GROUND WATER ATLAS of the UNITED STATES
Delaware, Maryland, New Jersey, North Carolina, Pennsylvania, Virginia, West Virginia
HA 730-L

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Regional summary

INTRODUCTION

Segment 11 consists of the States of Delaware, Maryland, New Jersey, North Carolina, West Virginia, and the Commonwealths of Pennsylvania and Virginia. All but West Virginia border on the Atlantic Ocean or tidewater. Pennsylvania also borders on Lake Erie. Small parts of northwestern and north-central Pennsylvania drain to Lake Erie and Lake Ontario; the rest of the segment drains either to the Atlantic Ocean or the Gulf of Mexico. Major rivers include the Hudson, the Delaware, the Susquehanna, the Potomac, the Rappahannock, the James, the Chowan, the Neuse, the Tar, the Cape Fear, and the Yadkin-Peedee, all of which drain into the Atlantic Ocean, and the Ohio and its tributaries, which drain to the Gulf of Mexico.

Although rivers are important sources of water supply for many cities, such as Trenton, N.J.; Philadelphia and Pittsburgh, Pa.; Baltimore, Md.; Washington, D.C.; Richmond, Va.; and Raleigh, N.C., one-fourth of the population, particularly the people who live on the Coastal Plain, depends on ground water for supply. Such cities as Camden, N.J.; Dover, Del.; Salisbury and Annapolis, Md.; Parkersburg and Weirton, W.Va.; Norfolk, Va.; and New Bern and Kinston, N.C., use ground water as a source of public supply.

All the water in Segment 11 originates as precipitation. Average annual precipitation ranges from less than 36 inches in parts of Pennsylvania, Maryland, Virginia, and West Virginia to more than 80 inches in parts of southwestern North Carolina (fig. 1). In general, precipitation is greatest in mountainous areas (because water tends to condense from moisture-laden air masses as the air passes over the higher altitudes) and near the coast, where water vapor

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Surficial aquifer system

INTRODUCTION

The surficial aquifer system is in the northern and western parts of Segment 11 (fig. 12) and consists of aquifers in unconsolidated sand and gravel deposits of Quaternary age. The aquifer system is in parts of all the physiographic provinces in the segment except the Coastal Plain. Most of the individual aquifers that compose the system are not hydraulically connected, but share common geologic and hydrologic characteristics and are therefore considered to be an aquifer system. Unconsolidated sand and gravel deposits that are the uppermost aquifers in parts of the Coastal Plain in Segment 11 are not mapped as part of the surficial aquifer system because they function as part of the Northern Atlantic Coastal Plain aquifer system.

Two principal types of unconsolidated sediments compose the surficial aquifer system. The first, and most widespread, type consists of sediments deposited by Pleistocene continental glaciers or by meltwater from the glaciers. The second type is Holocene alluvium in the valleys of major streams. The glacial sediments are restricted to the northern parts of Pennsylvania and New Jersey; the alluvial deposits are scattered through parts of West Virginia, Pennsylvania, and New Jersey (fig. 12). Some of the alluvial deposits are reworked glacial sediments.

HYDROGEOLOGIC SETTING

Glacial deposits consist mostly of clay, silt, sand, and gravel in various combinations, but also include cobbles and boulders. The general term "glacial drift" is used for all types of glacial

deposits, regardless of the particle size or the degree of sorting of the deposits, or how the deposits were emplaced. The glacial drift in Segment 11 was deposited during several advances and retreats of continental ice sheets. The most recent and widespread glacial stage, termed "Wisconsinan," ended only about 12,000 years ago; the last ice sheet, however, retreated out of the area of Segment 11 about 17,000 years ago.

Glacial ice and meltwater from the ice laid down several different types of deposits. Till, which is an unstratified, unsorted mixture of material that ranges in particle size from clay to boulders, was deposited under the ice or directly in front of the ice sheet. Deposits of till are the most extensive glacial deposits in Segment 11, but the till is not an aquifer. Glacial-lake deposits of clay and silt, which were laid down in lakes that formed between ice lobes or where the ice blocked pre-glacial streams, likewise are not aquifers. Outwash deposits, by contrast, generally consist of stratified sand and gravel (fig. 13) that form productive aquifers. Most of the outwash deposits in Segment 11 are in valleys; the intervening hills are mantled with till or underlain by consolidated rock. The ice sheets greatly altered topography and drainage in the part of the segment that has been glaciated. Before or during the Pleistocene Epoch, some streams in the glaciated area cut their channels as much as 300 feet deeper than their present streambeds. In some places, erosion of bedrock hills by the thick ice sheets smoothed and rounded the preglacial topography and deposition of glacial drift, primarily in bedrock valleys, further subdued the original relief of the bedrock surface. In other places, the ice scoured deep troughