recharge areas and stream-valley discharge areas is shown in figure 19. In this example, the altitude of the potentiometric surface in the upper parts of the Wabash River Basin in northeastern Indiana ranges from less than 600 to more than 1,100 feet above sea level. The regional hydraulic gradient in this basin is about 5 feet per mile, whereas local gradients range from as much as 30 feet per mile. The direction of ground-water movement is shown in figure 19B; it is typical of that in the surficial aquifer system throughout the segment. Most of the water moves through the aquifer along short flow paths toward forest streams where it is discharged to the streams as base flow. Some of the flow follows longer flow paths in the deeper parts of the aquifer system and discharges to larger streams.

Aquifer Hydraulic Characteristics and Well Yields

In parts of central and southern Ohio, the buried Teays Valley is filled with laminated clay and silt that are not aquifer material. Further to the north and west, in the upper part of the Wabash River Basin in Indiana, the valley is filled partly with sand and gravel. In western Indiana and central Illinois, sand and gravel aquifers have been mapped in and along the buried Wabash-Mahomet Valley (fig. 11). These coarse, permeable materials allow water to move through the sediments with little resistance to flow. The capacity of an aquifer to transmit water is known as transmissivity, which is a way of measuring the relative ease with which water moves through the aquifer. Transmissivity values for the permeable sediments in the buried Teays Valley in the upper Wabash River Basin range from 3,000 to about 40,000 feet squared per day (fig. 20). The water moves more readily through the aquifer where the transmissivity is greatest.
Aquifer Hydraulic Characteristics and Well Yields—Continued

The transmissivity of the surficial aquifer system varies through a wide range but generally is much larger than the transmissivity of underlying bedrock. Transmissivity values calculated for the surficial aquifer system range from less than 500 feet squared per day where the aquifer system is thin and contains fine-grained material to more than 50,000 feet squared per day where the aquifer system is thick and contains entirely of coarse-grained material. Transmissivity values of 5,000 to 25,000 feet squared per day are common where the thickness of the aquifer system ranges from 50 to 250 feet. If all other factors remain the same, yields of wells completed in an aquifer are directly proportional to the transmissivity of the aquifer. The largest yields can be obtained from wells that are completed in aquifers which have the largest transmissivity values. The potential yield of wells completed in the surficial aquifer system in the Central Lowland Province in Segment 10 ranges from less than 100 to more than 560 gallons per minute per foot (fig. 21). In general, the largest sustained withdrawals are in wells completed in coarse sand located in river valleys in the valleys where the aquifers and the river are hydraulically connected. Under such conditions, large withdrawals from a well near a river will cause the water level in the well to decline until it is below river level. The gradient created will induce water to move from the river into the aquifer and toward the well (fig. 22). Under these conditions, well yields of 2,500 gallons per minute are common, and maximum yields might exceed 4,000 gallons per minute. In some places, recharge ponds have been constructed to capture and impound surface water. The impounded water percolates downward to recharge the surficial aquifer system and subsequently moves into nearby pumping wells.

Ground-Water Quality

The quality of water in the sand and gravel aquifers of the surficial aquifer system is similar throughout Illinois, Indiana, and Ohio. The quality of the ground water is such that the water generally is adequate or can be treated and made adequate for most uses. However, in some areas in Illinois and Ohio, nitrate concentrations are larger than the maximum contaminant level of 10 milligrams per liter established by the U.S. Environmental Protection Agency for drinking water. These large nitrate concentrations are possibly due to contamination of the ground water by fertilizer or by septic tank effluent.

Water in the surficial aquifer system typically is a calcium magnesium bicarbonate type, is hard, and has large concentrations of iron. The water typically has a neutral pH. Concentrations of dissolved solids mostly range between about 60 and 250 milligrams per liter, which is the secondary maximum contaminant level recommended for drinking water by the U.S. Environmental Protection Agency (fig. 24). Median hardness concentrations, which are expressed as calcium carbonate, generally exceed 100 milligrams per liter. Most of the water contains iron concentrations of greater than 300 micrograms per liter, which causes the staining of laundry and porcelain plumbing fixtures. Concentrations of chloride and sulfate are generally less than 250 milligrams per liter, which is the secondary maximum contaminant level established by the U.S. Environmental Protection Agency for drinking water.

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Fresh Ground-Water Withdrawals

Approximately 2 billion gallons of fresh ground water was withdrawn each day during 1985 from all the aquifers in the Central Lowland Province in Segment 10. Of this amount, about 53 percent, or about 1.1 billion gallons per day, was withdrawn from the sand and gravel aquifers of the surficial aquifer system. About 445 million gallons per day was withdrawn from the surficial aquifer system in Illinois, 341 million gallons per day in Indiana, and 285 million gallons per day in Ohio (fig. 25). Withdrawals for public supply constituted the largest or second largest use category in each State, and accounted for about 165 million gallons per day in Illinois, 123 million gallons per day in Indiana, and 191 million gallons per day in Ohio. Large withdrawals were made for industrial, mining, and thermoelectric power uses in Illinois and Indiana.
Most of the water in the Pennsylvania aquifers is under confined conditions because the aquifers are interbedded with shale, clay, and sand and are overlain by Quaternary deposits that contain clay beds. The water primarily moves through secondary openings, such as fractures and joints or local solution channels in limestones. Recharge to the Pennsylvania aquifers takes place through the overlying Quaternary deposits. The large volumes of water stored in the surficial aquifer system serve to replenish ground water withdrawn from wells completed in the Pennsylvania aquifers. In some places, such as river valleys, water levels in the Pennsylvania aquifers are higher than those in the overlying surficial aquifer system, and ground water moves from the Pennsylvania aquifers to the surficial aquifer system.

The thickness of Pennsylvania rocks that is saturated with freshwater ranges from less than 100 feet to more than 300 feet (fig. 28). The thickest parts of the freshwater-yielding Pennsylvania rocks are in central and southeastern Illinois. Nearly the entire thickness of Pennsylvania rocks contains freshwater in the north-central part of Illinois (fig. 30). Toward the south, the depth to saltwater decreases, and the Pennsylvania rocks thicken. Near the southern limit of the area, only the upper 10 percent of the Pennsylvania rocks contains freshwater.

The sandstones and limestones that are the most productive aquifers in the Pennsylvania rocks have a distinct stratigraphic (vertical) and areal distribution. Sandstones are the predominant aquifers in the lower parts of the sequence of Pennsylvania rocks, whereas limestones are the predominant aquifers in the middle and upper parts of the sequence (fig. 31). The sandstone aquifers are saturated with freshwater only in peripheral parts of the area updield by the Pennsylvania rocks; elsewhere, they contain saltwater. Some of the limestones and shales of the middle and upper parts of the sequence grade into sandstones and silty sandstones in southeastern Illinois. Because these sandstones and silty sandstones are interbedded or are in the upper part of the sequence, they are interbedded with thin, low-permeability deposits, such as shales and black shales. The change in water from a sodium bicarbonate type to a sodium chloride type, such as the water represented by figure 32B, the change in water from a sodium bicarbonate type to a sodium chloride type, accompanied by a large increase in dissolved-solids concentrations, takes place with small changes in depth. Concentrations of calcium, magnesium, and bicarbonate are larger in water from the shallower parts of the Pennsylvanian aquifers. Large concentrations of fluoride (as much as 15 milligrams per liter) locally are present. In some instances, the fluoride content of the water is great enough to meet the needs of persons who drink it on a continuing basis.

**Figure 27** A typical sequence of beds deposited during a sedimentary cycle in the Paleozoic sedimentary rocks of Illinois contains about 10 bed of sandstone, shale, clay, and limestone. Some of the most productive aquifers in Illinois are in the area on the east of Segment 1 of the Pennsylvanian Province and some are in the northwest part of the State. Most of the water in the Pennsylvanian aquifers is under confined conditions because the aquifers are interbedded with shale, clay, and sandstone and are overlain by Quaternary deposits that contain clay beds. The water primarily moves through secondary openings, such as fractures and joints or local solution channels in limestones. Recharge to the Pennsylvanian aquifers takes place through the overlying Quaternary deposits. The large volumes of water stored in the surficial aquifer system are replenished by ground water withdrawn from wells completed in the Pennsylvanian aquifers. In some places, such as river valleys, water levels in the Pennsylvanian aquifers are higher than those in the overlying surficial aquifer system, and ground water moves from the Pennsylvanian aquifers to the surficial aquifer system.

The sandstones and limestones that are the most productive aquifers in the Pennsylvanian rocks have a distinct stratigraphic (vertical) and areal distribution. Sandstones are the predominant aquifers in the lower parts of the sequence of Pennsylvanian rocks, whereas limestones are the predominant aquifers in the middle and upper parts of the sequence (fig. 31). The sandstone aquifers are saturated with freshwater only in peripheral parts of the area updield by the Pennsylvanian rocks; elsewhere, they contain saltwater. Some of the limestones and shales of the middle and upper parts of the sequence grade into sandstones and silty sandstones in southeastern Illinois. Because these sandstones and silty sandstones are interbedded or interlayered with thin, low-permeability deposits, such as shales and black shales. The change in water from a sodium bicarbonate type to a sodium chloride type, such as the water represented by figure 32B, the change in water from a sodium bicarbonate type to a sodium chloride type, accompanied by a large increase in dissolved-solids concentrations, takes place with small changes in depth. Concentrations of calcium, magnesium, and bicarbonate are larger in water from the shallower parts of the Pennsylvanian aquifers. Large concentrations of fluoride (as much as 15 milligrams per liter) locally are present. In some instances, the fluoride content of the water is great enough to meet the needs of persons who drink it on a continuing basis.

**Figure 28** The depth to the top of the Pennsylvanian rocks ranges from less than 100 feet to about 400 feet below land surface. These rocks generally are deeper where the valleys eroded into them from the overlying Quaternary deposits of the surficial aquifer system. The Pennsylvanian sandstones and limestones are parts of repeating sequences of beds deposited during multiple sedimentary cycles. An ideal complete cycle consists of the following sequence of beds, listed from bottom to top: basal sandstone, sandy shale, limestone, underclay, coal, gray shale, limestone, black shale, black shale, and limestone. The Pennsylvanian sandstones are thin or fine grained or both. The Pennsylvanian aquifers in places where little water is available are in the middle and upper parts of the sequence (fig. 31). The sandstone aquifers are saturated with freshwater only in peripheral parts of the area updield by the Pennsylvanian rocks; elsewhere, they contain saltwater. Some of the limestones and shales of the middle and upper parts of the sequence grade into sandstones and silty sandstones in southeastern Illinois. Because these sandstones and silty sandstones are interbedded or interlayered with thin, low-permeability deposits, such as shales and black shales. The change in water from a sodium bicarbonate type to a sodium chloride type, such as the water represented by figure 32B, the change in water from a sodium bicarbonate type to a sodium chloride type, accompanied by a large increase in dissolved-solids concentrations, takes place with small changes in depth. Concentrations of calcium, magnesium, and bicarbonate are larger in water from the shallower parts of the Pennsylvanian aquifers. Large concentrations of fluoride (as much as 15 milligrams per liter) locally are present. In some instances, the fluoride content of the water is great enough to meet the needs of persons who drink it on a continuing basis.

**Figure 29** The thickest sections of Pennsylvanian rocks that contain freshwater are in central and southeastern Illinois. These rocks generally are deeper where the valleys eroded into them from the overlying Quaternary deposits of the surficial aquifer system. The Pennsylvanian sandstones and limestones are parts of repeating sequences of beds deposited during multiple sedimentary cycles. An ideal complete cycle consists of the following sequence of beds, listed from bottom to top: basal sandstone, sandy shale, limestone, underclay, coal, gray shale, limestone, black shale, black shale, and limestone. The Pennsylvanian sandstones are thin or fine grained or both. The Pennsylvanian aquifers in places where little water is available are in the middle and upper parts of the sequence (fig. 31). The sandstone aquifers are saturated with freshwater only in peripheral parts of the area updield by the Pennsylvanian rocks; elsewhere, they contain saltwater. Some of the limestones and shales of the middle and upper parts of the sequence grade into sandstones and silty sandstones in southeastern Illinois. Because these sandstones and silty sandstones are interbedded or interlayered with thin, low-permeability deposits, such as shales and black shales. The change in water from a sodium bicarbonate type to a sodium chloride type, such as the water represented by figure 32B, the change in water from a sodium bicarbonate type to a sodium chloride type, accompanied by a large increase in dissolved-solids concentrations, takes place with small changes in depth. Concentrations of calcium, magnesium, and bicarbonate are larger in water from the shallower parts of the Pennsylvanian aquifers. Large concentrations of fluoride (as much as 15 milligrams per liter) locally are present. In some instances, the fluoride content of the water is great enough to meet the needs of persons who drink it on a continuing basis.
MISSISSIPPIAN AQUIFERS

Hydrogeologic Setting

Mississippian rocks that are aquifers in the Central Lowland Province in Segment 10 lie beneath Quaternary deposits and Pennsylvanian rocks in parts of western Illinois, eastern Iowa, and southwestern Indiana (fig. 33). Generally, thick bedded limestones and sandstones constitute the aquifers. Although small amounts of water can be obtained from nearly all the Mississippian rocks, including shale, in the areas shown in figure 33, the most productive water-yielding rocks are limestones and sandstones. Limestone is the dominant rock type in the lower one-half of the Mississippian section (fig. 34), whereas sandstone is more abundant in the upper one-half. Some of the limestone formations in the lower part of the Mississippian rocks in western Illinois change to shale in the eastern part of the area. Thus, almost all the Mississippian rocks are considered to be aquifers in western Illinois, whereas only the middle and upper parts of Mississippian rocks are considered to be aquifers in eastern Illinois and southwestern Indiana.

Freshwater circulates to depths greater than 1,000 feet below sea level in west-central Illinois; consequently, all the Mississippian rocks that are directly overlain by Quaternary deposits and some that are directly overlain by Pennsylvanian rocks contain freshwater in this area (fig. 35). However, in southern Illinois and in areas toward the central part of the Illinois Basin, Mississippian rocks are at greater depths and are overlain by a thick, continuous sequence of Pennsylvanian rocks that impede deep freshwater circulation. In addition, some of the Mississippian limestones grade eastward to less-permeable shale. Downward toward the central part of the Illinois Basin, initially part and eventually all the Mississippian rocks contain water with dissolved-solids concentrations of greater than 1,000 milligrams per liter.

The distribution of wells that obtain water from the Mississippian aquifers is similar to that of wells completed in the Pennsylvania. The Mississippian aquifers generally are used for water supply where they are less than 200 feet below land surface and where more water can be obtained from them than from the overlying surficial aquifer system. Water in the Mississippian aquifers primarily moves through openings such as bedding planes, fractures, and solution channels. Generally, the water is under confined conditions where the water-yielding zones in the Mississippian rocks lie beneath clay or shale beds. Recharge to the Mississippian aquifers occurs primarily by water that percolates downward through the overlying Quaternary deposits and Pennsylvanian rocks. Water discharges to these younger rocks in places where the water level in the Mississippian aquifers is higher than that in the overlying rocks. Water stored in the overlying rocks, especially the Quaternary deposits, serves to replenish ground water withdrawn from the Mississippian aquifers.

Ground-Water Quality

A summary of the results of chemical analyses of water from wells completed in the Mississippian aquifers in Greene County, Ill., on the eastern side of the Illinois Basin, is shown in figure 36. The water is moderately hard and is a sodium calcium bicarbonate type. Water from wells deeper than 200 feet in Greene County can have concentrations of sulfate and chloride that exceed 250 milligrams per liter and dissolved solids that exceed 500 milligrams per liter. Sparse data indicate that water from the Mississippian aquifers in western Illinois is very hard, which reflects the predominance of limestone in this area. Slightly acidic ground water partially dissolves the limestone, thus increasing the concentration of calcium and magnesium ions (primary hardness-causing constituents) in the water.

Water quality and well depth data from the Mississippian and the Pennsylvanian aquifers in Greene and Sullivan Counties, Ind., indicate that well yields in well depth are accompanied by large increases in dissolved-solids concentrations (fig. 37). Wells shallower than 160 feet yield water that contains less than 500 milligrams per liter dissolved solids; water from deeper wells has dissolved-solids concentrations large as 3,400 milligrams per liter. At shallow depths, the water generally is hard and is a calcium bicarbonate type or a calcium sodium bicarbonate type, whereas water from deep wells in the Mississippian aquifers might be a sodium chloride type.

Well Yields and Fresh Ground-Water Withdrawals

The reported yields of wells completed in the Mississippian aquifers range from less than 1 to more than 100 gallons per minute; the average well yield is about 10 gallons per minute. Properly completed and developed wells commonly yield from 20 to 30 gallons per minute. The largest volumes of water are obtained from wells that penetrate large openings in the rocks, such as bedding planes, fractures, and solution openings. The specific capacity (well yield divided by water-level drawdown during pumping) of wells completed in the Mississippian aquifers generally ranges from 0.03 to 9 gallons per minute per foot of water-level drawdown (fig. 38). The specific capacity generally is greater for some Mississippian formations than others. Wells completed in the Rock Island and the Burlington limestone formations generally have the largest specific capacities, and those completed in the Six Mile, the St. Louis, and the Silurian limestone formations of the Warren Formation generally have the smallest specific capacities. Fresh ground water withdrawals from the Mississippian aquifers during 1985 were less than 3 percent of the total ground water withdrawals from Illinois. Withdrawals from Mississippian rocks in Illinois during the same period were less than 1 percent of the total ground water withdrawn.

SILURIAN-DEVONIAN AQUIFER

Hydrogeologic Setting

Dolomites and limestones of Silurian and Devonian age constitute one of the principal consolidated-rock aquifers throughout a large area in the Central Lowland Province in Segment 10 (fig. 39). The Silurian-Devonian aquifer lies beneath Upper Devonian shales, Mississippian rocks, or Quaternary deposits and is present from central Ohio across Indiana into northern and western Illinois.

The Silurian-Devonian aquifer has been referred to by a number of different names. It is known as the carbonate aquifer in Ohio, the Silurian-Devonian aquifer in Indiana, and the upper part of the shallow dolomite aquifer in Illinois. The aquifer was designated the “Silurian-Devonian aquifer” by a regional aquifer study that encompassed northern Illinois, Iowa, Wisconsin, and Minnesota. Because the name “Silurian-Devonian aquifer” has been applied regionally, this name is used in this chapter.
Hydrogeologic Setting—Continued

The Devonian rocks are less important hydrologically than the Silurian rocks because much of the lower part of the sec-
tion of Devonian rocks has been removed from most of the areas (fig. 41). Consequently, the Devonian part of the aquifer is present at depths beyond 1,000 feet below sea level, which is much deeper than the Silurian–Devonian section. The overlying shales impede the downward movement of freshwater. The Silurian–Devonian aquifer contains freshwater for only a short distance from where the overlying shales are removed. The Silurian–Devonian aquifer is commonly used for water supply where it is overlain by less than 200 feet of Ques-

tennine deposits.

Ground water generally is under confined conditions in the Silurian–Devonian aquifer. The water moves through fractures, bedding planes, and solution cavities in the dolomites and limestones. The Silurian–Devonian aquifer is recharged from the overlying surficial aquifer system in areas where water levels in the surficial aquifer system are higher than those in the Silurian–Devonian aquifer. Locally, where the water-level dif-

ferences are reversed, water discharges to the surficial aquifer system from the Silurian–Devonian aquifer. The water stored in the surficial aquifer system serves to replenish the water withdrawn from wells that are completed in the underlying Silurian–Devonian aquifer.

The Silurian–Devonian aquifer is most commonly used for 

Figure 41. The Silurian–Devonian aquifer in Illinois, Indiana, and Ohio is shown in figure 39. The probable yield of wells completed in the Silurian–Devonian rocks can be more than 100 million gallons per day in discharge areas of the Illinois River Group (fig. 42). The specific capacities of these wells range from 5 to 100 gallons per minute per foot of water-level drawdown, and average about 30 gallons per minute per foot of drawdown. The yield for wells located in the southern one-half of the area is about 200 gallons per minute and the average yields for the yield areas in the remainder of the yield area is about 450 gallons per minute. Specific capacities of large-

Figure 42. Water from the Silurian–Devonian aquifer generally has large concentrations of dissolved solids, silica, and iron that exceed the secondary maximum contaminant levels established for drinking water by the U.S. Environmental Protection Agency.

Figure 43. Densitometry by the Silurian–Devonian rocks in northwestern and north-central Illinois, the probable yield of wells completed in the Silurian–Devonian rocks is less than 100 million gallons per day in areas where they are exposed or thinly covered by the overlying shales. These are shown in figure 39. Discharge areas of the Illinois River Group and stratigraphic geology of the Illinois, Indiana, and Ohio Shale. The specific capacities of large-diameter test wells located outside the areas of large yield shown in figure 42 range from less than 0.5 to 2.5 gallons per minute per foot of water-level drawdown and average about 2.2 gal-

Figure 44. Calcium magnesium bicarbonate type in discharge areas and a calcium magnesium sulfate type in discharge areas (fig. 46). In samples from eastern Ohio, calcium, magnesium, bicarbonate, and sulfate are the most common ions. The large concen-

Figure 45. The quality of water from the Silurian–Devonian aquifer is most commonly used for water supply where it is overlain by less than 200 feet of Quaternary deposits. The Silurian–Devonian aquifer contains concentrations of dissolved solids, silica, and iron that exceed the secondary maximum contaminant levels established for drinking water by the U.S. Environmental Protection Agency. The maximum contaminant levels established for drinking water by the U.S. Environmental Protection Agency. The chemical quality of water from the freshwater part of the Silurian–Devonian aquifer generally is adequate or can be treated and made adequate, for most purposes. Concentra-

Figure 46. Calcium magnesium bicarbonate type in discharge areas and a calcium magnesium sulfate type in discharge areas (fig. 46). In samples from eastern Ohio, calcium, magnesium, bicarbonate, and sulfate are the most common ions. The large concen-

Figure 47. Fresh groundwater withdrawals during 1980–1984. Total withdrawals 34 million gallons per day in Ohio and 275 million gallons per day in Illinois. Withdrawal of public supply use is the largest use category in Illinois and Indiana. Industrial, mining, and thermoelectric power use is the largest use category in Ohio. The water withdrawn for all three States during 1980. The withdrawal from the Silurian–Devonian aquifer in Illinois, Indiana, and Ohio were about 488 million gallons per day. About 63 percent of this was withdrawn from wells completed in the aquifer in the Chicago Lowland drainage province. The remainder came from wells located in southernmost Illinois and Ohio in the interior low plateau Province. Water withdrawn from the Silurian–Devonian aquifer was about 21 percent of the total ground-water withdrawals for all three States during 1980. The withdrawals from the Silurian–Devonian aquifer was about 15 percent of the total ground-water withdrawn in Illinois, 18 percent in Ohio, and 34 percent in Indiana. The volume of water withdrawn for some of the ground-water use categories changes within each State from State to State. The ground-water withdrawal from the Silurian–Devonian aquifer for public supply use was about 92 million gallons per day in Illinois, 97 million gallons per day in Indiana, and 200 million gallons per day in Ohio. Public supply was the largest use category in Illinois and Indiana. In Ohio, about 67 million gallons per day were withdrawn for industrial, mining, and thermoelectric power use, the largest use category in the State.

Well Yields

The yields of wells completed in the Silurian–Devonian aquifer range from less than 5 to 100,000 gallons per minute. Yields of 5 to 15 gallons per minute can be obtained from most wells completed in the aquifer throughout the area shown in figure 39. Large well yields are possible locally in Illinois, Indiana, and Ohio, but the largest well yields, more than 1,500 gallons per minute, are reported from northern Illinois.

Large well yields in Ohio are possible in the west-central and northern parts of the State (fig. 42). Middle and Upper Silurian rocks are the major water-yielding rocks in this area due to the dissolved action of slightly acidic recharge water on the carbonate rocks where they are exposed or thinly covered by the overlying shales. The specific capacities of large-diameter test wells completed in this area exceed 200 gallons per minute per foot of water-level drawdown and average about 2.2 gallons per minute per foot of drawdown.

The largest use category in Ohio is thermoelectric power use, the largest use category in the State. The specific capacities of large-diameter test wells completed in this area exceed 200 gallons per minute per foot of water-level drawdown and average about 2.2 gallons per minute per foot of drawdown.
The aquifers in rocks of Cambrian and Ordovician age and the confining units that separate and overlie them are collectively known as the Cambrian-Ordovician aquifer system. Where this aquifer system is underlain by Jurassic and Triassic rocks in the Central Lowland Province in segment 10, it is separated from the underlying Silurian-Devonian aquifer by the Maquoketa confining unit, which consists of Upper Ordovician shale, dolomite, and dolosiltstone. Where the Maquoketa confining unit and younger Paleozoic rocks have been removed by erosion, the Cambrian-Ordovician aquifer system is overlain by the surficial aquifer system throughout the Central Lowland Province.

The Cambrian-Ordovician aquifer system is a major source of water supply in Segment 9 and is discussed in greater detail in the chapter of this Atlas that describes that segment. The Cambrian-Ordovician aquifer system contains freshwater in a large area in northern Illinois (fig. 48). The freshwater flow systems within individual aquifers are partially isolated from one another by leaky confining units that separate the aquifers. Freshwater circulates to great depths in northern Illinois because of the high permeability of the Cambrian-Ordovician aquifer system and the large amount of recharge that enters the system where the rocks crop out or subcrop around the Wisconsin Arch to the northeast.

Water in the Cambrian-Ordovician aquifer system primarily is under confined conditions and moves through primary and secondary openings in the rocks. The primary openings consist of bedding planes and the voids between the grains that compose the sandstones; the secondary openings consist of fractures and bedding planes in the clastic rocks and fractures and solution channels in the carbonate rocks.

Parts of three principal aquifers, which consist of consolidated rocks of Ordovician and Cambrian age, are present in northern Illinois—the St. Peter-Prarie du Chien-Jordan, the Ironton-Galesville, and the Mount Simon (fig. 49). These aquifers extend into northern Illinois from Wisconsin and Iowa. The Jordan Sandstones of Late Cambrian age is a major part of the St. Peter-Prarie du Chien-Jordan aquifer in Wisconsin and Iowa, but in Segment 10, this sandstone is part of the aquifer only in western Illinois. The relations among the three principal aquifers and their associated overlying and underlying confining units are shown in a hydrogeologic section from Stephenson County, Ill., to Howard County, Ind. (fig. 50).

The Jordan Sandstone is a major part of the aquifer in Iowa and Illinois. The Jordan aquifer is thinnest in northern Illinois where the aquifer contains freshwater. The slope of the top of the aquifer generally is toward the Illinois Basin. The St. Peter-Prarie du Chien-Jordan aquifer is more than 500 feet above sea level in the northernmost part of Illinois and 2,500 feet below sea level in northernmost Illinois (fig. 51). The average altitude of the top of the aquifer is about 250 feet above sea level in the area where the aquifer contains freshwater. The slope of the top of the aquifer generally is toward the Illinois Basin. The St. Peter-Prarie du Chien-Jordan aquifer is about 250 feet thick along the northern boundary of Illinois and about 1,250 feet thick in west-central Illinois. The thickness averages about 400 feet in the area where the aquifer contains freshwater. The aquifer is thinnest in northern Illinois where the rocks of the Prairie du Chien Group were completely eroded away before the deposition of the St. Peter Sandstone.

Before substantial volumes of ground water were withdrawn from the Cambrian-Ordovician aquifer system, water levels in the St. Peter-Prarie du Chien-Jordan aquifer are estimated to have ranged from more than 900 feet below sea level in parts of northern Illinois to about 500 feet above sea level along the Mississippi River in west-central Illinois (fig. 53). The direction of ground-water movement, as shown by the arrows on figure 53, was from upland recharge areas toward discharge areas at major streams and Lake Michigan.
Ironon–Galesville Aquifer

The Ironon–Galesville aquifer is separated from the overlying St. Peter–Prairie du Chien–Jordan aquifer by dolomite and poorly sorted, fine-grained clastic rocks of the Frazier Formation and the Post Oakville (fig. 49). These low-permeability rocks are collectively known as the Evansville confining unit in northern Illinois. The Ironon–Galesville aquifer consists of the Ironon and the Galesville Sandstones of Cambrian age. These units are lithologically similar and generally consist of fine- to coarse-grained quartzose sandstone. They comprise the most productive aquifer of the Cambrian–Ordovician aquifer system in northern Illinois and yield much of the groundwater withdrawn in the Chicago area.

The sandstones of the Ironon–Galesville aquifer were not deposed to the southwest of a line that marks the limit of the aquifer in west-central Illinois (fig. 54). In central and eastern Illinois, the line that represents water in the aquifer that contains dissolved-solids concentrations of 15,000 milligrams per liter marks the practical limit of the aquifer.

The top of the Ironon–Galesville aquifer slopes from about 250 feet above sea level in northern Illinois to about 2,500 feet below sea level in the west-central part of the State (fig. 55). The average altitude of the top of the aquifer in Illinois is about 1,000 feet below sea level. The thickness of the aquifer ranges from more than 100 feet southwest of Chicago to zero at the depositional limit. The average thickness of the aquifer is about 150 feet in northern Illinois.

Estimated water levels (hydraulic head) for the Ironon–Galesville aquifer before the development of substantial ground-water supplies from the Cambrian–Ordovician aquifer system are shown in figure 56. Water levels were about 800 feet above sea level along the northern border of Illinois and less than 700 feet above sea level in the southern part of the area. Water levels were slightly higher in the Ironon–Galesville aquifer than those in the deeper Mount Simon aquifer along the Illinois–Wisconsin State line. Ground-water flow in the Ironon–Galesville aquifer generally was southeastward toward the Illinois Basin from recharge areas in Wisconsin.

Mount Simon Aquifer

The Mount Simon aquifer underlies the northern part of Illinois and the northeastern part of Indiana in Segment 10. It is separated from the Ironon–Galesville aquifer by low-permeability stratigraphic and shale of the Eau Claire Formation. These low-permeability rocks are known as the Eau Claire confining unit (fig. 49).

The Mount Simon aquifer consists of sandstone that contains water with a wide range of concentrations of dissolved solids (fig. 57). In Segment 10, only the upper part of the aquifer in northern Illinois contains freshwater. Dissolved-solids concentrations increase with depth (fig. 58) and toward the south and east. The line that shows dissolved-solids concentrations of 10,000 milligrams per liter on figure 57 marks the practical southeastern limit of the aquifer.

The top of the Mount Simon aquifer ranges from slightly above sea level to more than 2,000 feet below sea level (fig. 58). The depth to the top of the aquifer decreases toward the north; the aquifer crops out on the flanks of the Wisconsin Arch in Wisconsin. The average depth to the top of the aquifer in northern Illinois is about 800 feet below sea level.

The thickness of the Mount Simon aquifer in northern Illinois ranges from slightly less than 1,000 feet in northeastern Illinois to more than 2,500 feet southwest of Chicago. The average thickness is between 1,200 and 2,000 feet in northern Illinois. The Mount Simon aquifer is by far the thickest aquifer in the Cambrian–Ordovician aquifer system in Segment 10.

Estimated hydraulic heads (water levels) in the Mount Simon aquifer before substantial ground-water supplies were developed from the Cambrian–Ordovician aquifer system in northern Illinois are shown in figure 59. The predevelopment potentiometric surface is estimated to have been more than 800 feet above sea level northwest of Chicago and less than 700 feet above sea level to the south, east, and west. Ground-water movement was away from the high hydraulic heads (high water levels) toward lower heads (lower water levels) present along major rivers and Lake Michigan.

Ground-Water Quality

Most of the data on the quality of water from the Cambrian–Ordovician aquifer system in northern Illinois are from wells that are open to more than one aquifer in the system. Thus, the data represent the average quality of water from the entire system. The quality of water from the Cambrian–Ordovician aquifer system in northern Illinois generally is suitable for most uses. However, the water commonly is hard and might contain concentrations of dissolved solids, sulfates, and iron that exceed secondary maximum contaminant levels established by the U.S. Environmental Protection Agency for drinking water (fig. 60).

Water from 74 wells completed in the Cambrian–Ordovician aquifer system in northern Illinois had concentrations of dissolved solids that ranged from about 260 to 1,180 milligrams per liter, concentrations of hardness-causing constituents that ranged from about 250 to 430 milligrams per liter, sulfates concentrations that ranged from less than 10 (detection limit) to about 400 milligrams per liter, and iron concentrations that ranged from less than 50 (detection limit) to about 2,000 micrograms per liter (fig. 60).

The composite water that represents the Cambrian–Ordovician aquifer system is a calcium magnesium bicarbonate type in northern Illinois (fig. 61). Toward the south where aquifers are deeply buried, the water changes to a calcium magnesium bicarbonate chloride type; to the southwest, it changes to a sodium bicarbonate chloride type as it moves down the hydraulic gradient. Still further downgradient, the water changes to a sodium chloride type. Sulfates is one of the dominant dissolved constituents in the water in the aquifer system in a small part of west-central Illinois.
Fresh Ground-Water Withdrawals

Major areas of ground-water withdrawal from the Cambrian-Ordovician aquifer system in northern Illinois are shown in figure 62. The areas of largest withdrawal are near Chicago.

About 260 million gallons per day were withdrawn from the Cambrian-Ordovician aquifer system in northern Illinois during 1980. Of this amount, 69 percent, or about 177 million gallons per day, was withdrawn in an eight-county area around Chicago. The increase in water use from 1964 to 1980 in this area is shown in figure 63. Total ground-water withdrawals from the Cambrian-Ordovician aquifer system in northern Illinois were about 315 million gallons per day during 1985. It is estimated that the 1985 withdrawals from the aquifer system were about three times the recharge rate.

As a result of withdrawals in the Chicago, Ill., and Milwaukee, Wis., areas, the potentiometric surface of the Cambrian-Ordovician aquifer system in northern Illinois was nearly 35 million gallons per day, and about 6 million gallons per day was withdrawn for agricultural purposes (fig. 65). The large cones of depression around these pumping centers spread westward and northwestward to areas where the Maquoketa confining unit is absent. Where this confining unit has been removed by erosion, the upper part of the Cambrian-Ordovician aquifer system is in direct contact with the overlying surficial aquifer system in north-central Illinois and south-central Wisconsin. Where the two systems are in contact, the Cambrian-Ordovician aquifer system received large amounts of recharge from the shallower system, thus limiting the spread of the cones of depression. Beginning in the mid-1980’s, withdrawals from the Cambrian-Ordovician aquifer system declined as some users switched to water from Lake Michigan as a source of supply. Water levels in the aquifer system had begun to rise by 1985 as a result of the decreased withdrawals.

Fresh ground-water withdrawals from the Cambrian-Ordovician aquifer system totaled 315 million gallons per day during 1985. About 197 million gallons per day was withdrawn for public supply and about 77 million gallons per day was withdrawn for industrial, mining, and thermoelectric power purposes. Withdrawals for commercial and domestic needs were nearly 35 million gallons per day, and about 6 million gallons per day was withdrawn for agricultural purposes (fig. 65).

Figure 62. The Cambrian-Ordovician aquifer system is relied on for large ground-water supplies in northern Illinois. During 1985, average ground-water withdrawals were about 277 million gallons per day in an eight-county area around Chicago. Of this amount, about 177 million gallons per day was withdrawn from Cook County, which includes Chicago.

Figure 63. Average fresh ground-water withdrawals from the Cambrian-Ordovician aquifer system in the eight-county area around Chicago increased from about 120 million gallons per day during 1864 to about 260 million gallons per day during 1980.

Figure 64. As a result of large ground-water withdrawals from the Cambrian-Ordovician aquifer system from 1984 to 1985, the potentiometric surface of the aquifer system declined more than 600 feet around pumping centers west of Milwaukee (fig. 64). Beginning in the mid-1980’s, withdrawals from the aquifer system decreased as some users switched to water from Lake Michigan as a source of supply. Water levels in the aquifer system had begun to rise by 1985 as a result of the decreased withdrawals.

Figure 65. Fresh ground-water withdrawals from the Cambrian-Ordovician aquifer system in northern Illinois were about 177 million gallons per day during 1980. Public supply withdrawals accounted for about 63 percent of the total, industrial, mining, and thermoelectric power withdrawals accounted for about 24 percent of the total, and domestic and commercial withdrawals accounted for 13 percent of the total.
The Interior Low Plateaus aquifers in Segment 10 consist of the same two general categories of rocks as those in the Central Lowland Province—unconsolidated sand and gravel deposits of Quaternary age that compose the surficial aquifer system and consolidated limestones, dolomites, and sandstones of Paleozoic age (figs. 66 and 67). The surficial aquifer system is present only along the Ohio River Valley and a few of its tributaries in the northern part of the Interior Low Plateaus Province (fig. 66A), in contrast with the large area extent of the aquifer system in the Central Lowland Province. The principal aquifers in Paleozoic rocks are sandstone and limestone aquifers in rocks of Pennsylvanian age, limestones and dolomites aquifers in rocks of Devonian, Silurian, and Ordovician age (figs. 66B and 67).

The major hydrogeologic difference between the Interior Low Plateaus and the Central Lowland Provinces is the restricted distribution of the Quaternary deposits of the surficial aquifer system and the consequent exposure of the Paleozoic rocks throughout most of the Interior Low Plateaus. As a result, recharge and discharge from the aquifers in rocks of Paleozoic age take place directly in the Interior Low Plateaus Province, whereas they take place mostly through the Quaternary deposits in the Central Lowland Province. Precipitation is the primary source of recharge in the Interior Low Plateaus Province. Most of the precipitation becomes overland runoff to streams, but some percolates downward through soil and recharges the aquifer system near pumping wells. The distance of wells from rivers and streams and the type of underlying bedrock affect the chemical characteristics of the water from wells completed in the surficial aquifer system. Concentrations of dissolved solids, hardness-causing constituents (calcium and magnesium in particular), and, in some cases, sulfate are likely to be larger in water from wells in areas underlain by limestone than in water from wells near rivers and streams. The larger concentrations of these constituents might result from mixing of the water in the surficial aquifer system with more highly mineralized water that is discharged from the underlying limestone into the sand and gravel aquifers. The smaller concentrations might result from the mixing of ground water with less mineralized river water that recharges the aquifer system near pumping wells.

**SURFICIAL AQUIFER SYSTEM**

The sand and gravel deposits of Quaternary age along the Ohio River compose the principal aquifers in unconsolidated rocks in the Interior Low Plateaus Province in Segment 10. These aquifers, which are collectively called the surficial aquifer system, consist primarily of alluvium reworked from the Quaternary glacial sand and gravel deposits of the surficial aquifer system in the Central Lowland Province to the north. The distribution and approximate thickness of the Quaternary deposits in the Interior Low Plateaus Province are shown in figure 68. Typically, the lower two-thirds or more of the alluvial deposits consist of coarse sand and gravel that directly overlie bedrock. Three coarser-grained sediments form the principal aquifers in unconsolidated rocks. The upper part of the alluvial deposits consists of fine sand, silt, and clay. All or part of these fine-grained sediments may be unconsolidated. The saturated thickness of the Quaternary deposits increases from east to west along the Ohio River. In Kentucky, the saturated thickness is about 35 feet in Lewis County, about 80 feet around Louisville in Jefferson County, and about 110 feet in Henderson County. If all other factors remain the same, the amount of water an aquifer will yield increases in direct proportion to the saturated thickness of the aquifer.

Aquifer text characteristics and well yields

Aquifer test data from Kentucky indicate that median values of transmissivity for different areas of the surficial aquifer system along the Ohio River range from about 4,400 to 28,000 feet squared per day. The greater the transmissivity, the more ready a water can move through the aquifer system. The median specific capacities reported for 173 wells completed in different areas of the surficial aquifer system along the Ohio River in Kentucky range from about 14 to 115 gallons per minute per foot of water-level drawdown. These data indicate that large yields can be expected from wells completed in the sand and gravel aquifers, particularly where the saturated deposits are coarse-grained and thick. It is common for wells near the Ohio River to have sustained yields of 1,000 gallons per minute if they are completed in coarse-grained, well-sorted, thick alluvial deposits that are hydraulically connected to the river.

**Fresh Ground-Water Withdrawals**

During 1985, about 113 million gallons per day was withdrawn from wells completed in the surficial aquifer system in the Interior Low Plateaus Province in Segment 10. Most of the withdrawals were along the Ohio River in Kentucky. The 113 million gallons withdrawn from this aquifer is about 55 percent of the total fresh ground-water withdrawn in Kentucky during 1985. Almost three-fourths of the water withdrawn from the surficial aquifer system during 1985 was used for industrial, mining, and thermoelectric power purposes (fig. 70). Withdrawals for public supply were the second largest use category.
Fresh Ground-Water Withdrawals—Continued

The history of withdrawals in the Louisville area in Jefferson County, Ky., is an example of how the need for ground water can change through time (fig. 71). From 1937 to 1940, fresh ground-water withdrawals were about 40 million gallons per day in the Louisville metropolitan area. The use of ground water rose sharply until withdrawals were about 100 million gallons per day during 1943 and 1944 because of increased industrial activity during World War II. After the war, withdrawals declined to the point that only about 15 million gallons per day was withdrawn in Jefferson County during 1950. The total withdrawal that year was less than one-half the average annual withdrawal from 1946 to 1952.

Water levels in the surficial aquifer system in the Louisville area have risen in response to the decrease in ground-water withdrawals. The hydrograph shown in figure 72 illustrates the decline and rise of the water level in a well in northeastern Louisville from 1937 to 1963. The water level began to rise in 1962 and continued to rise until 1980. The rise was more than 50 feet in a small part of downtown Louisville, as shown by the map in figure 72, and caused some problems in the area. Perhaps more important problems were the erosion of basements because of water leaks and local damage to underground gas, electric, water, and sewer lines.

Well Yields have low permeability, small areal extent, and limited recharge. Typically, large water-level declines are accompanied by high costs of the energy used to pump the water.

Pennsylvanian Aquifers

Hydrogeologic Setting

Sandstones of Pennsylvanian age are the principal aquifers in consolidated rocks throughout most of the northeastern part of the Interior Low Plateau Province in Segment 10. These sandstones are part of the northwestern part of Kentucky (known as the Western Coal Field), southwestern Indiana, and part of the southern tip of Illinois (fig. 73). Where present, these sandstones are used as a source of water except where they are underclay, coal, and limestone. Sandstones are more common north of the Rough Creek Fault System than south of it, and shale, sandy shale, and limestone are more common south of the fault system than to the north.

Part of the precipitation that falls on the exposed Pennsylvanian rocks percolates downward to the water table to recharge the aquifers in these rocks. The water then moves through fractures and bedding planes in the rocks. The general direction of regional ground-water movement is toward the Ohio River and its tributaries. Most of the ground water moves along short flow paths through the shallow parts of the zone of saturation to discharge at near-streams. Some water discharges to springs and wells. In most places, the freshwater-saltwater interface in the Pennsylvanian aquifer is at depths of less than 500 feet below land surface. The sandstones, like those in the Cincinnae Formation, are more than 400 feet thick along the Ohio River, or more than 1,000 feet below land surface. The origin of this deep freshwater is unknown.

Aquifer Characteristics and Well Yields

Limited data from wells completed in the Pennsylvanian aquifers in Kentucky indicate well yields range from 0.5 to 150 gallons per minute and average about 25 gallons per minute. The median well yield is 9 gallons per minute.

Large water-level declines might result from small to moderate ground-water withdrawals in Pennsylvanian aquifers. Such declines are more probable in aquifers that have low permeability, small areal extent, and limited recharge. Water levels in the sandstone aquifers that lie at depths of greater than 500 feet below land surface and that are completely surrounded by rocks of low permeability are the most likely to show large declines. Typically, large water-level declines are accompanied by high costs of the energy used to pump the water.

Ground-Water Quality

Sparse data indicate that the aquifers in Upper Pennsylvanian rocks contain hard water that is a calcium-magnesium bicarbonate type. The calcium and magnesium in the water probably are derived from the partial dissolution of limonite beds or carbonate cements in sandstone beds.

The quality of the ground water from the sandstone aquifers in Lower Pennsylvanian rocks in the Interior Low Plateau Province generally is suitable for most uses. The water typically is soft and is a sodium bicarbonate type (fig. 76). In places, the water contains concentrations of iron that exceed 0.3 milligrams per liter. Water from wells deeper than 500 feet might contain concentrations of chloride that exceed 250 milligrams per liter. In places, dissolved-solids concentrations exceed 500 milligrams per liter. Saltwater locality is present in the Pennsylvanian aquifers at depths as shallow as 100 feet. The shallow saltwater usually is beneath the valleys of major streams.

Fresh Ground-Water Withdrawals

Only small quantities of freshwater are withdrawn from the sandstone aquifers in Pennsylvanian rocks in the Interior Low Plateau Province in Segment 10. Total withdrawals during 1985 were estimated to be about 10 million gallons per day, of which about 6 million gallons per day was withdrawn in Kentucky and about 2 million gallons per day was withdrawn in each of Illinois and Indiana. During 1985, 74 percent of the water withdrawn from these aquifers in Kentucky was used for domestic and commercial purposes, and 18 percent was withdrawn for industrial, mining, and thermoelectric power uses (fig. 77). Practically all the remaining withdrawals were for public supply.

Pennsylvania Geologic Society
MISSISSIPPIAN AQUIFERS

Hydrogeologic Setting

A large part of the Interior Low Plateaus Province in Segment 10 is underlain by limestone aquifers in Mississippian rocks (fig. 78). These aquifers have been called the Mississippian Plateau aquifers in Kentucky and the Highland Rim aquifer system in Tennessee. They are present in limestone that is either flat lying or gently dipping and are capped by a layer of regolith that varies greatly in thickness. In general, the limestone aquifers yield the largest quantities of water to wells and springs.

In most places, the Mississippian aquifers are covered by regolith, which mostly consists of weathered material, or residuum (fig. 80). This material consists of clay, silt, sand, and pebble-sized particles of limestone or chert, which are derived mostly from weathering of the underlying bedrock. In the southwestern part of central Tennessee, the regolith might consist mostly of silt left from the weathering of the Fort Payne Formation. Where thick and saturated, this chert rubble constitutes a productive local aquifer. The regolith can store large quantities of water that subsequently percolate slowly downward to recharge aquifers in the underlying consolidated rock. The regolith is as thick as 150 feet in several places in the Interior Low Plateaus Province in Tennessee.

Pervious gravel layers in the regolith store water, which percolates downward to recharge groundwater in the underlying, unconsolidated residuum. Water entering the regolith moves through intergranular spaces in the unconsolidated material of the regolith. However, in the underlying limestone bedrock, the water moves through zones of secondary permeability created by dissolution enlargement of bedding planes and fractures by the slightly acidic water. The solution openings store and transmit most of the water that moves through the limestone and discharges to streams, springs, and wells. Little water passes through the blocks of limestone between the bedding planes and fractures.

Figure 78. Rocks of Mississippian age underlie a large part of the Upper Low Plateaus Province. Typical major aquifers are the principal aquifers in these rocks primarily in the Upper Mississippian limestones.

The Mississippian aquifers are the principal aquifers in the Appalachian Plateau and the Interior Low Plateaus Province in Tennessee. They are present in limestone that underlies many local horizontal and vertical components. Most of the water that moves through the limestone and percolates downward to the water table, which marks the top of the zone of saturation. The water moves through intergranular spaces in the unconsolidated material of the regolith. However, in the underlying limestone bedrock, the water moves through zones of secondary permeability created by dissolution enlargement of bedding planes and fractures by the slightly acidic water. The solution openings store and transmit most of the water that moves through the limestone and discharges to streams, springs, and wells. Little water passes through the blocks of limestone between the bedding planes and fractures.

Figure 80. In general, regolith that consists mostly of unconsolidated residuum near the surface is the most productive in the area. Ground-water percolation dissolves through the unconsolidated regolith and then moves through fractures, bedding planes, and solution openings in the limestone to eventually discharge to springs and streams.

Figure 81. Fresh ground water circulates to depths as great as 500 feet below land surface in the Mississippian aquifers. Most of the discharge circulation is at depths of less than 100 feet. The level of this section is shown in figure 78.

The altitude and configuration of the potentiometric surface and the general direction of ground-water movement in the Mississippian aquifers (the St. Genevieve and the St. Louis Limestones) in western Kentucky are shown in figure 82. The altitude of the potentiometric surface ranges from less than 400 feet above sea level in the west to more than 500 feet above sea level in three small areas in the east. However, little, if any, regional ground-water flow occurs. Most of the flow is local, toward springs and the few streams that drain the area. An escarpment that bounds the aquifer on the north is aptly named the "Dripping Springs Escarpment" because of the many small springs and springs that discharge water along it.

Water in the Mississippian aquifers generally moves in a direction perpendicular to the potentiometric contour, as shown by the arrows in figure 82. However, the water locally moves along fractures and bedding planes that might be nearly perpendicular to one another. Consequently, the arrows that show ground-water flow direction indicate only the general direction of water movement in a complex flow system that has many local horizontal and vertical components.
Effects of Dissolution

An idealized diagram of some of the common types of features that develop on the land surface where Mississippian limestones are exposed and are partially dissolved by circulating, slightly acidic ground water is shown in Figure 83. Recharge water enters the limestone aquifers through sinkholes, swallow holes, and sinking streams. Stream density, as measured by the total length of perennial streams in a square mile, is low in areas underlain by the limestone; this indicates that most of the surface runoff is quickly routed underground through solution openings in the rocks. In the subsurface, most of the water moves through caverns and other types of large solution openings.

An excellent example of the extent and interconnection of large solution cavities that form as a result of the dissolution of limestone by circulating freshwater is the Mammoth Cave area in Kentucky (Fig. 84). The Mississippian limestones that underlie the Mammoth Cave Plateau are riddled with sinkholes and solution cavities that have developed along bedding planes and joints. Some of these solution openings form the large caves that have fascinated visitors and area residents since pioneer times (Fig. 85). As the network of caverns and sink­

des continues to develop, surface streams might be diverted into sinkholes and flow through the larger solution openings or underground streams. Sand and other sediment carried by the underground streams abrade the limestone; this further enlarges the opening through which the stream flows. The solution openings in the limestone are so well developed in the Mammoth Cave area that most surface runoff enters the rocks through sinkholes and moves through solution cavities to springs (Fig. 86). Accordingly, stream density in the area is low. Most of the water moves rapidly downward through enlarged, well-connected solution openings to the main water table and then moves laterally to discharge from springs into the Green River. Some of the solution openings are large enough to contain underground streams, such as Echo River (Fig. 87). However, some of the water moves more slowly through openings that are small and poorly interconnected; for example, small quantities of water move slowly through interstratified spaces and small fractures in the Big Clifty Sandstone Member of the Golconda Formation. Larger quantities of water move more rapidly through small openings. In some parts of the limestone of the underlying Girkin Formation, and very large quantities of water move rapidly through a large network of solution openings in the Ste. Genevieve and the St. Louis Limestones (Fig. 86). Discontinuous layers of shale in the Girkin Formation impede the downward movement of water where the shales are present and help support perched water bodies. The top of the perched water bodies might be 300 feet or more above the main water table. The presence or absence of solution openings affects aquifer recharge and discharge in the Mammoth Cave area and is reflected in the way in which water moves in wells completed in different aquifers. The Mississippian limestone aquifers are underlain by the Big Clifty Sandstone Member of the Golconda Formation (Fig. 86), which is a rock unit with few large openings. The water levels in this well show that recharge to the Big Clifty is rapid and mostly takes place from late winter to early spring. Most of the water discharges to springs, but most of the stream flows gradually into deeper aquifers during the rest of the year. When the hydraulic head (water level) in the Big Clifty is high, the water slowly drains into the rocks below, but as the water level continues to decline, the water drains more and more slowly. In contrast, the water level in the Ste. Genevieve and the St. Louis Limestones (Fig. 86), which are characterized by an abundance of well-connected solution openings, drops rapidly depending on antecedent conditions, the season of the year, and local precipitation. The water level in the well at CCC No. 2 showed almost no change during dry weather and after light summer rain, however, following periods of greater-than-normal precipitation (Fig. 88C), the water level rose sharply. This water-level response indicates that the well at CCC No. 2 is open to solution openings in the Ste. Genevieve limestone. These openings allow rapid recharge to and equalized rapid discharges from the aquifer during and immediately following periods of intense precipitation.

Aquifer Characteristics, Yields of Wells, and Discharges of Springs

The hydraulic characteristics of the Mississippian aquifers vary greatly over short distances. For example, the ability of limestone with large, interconnected solution openings to transmit and yield water is several orders of magnitude greater than that of the almost impermeable blocks of limestone between solution openings, fractures, and bedding planes. These large differences are reflected in the yield and specific capacity of wells completed in the Limestone aquifers and the discharges of springs issuing from solution openings.

The data in Table 1 indicate that the yields of wells completed in the Mississippian aquifers vary greatly. Well yields commonly range from 2 to 50 gallons per minute, and reported maximum yields range from about 100 gallons per minute in Illinois to 1,000 gallons per minute in Illinois. Wells that penetrate large, saturated solution openings may yield several thousands of gallons per minute. However, such openings constitute only a small part of the rock and might be difficult to locate.

<table>
<thead>
<tr>
<th>State</th>
<th>Range of Yields of Wells Completed in Mississippian Aquifers (gallons per minute)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Illinois</td>
<td>2 to 50: 1,000</td>
</tr>
<tr>
<td>Indiana</td>
<td>1 to 25: 100</td>
</tr>
<tr>
<td>Kentucky</td>
<td>1 to 10: 500</td>
</tr>
<tr>
<td>Tennessee</td>
<td>1 to 50: 400</td>
</tr>
</tbody>
</table>

The data indicate that well yields commonly range from 2 to 50 gallons per minute, and reported maximum yields range from about 100 gallons per minute in Illinois to 1,000 gallons per minute in Illinois. Wells that penetrate large, saturated solution openings may yield several thousands of gallons per minute. However, such openings constitute only a small part of the rock and might be difficult to locate.
Aquifer Characteristics, Yields, and Discharges of Springs—Continued

The discharges of 31 selected springs that issue from Mississippian aquifers in the western part of the Interior Low Plateau Province in Tennessee range from about 3 to 1,100 gallons per minute, with a median discharge of about 200 gallons per minute (fig. 89). These springs issue mainly from the Warrick Limestone and the Fort Payne Formation, and those that discharge several hundred gallons per minute or more are equally distributed between the Warrick and the Fort Payne. These data indicate that discharge can vary from spring to spring.

The distribution of discharges for six large springs in Kentucky is shown in figure 90. These springs issue primarily from the St. Louis Limestone. These discharges, which were measured from 1951 to 1968, indicate the variability from spring to spring and through time at a given spring. The difference between the high and low discharges measured at a spring varies by a factor of about 5 to about 250. Knowledge of such discharge variability is important when planning the use of springs for water supply. Discharges of the springs shown in figure 90 are more variable than those of the springs shown in figure 90A.

Ground-Water Quality

The quality of water in the Mississippian aquifers in Kentucky is somewhat different from that in Tennessee (fig. 91). The range of concentrations and the median concentration of dissolved solids, iron, and the median hardness are greater for water from these aquifers in Kentucky than in Tennessee. However, median concentrations of dissolved solids and iron in both States are less than the secondary maximum contaminant levels for drinking water established by the U.S. Environmental Protection Agency. The quality of the water generally is adequate, or it can be treated and made adequate for most uses.

Water-quality data from wells and springs in the Mississippian aquifers in Kentucky (fig. 92) and from wells from the St. Louis Limestone (fig. 93) indicate that the water is either a calcium magnesium bicarbonate type or a calcium bicarbonate type. The water type changes slightly as the proportion of magnesium and sulfate vary. Chemical analyses of water from wells and springs in the St. Louis Limestone were selected to represent the quality of water in the Mississippian aquifers in Kentucky (fig. 93). Water from wells (fig. 90A) has a larger proportion of magnesium and sulfate and a slightly larger proportion of chloride than that from springs (fig. 90B). Sulfate data from wells and springs in Tennessee indicate that the quality of the water in the Mississippian aquifers is similar to that of Mississippian aquifer spring water in Kentucky.

Ground water with the large concentrations of sulfate is from wells that penetrate anhydrite and gypsum beds in the deeper parts of the Mississippian aquifers in Kentucky. The water moves slowly and follows low flow paths in the deep parts of the aquifers; therefore, the water is in contact with the aquifer minerals for a long time and dissolves much mineral material. In contrast, water that discharges from springs and water from wells that penetrate only shallow parts of the aquifers have smaller concentrations of dissolved solids because the water has moved only short distances or has had limited residence time in the aquifers and thus has had little opportunity to dissolve minerals.

Contaminated and turbid water are problems that can plague the users of water from wells and springs in limestone aquifers. Stalkholes are sometimes used to dispose of solid and liquid wastes. Water that recharges limestone aquifers through waste-filled sinksholes can transport contaminants into the aquifer, and the contaminated water can spread rapidly through a system of interconnected solution openings until it reaches wells or springs. Solution features, such as swallow holes, in streambeds allow sediment-laden storm runoff to enter the aquifers directly. Turbid water also can be caused by pumping of large-capacity wells, which results in the rapid movement of water through solution openings filled with silt or clay. Contamination and turbidity problems can become worse during periods of prolonged, intense rainfall.

Fresh Ground-Water Withdrawals

Total fresh ground-water withdrawals during 1985 from the Mississippian aquifers in the Interior Low Plateau part of Segment 10 were about 64 million gallons per day (table 2). No 1985 withdrawal data were available for the Mississippian aquifers in Illinois; therefore, 1980 withdrawals were used for comparison. About 80 percent of the total withdrawals were in Tennessee and Kentucky where the Mississippian aquifers are most areally extensive. Ground-water withdrawals in Tennessee and Kentucky were primarily for public supply and domestic and commercial uses (fig. 93). These use categories accounted for about 73 percent of the total withdrawals in Tennessee and about 52 percent in Kentucky during 1985. The remaining withdrawals were for agricultural and industrial and mining purposes. No water was withdrawn from the Mississippian aquifers in Tennessee and Kentucky for thermoelectric power use during 1985.

Table 2. The Mississippian aquifers are an important source of fresh ground water in the Interior Low Plateau part of segment 10. About one third of the water withdrawn from these aquifers was used in Tennessee and about one quarter was used in Kentucky.

<table>
<thead>
<tr>
<th>State</th>
<th>Ground water withdrawn from limestone aquifers in Mississippian rocks (estimated in millions of gallons per day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Illinois</td>
<td>6b</td>
</tr>
<tr>
<td>Indiana</td>
<td>4b</td>
</tr>
<tr>
<td>Kentucky</td>
<td>16b</td>
</tr>
<tr>
<td>Tennessee</td>
<td>33b</td>
</tr>
<tr>
<td>Total</td>
<td>64</td>
</tr>
</tbody>
</table>

Figure 89. The discharges of 31 selected springs that issue from Mississippian aquifers in the western part of the Interior Low Plateau Province in Tennessee range from about 3 to 1,100 gallons per minute, with a median discharge of about 200 gallons per minute (fig. 89). These springs issue mainly from the Warrick Limestone and the Fort Payne Formation, and those that discharge several hundred gallons per minute or more are equally distributed between the Warrick and the Fort Payne. These data indicate that discharge can vary from spring to spring.

Figure 90. The discharges of six large springs in Kentucky are shown in figure 90. These springs issue primarily from the St. Louis Limestone. These discharges, which were measured from 1951 to 1968, indicate the variability from spring to spring and through time at a given spring. The difference between the high and low discharges measured at a spring varies by a factor of about 5 to about 250. Knowledge of such discharge variability is important when planning the use of springs for water supply. Discharges of the springs shown in figure 90 are more variable than those of the springs shown in figure 90A.

Figure 91. Water from the Mississippian aquifers in Kentucky and Tennessee is hard water that contains relatively large concentrations of ions in some samples. Dissolved solids concentrations generally are larger in water from the aquifers in Kentucky than from those in Tennessee.

Figure 92. Water from selected wells completed in the Mississippian aquifers in Kentucky is a calcium magnesium bicarbonate type (A). Water from springs that issue from the aquifer is a calcium bicarbonate type (B).

Figure 93. During 1985, about 92 percent of the fresh ground water withdrawn from the Mississippian aquifers was used for public supply and for commercial and domestic purposes in Kentucky. About 73 percent of the water withdrawn from these aquifers in Tennessee was used for the same purposes. Much more water was withdrawn for agricultural and for industrial and mining uses in Tennessee than in Kentucky during 1985.
DEVENSIAN, SILLURIAN, AND ODORVICIAN AQUIFERS

Hydrogeologic Setting

Carbonate rocks of Devonian, Silurian, and Ordovician age, which are approximately lithologically similar, are the principal aquifers in large areas of central Kentucky and central Tennessee in the Interior Low Plateau Province in Segment 10 (fig. 94). The Devonian rocks crop out in the central part of these areas and are beneath Silurian and Ordovician rocks on the periphery of the province. The Devonian carbonate rocks consist of almost pure limestone and minor dolomite and are interlayered with confining units of shale and shaly limestone. Where these aquifers are in the subsurface, they are overlain and separated from the Mississippian aquifers by a confining unit of Upper Devonian shale.

The middle portion of the carbonate rocks are in Ordovician rocks. The Middle Ordovician High Bridge and Stones River Groups and the Lexington Limestone and equivalent rocks are the most important carbonate-rock aquifers (fig. 95). Locally, the Upper Ordovician Grant Lake and the Callaway Creek Limestones and calcarceous shales of the Middle Ordovician Nashville Group yield small volumes of water, but these units are not considered to be principal aquifers. The Middle Ordovician High Bridge and Stones River Groups and the Lexington Limestone and equivalent rocks are interlayered with confining units of shale and shaly limestone and dolomite. The Ordovician rocks compose the aquifers in Devonian rocks. These geologic formations, excluding the Knox Group, have been referred to as the "Central Basin aquifer system" in Tennessee and the "aquifers of the Blue Grass region" in Kentucky.

The depth of freshwater in the limestone and dolomite aquifers can vary greatly, but wells completed in these aquifers generally range from 50 to 200 feet deep in Kentucky and Tennessee (table 3). The depth to saltwater generally is greater in areas where the limestone and dolomite aquifers crop out and extend where they are covered with younger rocks that impede deep circulation of ground water. In a large area in central Tennessee, the upper parts of these aquifers are beneath a thin layer of Mississippian limestone or the Chattanooga Shale of Mississippian and Devonian age or both (fig. 96) and contain freshwater. The upper part of Lower Ordovician rocks in central Tennessee (the Knox Group) also contains freshwater but is separated from the shallower aquifers by a Middle Ordovician confining unit that contains a highly mineralized water. The Knox Group in this area apparently is recharged through fractures that traverse the confining unit. The freshwater-saltwater interface in the Knox Group does not coincide with that in the shallower aquifers.

The occurrence and movement of ground water in the limestone and dolomite aquifers in Kentucky, Silurian, and Devonian rocks are similar to those in the Mississippian aquifers. However, where the Devonian, Silurian, and Ordovician rocks generally contain small quantities of insoluble material, the aquifers in these rocks are generally ovend in by the zone of dynamic circulation above the basin. In areas where these rocks are continuous, the downward movement of water is restricted. This restriction isolates the ground water below the basin from the zone of dynamic circulation above the basin. In areas where the basin is pierced by vertical fractures or has been eroded by stream valleys, ground water below the basin is more readily discharged and is part of the zone of dynamic circulation. In such places, solution-enlarged openings will develop beneath the basin.

Ground water in the limestone and dolomite aquifers moves from upland recharge areas where water-level altitudes are high to low-lying discharge areas where they are low. Most of the discharge areas are located along streams. In Kentucky, the streams that receive discharge from the carbonate-rock aquifers generally drain to the north and northwest into the Ohio River. Areas underlain by the freshwater-yielding limestone and dolomite aquifers in Tennessee are drained by the Cumberland and the Tennessee Rivers.
Yield of Wells and Discharges of Springs

The yields of wells completed in the limestone and dolomite aquifers in rocks of Devonian, Silurian, and Ordovician age vary considerably throughout the area. This variability is caused primarily by large variations in hydraulic properties over short distances in the aquifers. The yields of wells completed in the carbonate-rock aquifers in Kentucky and Tennessee commonly range from 2 to 20 gallons per minute and can exceed 300 gallons per minute (Table 4). Yields reported from 8,000 wells, drilled primarily to supply water for households and completed in limestone aquifers in Ordovician rocks in Tennessee, indicate that more than 90 percent of the wells obtained a supply of ground water adequate for domestic use: 70 percent had yields of more than 3 gallons per minute, 8 percent had yields of more than 25 gallons per minute, and slightly less than 1 percent had yields of 50 gallons per minute or more. The maximum well yield was 600 gallons per minute. About 90 percent of the wells that had yields of more than 25 gallons per minute were located in flat-bottomed valleys underlain by depressions in the carbonate bedrock.

Spring discharge also is extremely variable. Discharges reported for 89 springs that issue from aquifers in the Silurian and Ordovician rocks in the south-central part of Tennessee range over more than four orders of magnitude (from 0.1 to about 2,500 gallons per minute) with a median discharge of about 6 gallons per minute. From 1951 to 1990, the reported discharge of four large springs that issue from the limestone in Kentucky ranged over more than three orders of magnitude (Fig. 98). Two of the springs issue from aquifers in Silurian rocks (Fig. 98A) and had discharges that ranged from 300 to 40,000 gallons per minute. The other two springs issue from aquifers in Ordovician rocks (Fig. 98B) and had discharges that ranged from 75 to 9,500 gallons per minute. These data indicate that discharge can vary greatly at a spring from season to season and from year to year.

Ground-Water Quality

The quality of the water in the limestone and dolomite aquifers in Ordovician rocks in Kentucky and Tennessee is shown in Figure 99. Sparse data indicate that the quality of water in the Devonian and Silurian carbonates is similar. The range and median concentrations of dissolved solids, hardness, and iron are larger in Kentucky than in Tennessee. However, the median concentrations for the constituents shown generally are equal to or less than the second maximum contaminant levels for drinking water established by the U.S. Environmental Protection Agency. The quality of the water generally is adequate, or it can be treated and made adequate for most uses.

The water from Ordovician aquifers in Kentucky is a hard, calcium magnesium bicarbonate type (Fig. 100). The absence of these dominant ions results primarily from dissolution of the carbonate rocks as slightly acidic recharge water moves through the aquifers.

The quality of the water from wells completed in the Ordovician aquifer in Kentucky (Fig. 100A) and from springs that issue from the same aquifer (Fig. 100B) is similar. The concentrations of constituents in the Devonian and Silurian aquifers probably are similar to those in water from the Ordovician aquifers. Dissolved solids concentrations generally are larger in water from wells than from springs (Fig. 100). In addition, the water from wells contains larger concentrations of chloride, sodium, and potassium than the spring water.

As with the Mississippiian aquifers, contaminated and turbid waters are common problems for the users of water from the limestone and dolomite aquifers in Devonian, Silurian, and Ordovician rocks in Kentucky and Tennessee. The thin soil and mineral soil at the surface of solution features, such as sinkholes, swallow holes, and solution-entrenched fractures, allow water from the land surface to recharge the aquifer quickly and rapidly. Contaminated and sediment-laden waters can then spread rapidly through the system of interconnected solution openings to eventually reach wells and springs.

Fresh Ground-Water Withdrawals

More fresh ground water is withdrawn from the limestone and dolomite aquifers in Kentucky than in Tennessee. About 22 million gallons per day were withdrawn from these aquifers in Tennessee and about 12 million gallons per day were withdrawn in Kentucky during 1985 (Fig. 101). During the same year, about 93 percent of the ground water withdrawn in Tennessee (about 21 million gallons per day) and about 99 percent of that withdrawn in Kentucky (nearly 12 million gallons per day) were pumped for public-supply, domestic, and commercial, and agricultural uses. Most of the withdrawals in both States were for domestic and commercial purposes. Withdrawals for domestic and commercial uses during 1985 amounted to about 13 million gallons per day in Tennessee and about 10 million gallons per day in Kentucky. Public supply withdrawals were about 4 million gallons per day in Tennessee and about 1 million gallons per day in Kentucky. Withdrawals for agricultural purposes during 1985 amounted to about 4 million gallons per day in Tennessee and about 1 million gallons per day in Kentucky. The remainder of the withdrawals during 1985 were for industrial and mining uses and were greater than 1 million gallons per day in Tennessee but less than 100,000 gallons per day in Kentucky. No water was withdrawn for thermoelectric power purposes in either State.

Table 4. Yields of wells in limestone and dolomite rocks in Kentucky and Tennessee commonly range between 2 and 20 gallons per minute and might exceed 300 gallons per minute

<table>
<thead>
<tr>
<th>State</th>
<th>Common</th>
<th>May</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kentucky</td>
<td>2 to 10</td>
<td>3</td>
</tr>
<tr>
<td>Tennessee</td>
<td>5 to 20</td>
<td>36</td>
</tr>
</tbody>
</table>

Figure 99. Water from the limestone and dolomite aquifers in Ordovician rocks in Kentucky and Tennessee commonly is hard and can contain large concentrations of dissolved solids, chloride, and iron.

Figure 100. Well and spring waters from the Ordovician aquifer in Kentucky are a calcium magnesium bicarbonate type. The quality of the water in the Devonian and Silurian aquifers probably is similar to that in the Ordovician aquifers. Water from wells generally contains larger concentrations of dissolved solids than the spring water.
INTRODUCTION

The part of the Appalachian Plateau Physiographic Province included in Segment 10 is present in the eastern parts of Ohio, Kentucky, and Tennessee (fig. 102). The eastern boundary of the province coincides with the Cumberland Front Escarpment in Kentucky and Tennessee. North of the escarpment, the province extends into the western parts of Virginia, West Virginia, and Maryland and into western and northern Pennsylvania, all of which are described in Segment 11 of this Atlas. The part of the province that extends into western and southern New York is discussed in Segment 12 of this Atlas. The province extends southward into northeastern Alabama and northeastern Georgia for a short distance; this extension is described in Segment 6 of this Atlas. The western boundary of the province in Segment 10 approximately coincides with the contact between Devonian and Mississippian rocks in northeastern Kentucky and Ohio and with the contact between Mississippian and Pennsylvanian rocks farther south.

Aquifers in the Appalachian Plateau Physiographic Province can be divided into two categories — the surficial aquifer system in unconsolidated deposits and the aquifers in consolidated rocks. The surficial aquifer system consists of alluvial deposits that are highly permeable, yield more water than wells completed in the sand and gravel deposits of the consolidated aquifers, and their locations are easy to predict because they are located at or near land surface. These deposits cover the northern part of the province coincides with the Cumberland Front Escarpment. The line of the section shown in figure 105 has been pushed westward along the Pine Mountain Thrust Fault. A deep well drilled on the Pine Mountain Thrust Fault Block might penetrate the Pennsylvania-Devonian sediment sequence twice.

HYDROGEOLOGIC UNITS

Surficial Aquifer System

The surficial aquifer system consists of sand and gravel deposits of glacial and alluvial origin. Some of the glacial material was deposited directly by the ice, and some was transported by meltwater. The coarse-grained glacial material that constitutes productive aquifers was deposited as alluvium, which filled bedrock valleys, and as kame deposits surrounded by or buried beneath glacial till. The alluvial material is present along present-day streams and consists mostly of reworked glacial deposits. Aquifers that consist of sand and gravel beds in the glacial and alluvial deposits are locally present throughout eastern Ohio and in northeastern Kentucky along the Ohio River (fig. 106). Wells completed in the sand and gravel deposits, which are highly permeable, yield more water than wells completed in any of the other aquifers in the Appalachian Plateau Province. As a result, ground-water development in Ohio has primarily focused on the coarse-grained alluvial and glacial deposits.

The aquifers of the surficial aquifer system are of two types — alluvium that is in present-day stream valleys and glacial drift that occurs in valley- and upland-terrace deposits in bedrock valleys. Some kame deposits consist of sand and gravel surrounded by or buried beneath poorly permeable glacial till. In many stream valleys, stratified glacial drift, consisting of sand, gravel, and clay, was deposited by meltwater as the glaciers retreated. Today, most of these valleys are occupied by perennial streams. Sand and gravel deposits in the valleys are the primary aquifer materials, and their locations are easy to predict because they are located at or near land surface. These deposits range in thickness from 20 to 200 feet in thickness but may exceed 300 feet in large stream valleys. The kame deposits commonly range from 50 to 200 feet in thickness (fig. 106). The kame deposits are generally less than 100 feet thick, and the occurrence of sand and gravel aquifers is difficult to locate.

Aquifers in the Appalachian Plateau Physiographic Province can be divided into two categories — the surficial aquifer system in unconsolidated deposits and the aquifers in consolidated rocks. The surficial aquifer system consists of alluvial deposits that are highly permeable, yield more water than wells completed in the sand and gravel deposits of the consolidated aquifers, and their locations are easy to predict because they are located at or near land surface. These deposits cover the northern part of the province coincides with the Cumberland Front Escarpment. The line of the section shown in figure 105 has been pushed westward along the Pine Mountain Thrust Fault. A deep well drilled on the Pine Mountain Thrust Fault Block might penetrate the Pennsylvania-Devonian sediment sequence twice.

Figure 103. The principal aquifers in the Appalachian Plateau Province. In Segment 10, the surficial aquifer system in unconsolidated deposits and the aquifers in consolidated rocks of Mississippian age. The gray areas represent missing rocks.

Figure 104. Generally, the Pleistocene rocks dip toward the east in the northern part of the Appalachian Plateau Province. The line of the section shown in figure 102 is the Appalachian Plateau Province boundary.

Figure 105. Movement along faults such as the Pine Mountain Thrust Fault has emplaced older rocks atop younger ones in some of the southern parts of the Appalachian Plateau Province. Such movement can cause parts of the geologic section to be repeated. The line of the section is shown in figure 102.

Figure 106. The surficial aquifer system is present in eastern Ohio and locally in northeastern Kentucky along the Ohio River Valley, and consists of deposits of glacial and alluvial origin. Sand and gravel deposits in the valleys are the primary aquifer materials, and their locations are easy to predict because they are located at or near land surface. These deposits range in thickness from 50 to 200 feet in thickness but may exceed 300 feet in large stream valleys. The kame deposits commonly range from 50 to 200 feet in thickness (fig. 106). The kame deposits are generally less than 100 feet thick, and the occurrence of sand and gravel aquifers is difficult to locate.

Figure 102. Consolidated rocks of Pennsylvanian and Mississippian ages form aquifers in the Appalachian Plateau Physiographic Province in Segment 10. Geologic sections in this segment show where Pennsylvanian and Mississippian rocks are present or are covered by Quaternary deposits, and display the consolidated rock aquifers in northeastern Ohio.
Pennsylvanian Aquifers

Pennsylvanian aquifers in the Appalachian Plateau Province mostly consist of sandstone and limestone that are parts of repeating sequences of beds deposited during multiple sedimentary cycles. A complete, ideal cycle consists of the following sequence of beds, listed from bottom to top: underclay, coal, gray shale or black shale, freshwater limestone, and sandstone or silt shale. Not all the beds listed are present in each cycle. The sandstones and limestones are the most productive aquifers. Sandstone aquifers also are present in rocks of Permian age. In the following description, rocks of Pennsylvanian age are grouped into Upper Pennsylvanian aquifers and Middle and Lower Pennsylvanian aquifers, water-yielding rocks of Permian age are discussed with the Upper Pennsylvanian aquifers.

Upper Pennsylvanian aquifers mostly are present in the Pennsylvania Monongahela and Connellsville Groups but also are present in the sandstones of the Pittsburgh, Black Hawk, and Leonard Formations. Lower Pennsylvanian aquifers include the Allegheny Formation and the Kittanning and Kittanning-Pottsville Groups in Ohio, the Blountville Formation in Kentucky, and several equivalent formations in Tennessee (fig. 103). The Allegheny Formation and the Pottsville Group are primarily interbedded sandstones, siltstones, and shales, whereas the Lee Formation is predominantly sandstone so that by some geologists the Mississippian rocks are considered to be a separate group. These rocks are considered to be a separate group. The Allegheny Formation and the Kittanning-Pottsville Groups are primarily interbedded sandstone, siltstone, and shale, whereas the Lee Formation is predominantly sandstone so that by some geologists the Mississippian rocks are considered to be a separate group. These rocks are considered to be a separate group. The Allegheny Formation and the Kittanning-Pottsville Groups are primarily interbedded sandstone, siltstone, and shale, whereas the Lee Formation is predominantly sandstone so that by some geologists the Mississippian rocks are considered to be a separate group. These rocks are considered to be a separate group. The Allegheny Formation and the Kittanning-Pottsville Groups are primarily interbedded sandstone, siltstone, and shale, whereas the Lee Formation is predominantly sandstone so that by some geologists the Mississippian rocks are considered to be a separate group. These rocks are considered to be a separate group. The Allegheny Formation and the Kittanning-Pottsville Groups are primarily interbedded sandstone, siltstone, and shale, whereas the Lee Formation is predominantly sandstone so that by some geologists the Mississippian rocks are considered to be a separate group. These rocks are considered to be a separate group. The Allegheny Formation and the Kittanning-Pottsville Groups are primarily interbedded sandstone, siltstone, and shale, whereas the Lee Formation is predominantly sandstone so that by some geologists the Mississippian rocks are considered to be a separate group. These rocks are considered to be a separate group. The Allegheny Formation and the Kittanning-Pottsville Groups are primarily interbedded sandstone, siltstone, and shale, whereas the Lee Formation is predominantly sandstone so that by some geologists the Mississippian rocks are considered to be a separate group. These rocks are considered to be a separate group. The Allegheny Formation and the Kittanning-Pottsville Groups are primarily interbedded sandstone, siltstone, and shale, whereas the Lee Formation is predominantly sandstone so that by some geologists the Mississippian rocks are considered to be a separate group. These rocks are considered to be a separate group. The Allegheny Formation and the Kittanning-Pottsville Groups are primarily interbedded sandstone, siltstone, and shale, whereas the Lee Formation is predominantly sandstone so that by some geologists the Mississippian rocks are considered to be a separate group. These rocks are considered to be a separate group. The Allegheny Formation and the Kittanning-Pottsville Groups are primarily interbedded sandstone, siltstone, and shale, whereas the Lee Formation is predominantly sandstone so that by some geologists the Mississippian rocks are considered to be a separate group. These rocks are considered to be a separate group. The Allegheny Formation and the Kittanning-Pottsville Groups are primarily interbedded sandstone, siltstone, and shale, whereas the Lee Formation is predominantly sandstone so that by some geologists the Mississippian rocks are considered to be a separate group. These rocks are considered to be a separate group. The Allegheny Formation and the Kittanning-Pottsville Groups are primarily interbedded sandstone, siltstone, and shale, whereas the Lee Formation is predominantly sandstone so that by some geologists the Mississippian rocks are considered to be a separate group. These rocks are considered to be a separate group. The Allegheny Formation and the Kittanning-Pottsville Groups are primarily interbedded sandstone, siltstone, and shale, whereas the Lee Formation is predominantly sandstone so that by some geologists the Mississippian rocks are considered to be a separate group. These rocks are considered to be a separate group. The Allegheny Formation and the Kittanning-Pottsville Groups are primarily interbedded sandstone, siltstone, and shale, whereas the Lee Formation is predominantly sandstone so that by some geologists the Mississippian rocks are considered to be a separate group. These rocks are considered to be a separate group. The Allegheny Formation and the Kittanning-Pottsville Groups are primary...
Aquifers in Consolidated Rocks

The principal factors that govern the chemical quality of ground water in the aquifers in consolidated rocks are aquifer mineralogy and residence time (the amount of time the water has been in contact with the rocks). Water from sandstone aquifers that contain few soluble minerals generally is soft, whereas hard water is obtained from limestone or shale that contain a great variety of soluble minerals. In sandstone, water in the deeper parts of the aquifer tends to be more mineralized than water from shallow depths because the deeply circulating water generally has followed longer flow paths and has been in contact with aquifer minerals for a longer period of time. Generally, water from wells located in recharge areas or on ridges is less mineralized than elsewhere because of a shorter residence time in the aquifer. Water from wells located in valleys where discharge occurs is more mineralized than elsewhere. Water from areas where coal and black shale are close to the land surface tends to be acidic, whereas water from limestone tends to be alkaline.

Chloride concentrations can be large in water from aquifers in consolidated rocks beneath valley bottoms because of deep-circulation of the water to zones at or near the saltwater-water interface and subsequent rise of the mixed water along fractures. In addition, saltwater is relatively close to shallow depths in the vicinity of oil and gas fields because saltwater can migrate upward through improperly plugged, corroded, or abandoned oil and gas test wells. This type of contamination has been reported near Keaton in Johnson County, Indiana, and other places. Sabine, along with the calcite and minor dolomite in the limestone beds, are the source of the calcium and magnesium. Iron (Fe) and aluminum (Al) in water that has a dissolved solids concentration of more than 1,000 milligrams per liter, generally is at depths greater than 300 feet below land surface in Kentucky. However, salt water is at depths of less than 150 feet at the western boundary of the Appalachian Plateaus Province, perhaps because of its proximity to the principal tributaries. Locally, however, fresh water is reported to be present at greater depths in areas in Kentucky adjacent to major faults; for example, chloride concentrations of only 2 milligrams per liter were present in water from two wells reported to be 1,050-foot deep in Bell County, Kentucky. In fresh water probably circulated to this depth in fractures or steeply dipping bedding planes associated with the Pine Mountain Thrust Fault. Speak data indicate that water from Pennsylvania aquifers in Tennessee are usually more mineralized than water from Middle and Lower Pennsylvania aquifers. Large concentrations of sodium carbonate are present in water from wells completed in Pennsylvania rocks.

Effects of Coal Mining and Reclamation on Groundwater Quality

Surface coal mining and reclamation activities can affect the quality of ground water. Changes in ground-water quality that can occur as a result of mining and reclamation are characterized below for three small withdrawals in eastern Ohio (Fig. 11A).

The ground-water flow system in coal mining areas generally is controlled by undercuts that typically are present near each of several coal beds (Fig. 11B). These undercuts impede the vertical flow of water to underlying aquifers, thereby creating one or more perched aquifers. In the example shown in Figure 11B, two perched aquifers overlie a regional aquifer in which the direction of ground-water movement is different from that in the perched aquifers. Water moves laterally along the top of the undercuts and discharges springs or seeps where the clay crops out in valley walls. In this example, during surface mining of the uppermost coal, the aquifer system and the coal bed overlaying the shallowest undercuts is removed and replaced with broken waste rock (spoil material) as part of the reclamation process.

The quality of the water in the aquifers can be altered by mining activity. In some cases, mining can change water quality by increasing its total dissolved solids, by changing the mineral content of the water, or by introducing toxic contaminants. In these cases, mining can be considered to have altered the chemistry of the water. Depending on the hydrogeologic setting and the amount and type of mining activity, the quality of the water in the deeper, regional aquifer may undergo many water-quality changes as a result of mining and reclamation. Water in the middle aquifer undergoes some chemical changes that result from mining and reclamation. Water in the uppermost coal aquifer undergoes quite different in other places from those shown in this example. The exact changes depend on the chemical composition of the coal and the spoil material.

FRESH GROUND-WATER WITHDRAWALS

Ground water is an important source of freshwater in the Appalachian Plateaus Province of northern Ohio. Water withdrawn from the largest quantity of ground water during 1985—a total of 10 million gallons per day used for industrial, mining, and thermoelectric power uses (Fig. 13) shows that Ohio withdraws the largest quantities of available ground water and had the largest quantity of groundwater withdrawals exceeded surface-water withdrawals. Severe counties in Ohio that had withdrawals of greater than 10 million gallons per day are located where geologic and hydrogeologic conditions of the surficial aquifer system are present. The principal tributaries are the major sources of ground water because they have the largest well yields of any aquifers in the Appalachian Plateaus Province and because many of Ohio urban areas are located near major streams whose valleys filled with sand and gravel deposits of the surficial aquifer system. Access to water in Ohio in water use from the surficial aquifer system and the aquifers in consolidated rocks for their freshwater supply. Despite their generally lower yields, the aquifers in consolidated rocks are important sources of freshwater in the Appalachian Plateaus Province of northern Ohio. Upper Pennsylvania aquifers provide domestic supplies, and Mississippian aquifers provide domestic and small public supplies. Middle and Lower Pennsylvania aquifers are used primarily for domestic, stock, and small public and industrial supplies throughout the Appalachian Plateaus Province. During 1985, most of the ground water drawn on in Ohio (51 percent of total withdrawals) was used for public supply (Fig. 114) withdrawals for domestic and commercial uses accounted for 31 percent. In contrast, most of the ground water in Kentucky (76 percent) and Pennsylvania (52 percent) was withdrawn for industrial and thermoelectric power uses. In Ohio, ground water is used for industrial, mining, and thermoelectric power uses (14 percent) in Kentucky and public-supply withdrawals for industrial, mining, and thermoelectric power uses made up a significant percentage of the total ground water withdrawals.

RECLAMATION

Figure 13. During 1985, most of the counties that withdraw more than 0.5 million gallons per day used the water withdrawn from the surficial aquifer system in Ohio. Aquifers that withdraw more than 10 million gallons per day per year in areas where water can be obtained from the surficial aquifer system are shown.

EXPLANATION

Fresh ground-water withdrawals by county in 1985, million gallons per day

- 0 to 1
- 10 to 20
- 20 to 50
- 50 to 100
- 100 to
- > 1,000

No Data

County where ground-water withdrawals exceed 1,000 million gallons per day

No Data

Creation of fresh ground-water withdrawals exceed 1,000 million gallons per day

No Data

Ohio Total withdrawals 289 million gallons per day

Kentucky Total withdrawals 133 million gallons per day

Tennessee Total withdrawals 12 million gallons per day

Public supply

Domestic and commercial

Agricultural

Industrial, mining, and thermoelectric power

Ohio Total withdrawals 289 million gallons per day

Kentucky Total withdrawals 133 million gallons per day

Tennessee Total withdrawals 12 million gallons per day

Ground-water withdrawals during 1985, trillion gallons per day

EXPLANATION

Ground-water withdrawals during 1985, trillion gallons per day

- 0 to 1
- 10 to 20
- 20 to 50
- 50 to 100
- 100 to
- > 1,000

No Data

Location

Ohio

Kentucky

Tennessee

EXPLANATION

Ground-water withdrawals during 1985, trillion gallons per day

- 0 to 1
- 10 to 20
- 20 to 50
- 50 to 100
- 100 to
- > 1,000

No Data

Location

Ohio

Kentucky

Tennessee

Ground-water withdrawals during 1985, trillion gallons per day

No Data

Location

Ohio

Kentucky

Tennessee

Table:<br>EXPLANATION<br>Ground-water withdrawals during 1985, trillion gallons per day

- 0 to 1<br>10 to 20<br>20 to 50<br>50 to 100<br>100 to
> 1,000

No Data

Location
Ohio
Kentucky
Tennessee
INTRODUCTION

The Valley and Ridge Physiographic Province is characterized by a sequence of folded and faulted, northeast-trending Paleozoic sedimentary rocks that form a series of alternating valleys and ridges that extend from Alabama and Georgia to New York. The province is more extensively in Segment 11 than in Segment 10. Therefore, the aquifers in the province are discussed in greater detail in that Atlas Chapter. The Valley and Ridge Province, which is the eastern part of the state, is underlain by rocks that are primarily Cambrian, Ordovician, and Mississippian in age. Many Silurian, Devonian, and Mississippian rocks also are present in the province. Soluble carbonate rocks and some rhyolite dikes underlie the valley provinces, and more erosion-resistant siltstone, sandstone, and some cherty dolomite underlie the ridges.

HYDROGEOLOGIC UNITS

The principal aquifers in the Valley and Ridge Province are discussed in greater detail in that Atlas Chapter. The principal aquifers in the Valley and Ridge Province in eastern Tennessee range from about 1 to 250 gallons per minute. The largest yields (250 gallons per minute) are reported for wells completed in the Limestone of the Conasauga Group. The largest values for dissolved solids are for wells completed in the Coal Seam Limestone of the Conasauga Group. The largest spring discharge is from the principal aquifers is 4,000 gallons per minute. The principal aquifers are discussed in greater detail in that Atlas Chapter.

Table 1. Yields of wells completed in the principal Valley and Ridge aquifers range from about 1 to 2,500 gallons per minute. The largest yields (1,500 gallons per minute) are reported for wells completed in the Limestone of the Conasauga Group. The largest values for dissolved solids are for wells completed in the Coal Seam Limestone of the Conasauga Group. The largest spring discharge is from the principal aquifers is 4,000 gallons per minute. The principal aquifers are discussed in greater detail in that Atlas Chapter.

Table 2. Yields of wells completed in the principal Valley and Ridge aquifers range from about 1 to 2,500 gallons per minute. The largest yields (1,500 gallons per minute) are reported for wells completed in the Limestone of the Conasauga Group. The largest values for dissolved solids are for wells completed in the Coal Seam Limestone of the Conasauga Group. The largest spring discharge is from the principal aquifers is 4,000 gallons per minute. The principal aquifers are discussed in greater detail in that Atlas Chapter.

Figure 115. The Valley and Ridge aquifers in Segment 10 are in eastern Tennessee, in the region east of the Sequatchie Valley, which has the same rocks and similar structures as the Valley and Ridge Physiographic Province.

Figure 116. The sequence of Cambrian and Ordovician formations that includes the carbonate rock aquifers in the Valley and Ridge Province is repeated several times by thrust faults in eastern Tennessee. The Rome Formation, which is a coaly unit, also is repeated. This repetition is indicated schematically in many local groundwater flow systems.

EXPLANATION

Figure 117. The carbonate rocks units shown in color constitute the principal aquifers in the Valley and Ridge Province in eastern Tennessee. Most of these aquifers are in Cambrian and Ordovician rocks.

Figure 118. Ground water moves downslope through intercalated carbonate and noncarbonate rocks where it moves along fractures, bedding planes, and solution zones to finally discharge at springs that issue from the principal aquifers. The discharges of springs that issue from the principal aquifers range from about 1 to 2,500 gallons per minute. The largest yields (1,500 gallons per minute) are reported for wells completed in the Limestone of the Conasauga Group. The largest values for dissolved solids are for wells completed in the Coal Seam Limestone of the Conasauga Group. The largest spring discharge is from the principal aquifers is 4,000 gallons per minute. The principal aquifers are discussed in greater detail in that Atlas Chapter.

Figure 119. Water quality is similar for flows (A) and springs (B) in the principal Valley and Ridge aquifers. The water is hard, is a calcium magnesium bicarbonate type, and typically has a dissolved solids concentration of 170 milligrams per liter or less. The ranges of concentrations are thought to be indicative of the depth and rate at which ground water flows through the carbonate rock aquifers. In general, the smaller values for a constituent represent water that is moving rapidly along shallow, short flow paths from recharge areas to points of discharge. The larger values represent water that is moving more slowly along deep, long flow paths. This water has been in contact with aquifer minerals for a longer time and thus has had greater opportunity to dissolve the minerals. Also, water that moves into deeper parts of the aquifers can mix with saltwater that might be present at depth.

FRESH GROUND-WATER WITHDRAWALS

Fresh ground-water withdrawals from the aquifers in the Valley and Ridge Province in eastern Tennessee were about 82 million gallons per day during 1995 (fig. 120). About 10 percent of the ground water used in the state (about 31 million gallons per day) was withdrawn from carbonate rocks. Geothermal power plants are one use where about 82 million gallons per day during 1995. About 19 million gallons per day was withdrawn for domestic and commercial supplies, and about 1.2 million gallons per day was withdrawn for agricultural use.
The Blue Ridge Physiographic Province in Segment 10 is in easternmost Tennessee (fig. 121). Rocks that underlie the province range in age from Precambrian to Ordovician. Precambrian rocks (include sandstone and metamorphic rock). Cambrian rocks consist of sandstone with some dolomite, and Ordovician rocks are primarily limestone and dolomite. Blue Ridge aquifers are discussed in more detail in the Atlas that describes Segment 6, where these aquifers are more extensive. A complete description of the aquifers system underlies a small area in eastern Tennessee. Rocks of Precambrian age underlie most of the province, but rocks of Cambrian and Ordovician age are locally present.

Ground water in the Blue Ridge Physiographic Province is generally present in fractured bedrock. The bedrock, which consists of sedimentary, metamorphosed, and crystalline igneous and metamorphic rocks, is progressively more deformed and metamorphosed toward the southeast. Sedimentary rocks in the Blue Ridge Province are generally well cemented sandstone, limestone, and dolomite with minor shale. Locally, regolith and stream-valley alluvium can also provide ground water. The bedrock is cut by regolith that ranges from 1 to 150 feet thick. Alluvium that consists of boulders, gravel, silt, sand, and clay locally covers the floor of major stream valleys and can be several tens of feet thick.

Ground water from the Blue Ridge aquifers is used primarily for domestic supplies. Wells yield from these aquifers are adequate for domestic, livestock, and small public supplies. The specific capacities of 13 wells finished in sandstone and gravel range from 0.57 to 104 gallons per minute with a median of 6 gallons per minute. Wells completed in Cambrian sandstone, metamorphic rocks, and crystalline rocks rarely have large yields, unless wells are open to major fracture zones.

GROUND-WATER OCCURRENCE

Ground-water occurrence in the Blue Ridge aquifers is determined by the number, size, and degree of interconnection of fractures. Rocks in the Blue Ridge Province generally are massive and have little or no primary porosity. The rocks generally are nonporous and impermeable except within a few hundred feet of land surface where fractures (present in all rock types) provide secondary permeability (fig. 122). Fractures are less common at depth, and, therefore, regional ground-water flow is not significant. Most of the water available from these fractures is within about 300 feet of land surface. However, sparse data indicate that fresh ground water can be obtained 100 feet or more to several hundred feet below land surface. The saturated regolith that overlies the bedrock and the alluvium in major stream valleys store ground water and release it slowly into the bedrock fractures. The regolith and alluvium, which locally are aquifers, supply sufficient water for domestic wells. However, wells completed in regolith might go dry during late summer and early autumn when water levels usually decline because of a decrease in precipitation or increased evapotranspiration.

Ground-water circulation in the Blue Ridge aquifers is localized. Most of the ground water moves along short, shallow flow paths. Precipitation recharges the regolith and alluvium and then percolates downward into the bedrock aquifers. Discharge is to springs and streams, as base flow to streams and rivers, and as withdrawals from wells. The amount of ground-water discharge to streams and rivers ranges between 400,000 and 800,000 gallons per day per square mile of area and averages about 600,000 gallons per day per square mile of area throughout the Blue Ridge. This large rate of discharge is controlled by large quantities of precipitation and large infiltration rates.

GROUND-WATER QUALITY

The chemical quality of the water in the Blue Ridge aquifers generally is suitable for most uses. Water from wells completed in sandstone aquifers (fig. 123) typically is a calcium magnesium bicarbonate type, dissolved-solids concentrations is less than 300 milligrams per liter. Water from wells completed in crystalline rocks of Precambrian age has a smaller dissolved-solids concentration and is softer than water from wells completed in sandstone aquifers.

Blue Ridge, Ozark Plateaus, and Southeastern Coastal Plain aquifers

OZARK PLATEAUS AQUIFER SYSTEM

Because only a small part of the Ozark Plateaus aquifer system is within Segment 10 (fig. 124), the aquifer system is only briefly summarized here. A complete description of the geology, hydrology, and water-quality of the aquifer system is presented in the chapter of this Atlas that describes Segment 3.

The principal aquifers in consolidated rocks of the Ozark Plateaus aquifer system consist of limestone and minor dolomite of Mississippian and Cambrian age. Unconsolidated sand and gravel aquifers in Quaternary deposits overlay the aquifers in consolidated rocks along the Mississippi River and its tributaries.

Water in the limestone and dolomite aquifers of the Ozark Plateaus aquifer system primarily is stored in and moves through fractures and bedding planes because of the low primary porosity and permeability of the rocks. Dissolution of the carbonate rocks creates enlarged openings along the fractures and bedding planes; these openings allow water to move rapidly through the aquifers. The aquifers are recharge by downward leakage through overlying sand and gravel deposits and directly through fractures, sinkholes, and swallow holes where the aquifers crop out. Springs are common points of discharge for the limestone and dolomite aquifers. Wells of yields completed in the Ozark Plateaus aquifer system in Illinois generally range from 25 to 200 gallons per minute but might be several hundred gallons per minute where wells withdraws induce additional recharge from nearby springs or streams. Wells of yields completed in the consolidated rocks generally range from 500 to 1,000 milligrams per liter and increase toward the northeast as the aquifers dip into the Illinois Basin. Hardness (as calcium carbonate) generally ranges from 200 to 400 milligrams per liter; sulfate concentrations generally range from 25 to 125 milligrams per liter; nitrate typically is less than 5 milligrams per liter. Chloride concentrations range from less than 50 milligrams per liter near the Mississippi River to more than 1,000 milligrams per liter toward the northeast. Iron concentrations generally range from 0.3 to more than 5 milligrams per liter.

SOUTHEASTERN COASTAL PLAIN AQUIFER SYSTEM

The part of the Southeastern Coastal Plain aquifer system that underlies Segment 10 is at small area in eastern Tennessee. Although the aquifer system is thin, sand body of the system provides a minimal quantity of water to users.

Water entering the Black Warrior River aquifer in upland recharge areas and moves westward and southwestward, down tributary streams and small watercourses. A small amount of the water moves into deep, confined parts of the aquifer. The water is stored in and moves through intergranular pore spaces. Water generally is present under unconfined conditions in and near aquifer recharge areas except where lenses of clay form local confining beds. Although the Black Warrior River aquifer is moderately permeable, the aquifer is thin, and its transmissivity is accordingly moderate. Estimated transmissivity values for the part of the aquifer in Tennessee are 5,000 feet squared per day or less. Wells of yields completed in the aquifer generally are less than 50 gallons per minute, but, locally, yields of as much as 300 gallons per minute have been reported.

Water from the Black Warrior River aquifer is hard to moderately hard and is a calcium bicarbonate type. Dissolved-solids concentrations in water from the aquifer are small because the silica minerals that compose the aquifer do not readily dissolve. Locally, objectionable concentrations of iron have been reported.
**INTRODUCTION**

The aquifers that comprise the Mississippi embayment aquifer system (fig. 126) are located in the southeastern part of Segment 10 on the eastern side of the Mississippi Embayment section of the Coastal Plain Physiographic Province. These aquifers consist of unconsolidated to semiconsolidated sediments that range in age from Late Cretaceous through late Eocene. They are a major source of freshwater, whereas consolidated rocks of Ordovician through Triassic age that underlie these aquifers contain saltwater. The Mississippi embayment aquifer system is present in parts of Alabama, Arkansas, Florida, Illinois, Kentucky, Louisiana, Mississippi, Missouri, and Tennessee. It is nearly extensive in Segment 5 and is described in greater detail in the Atlas Chapter describing that segment.

**HYDROGEOLOGIC UNITS**

Six aquifers and two confining units compose the Mississippi embayment aquifer system in Segment 10 (fig. 127). The Mississippi River Valley alluvial aquifer, which consists of sediments of Quaternary age, is present in a narrow band along the Mississippi River (fig. 126). It overlies the Mississippi embayment aquifer system and is in hydraulic contact with the system. East of this band, five aquifers in Tertiary rocks that range in age from Late Cretaceous through late Eocene crop out. They are a major source of freshwater, whereas consolidated rocks of Ordovician through Triassic age that underlie these aquifers contain saltwater. The Mississippi embayment aquifer system is present in parts of Alabama, Arkansas, Florida, Illinois, Kentucky, Louisiana, Mississippi, Missouri, and Tennessee. It is nearly extensive in Segment 5 and is described in greater detail in the Atlas Chapter describing that segment.

The Mississippi River Valley alluvial aquifer is present only along the Mississippi River in Segment 10. The alluvial aquifer consists primarily of Quaternary sediments that range from clay to coarse gravel. The sediments commonly grade downward from fine sand, silt, or clay at the top to coarse sand or gravel at the base. These sediments reach a maximum thickness of about 100 feet and have a total thickness of sand and gravel of about 80 feet in northwestern Tennessee and western Kentucky.

The Mississippi River Valley alluvial aquifer is capable of sustaining well yields of several thousand gallons per minute because it is hydrologically connected to the Mississippi River. Thus, recharge may be induced from the river to the aquifer in places where pumping wells located near the river have lowered the water level in the aquifer below that of the river. However, this aquifer is not a major source of ground water in Segment 10 because of its small areal extent. Where the alluvial aquifer crows aquifers in Tertiary rocks, there is direct hydraulic connection between the alluvial aquifer and the underlying aquifers.

**Figure 126.** The aquifers and confining units of the Mississippi embayment aquifer system crop out in a sequence of areal units in Segment 5 on the eastern side of the Mississippi Embayment, which is a large structural depression in the Coastal Plain Physiographic Province.

**Figure 127.** Geologic units that range in age from Late Cretaceous to late Eocene are separated into regional aquifers and confining units that comprise the Mississippi embayment aquifer system. The six aquifers are separated by confining units; other, unconsolidated material in the lower parts of some aquifers restricts vertical ground-water movement. The gray area represents missing rocks.

**Figure 130.** The altitude of the top of the lower Wilcox aquifer is shown at about 300 feet above sea level where the aquifer crops out in Hardeman County, Tennessee. The top of this aquifer is shown at 1,000 feet above sea level near the axis of the Mississippi Embayment along the Mississippi River.
Middle Claiborne Aquifer

The middle Claiborne aquifer is a major source of ground water in the Mississippi embayment aquifer system in Segment 10. This aquifer primarily consists of the Sparta Sand in Kentucky and Tennessee (fig. 127), and the upper part of the Memphis Sand in Tennessee. The lower part of the Memphis Sand is considered to be part of the regional lower Claiborne-upper Wilcox aquifer. The middle Claiborne aquifer includes sands of the Talahatta Formation in Kentucky.

The thickness of the middle Claiborne aquifer is variable (fig. 132). Sands of the middle Claiborne aquifer are derived from continental sources and are thick and massive in fine or no clay layers. Therefore, these sands are hydrodynamically well connected, which allows large quantities of water to be withdrawn from the aquifer.

The middle Claiborne aquifer is distributed in the upper Claiborne aquifer, which is overlain by the Mississippi River Valley alluvial aquifer. Sand beds of the middle Claiborne aquifer are connected to each other laterally and, to a lesser degree, vertically.

The lower Claiborne-upper Wilcox aquifer

The lower Claiborne-upper Wilcox aquifer is part of the Wilcox Formation. It is more than 200 feet thick in large parts of several counties in southeastern Tennessee and Arkansas. sands of this aquifer are hydraulically well connected to the middle Claiborne aquifer in Kentucky and Tennessee and the Mississippi River Valley alluvial aquifer in Illinois.

The lower Claiborne-upper Wilcox aquifer thicknesses are less than the upper Claiborne aquifer, but they are hydraulically well connected to the middle Claiborne aquifer. The lower Claiborne-upper Wilcox aquifer is considered to be the primary source of water supply for the city of Memphis and much of westernmost Tennessee.

Middle Wilcox Aquifer

The middle Wilcox aquifer is the uppermost hydrogeologic unit of the Mississippi embayment aquifer system. Locally, it is overlain by the Mississippi River Valley alluvial aquifer. Sand of the Cockfield Formation is the most productive part of the upper Wilcox aquifer; locally, sand of the Jackson Formation is the most productive part of the upper Wilcox aquifer.

The thickness of the middle Wilcox aquifer increases from more than 400 feet in parts of Lauderdale and Tipton Counties, Tenn. (fig. 131). The aquifer thins updip toward outcrop areas and downdip toward the southwest as the sand thins. Where present, the Flour Island Formation (fig. 129) underlies the upper Claiborne aquifer everywhere and retards the downward movement of ground water from the upper Claiborne aquifer to deeper aquifers.
McNairy-Nacatoch Aquifer

The McNairy-Nacatoch aquifer is in Upper Cretaceous rocks and is the lowermost hydrogeologic unit included in the Mississippi Embayment aquifer system (fig. 127). The McNairy-Nacatoch aquifer is included in the aquifer system because of the local hydraulic connection between this aquifer and the overlying aquifers in Tertiary rocks in the northern part of the Mississippi Embayment where the Midway confining unit is thin. However, the McNairy-Nacatoch aquifer appears to be hydraulically separated from the overlying aquifers throughout most of the Mississippi Embayment. The McNairy-Nacatoch aquifer primarly consists of the McNairy Sand in Segment 10 but also includes the Nacatoch Sand. Other clayey sands of Late Cretaceous age, including the Coffee Sand and sand beds in the Demopolis, the Eutaw, and the Nacatoch Formations, are discontinuous in Segment 10. The McNairy-Nacatoch aquifer thickness is less than 50 feet near its updip limit to a maximum of more than 400 feet (fig. 136). Sand in the McNairy-Nacatoch aquifer is present as a single thick bed or as two or more thick sand beds separated by thin clay or marl layers. The sand facies locally is overlain by clay and marl of Late Cretaceous age, which, in turn, are overlain by clays of the Midway confining unit. The thin, fine sands change laterally to clay, marl, and limestone toward the southwest and are accompanied by calcarenite cationization that fills the pore space between sand grains and greatly reduces the permeability of the sand. This abrupt facies change is in Mississippi, south of Segment 10.

Ground-Water Movement

The principal aquifers in the Mississippi Embayment aquifer system that are used for water supply in Segment 10 are the middle Claiborne, the lower Wilcox, and the McNairy-Nacatoch aquifers. The middle Claiborne and the lower Wilcox aquifers are recharged by precipitation on aquifer outcrop areas and by downward leakage from overlying aquifers. Because the outcrop area of the lower Wilcox aquifer is small, the primary source of recharge to this aquifer is downward leakage. Most recharge to the McNairy-Nacatoch aquifer is from precipitation on outcrop areas; a small quantity of recharge is by upward leakage from underlying aquifers. Discharge from all aquifers in this system is mainly to streams in outcrop areas or to the Mississippi River Valley alluvial aquifer where the alluvial aquifer is present at some distance from the wells. In the deeper, confined parts of the aquifers, upward leakage to shallow aquifers occurs.

Regional ground-water movement in the aquifers of the Mississippi Embayment aquifer system generally is from aquifer outcrop areas toward the axis of the Mississippi Embayment. The potentiometric surface of the lower Wilcox aquifer (fig. 137) is representative of the configuration of hydraulic heads in these aquifers. Water enters the aquifers at the updip, higher altitude outcrop areas and moves down the dip of the aquifers. In the example shown in figure 137, water also enters the lower Wilcox aquifer in subcrop areas in Missouri and Arkansas by discharge from all aquifers in the system is mainly to streams in outcrop areas. However, dissolved solids concentrations in water from the aquifers in the Mississippi Embayment aquifer system generally increase from aquifer outcrop areas toward the deeper parts of the aquifers. Water entering the aquifer at the axis of the Mississippi Embayment is the major source of water for public supply. In comparison, only about 11 million gallons per day of all the water withdrawn from the aquifers in the Mississippi Embayment aquifer system was supplied by ground water in 1985. Withdrawals of ground water for public supply and for industry, commercial, and thermoelectric power used accounted for more than 90 percent of the ground water withdrawn from the aquifers in Tertiary and Cretaceous rocks in Kentucky and the aquifers in Tertiary rocks in Tennessee. Public-supply withdrawals accounted for about 60 to 70 percent of the water withdrawn from all the aquifers in the Mississippi Embayment aquifer system in Tennessee.

HYDRAULIC CHARACTERISTICS OF PRINCIPAL AQUIFERS

Yields from the Mississippi Embayment aquifer system in Segment 10 tend to be greater for wells completed in the aquifers in Tertiary rocks than for those completed in the McNairy-Nacatoch aquifer. In Tennessee, wells completed in the middle Claiborne and the lower Wilcox aquifers commonly yield from 200 to 1,000 gallons per minute, but yields locally exceed 2,000 gallons per minute. Wells completed in the McNairy-Nacatoch aquifer commonly yield from 50 to 500 gallons per minute, but yields might locally exceed 1,000 gallons per minute. Yields for wells completed in these aquifers in Kentucky are smaller. Wells completed in the middle Claiborne and the lower Wilcox aquifers in Kentucky yield from 2 to 150 gallons per minute, and wells completed in the McNairy-Nacatoch aquifer in Kentucky yield from 5 to 25 gallons per minute.

Transmissivity is a measure of the ease with which water can move through an aquifer. The larger the transmissivity, the faster the ground water moves through an aquifer. The larger the transmissivity, the greater the amount of water that can move through an aquifer. The larger the transmissivity, the more easily water can move through the aquifer. The middle Claiborne aquifer in Segment 10 has an average transmissivity of about 20,000 feet squared per day, as indicated by 80 aquifer tests. The lower Wilcox aquifer in this segment has an average transmissivity of about 13,000 feet squared per day, as indicated by 24 aquifer tests. The McNairy-Nacatoch aquifer for this segment has an average transmissivity of about 4,000 feet squared per day, as indicated by two aquifer tests.

GROUND-WATER QUALITY

The chemical quality of water from the aquifers in the Mississippi Embayment aquifer system generally is suitable for most uses. The areal distribution of constituents in water from the aquifers in the Mississippi Embayment aquifer system were about 311 million gallons per day during 1985. Most of this water, about 272 million gallons per day, or about 87 percent of the total, was withdrawn from wells in Kentucky and Tennessee. Of this, 272 million gallons per day was withdrawn from the aquifers in Tertiary rocks, 11 million gallons per day was withdrawn from the aquifers in Cretaceous rocks, and about 25 million gallons per day was withdrawn from the aquifers in the Mississippi Embayment aquifer system in Kentucky. In comparison, about 25 million gallons per day was withdrawn from the aquifers in Tertiary rocks in Tennessee, and about 70 percent of this water was supplied by aquifers in Tertiary rocks and about 30 percent by aquifers in Cretaceous rocks. About 2.5 million gallons per day was withdrawn from the Mississippi River Valley alluvial aquifer in Tennessee during 1985. Ground water is the major source of water for public supply throughout the Coastal Plain Province in Segment 10. During 1985, withdrawals for public supply and for industry, commercial, and thermoelectric power used accounted for more than 90 percent of the ground water withdrawn. The potentiometric surface shown represents hydraulic heads for the potentiometric surface of the lower Wilcox aquifer as determined by a computerized thin model.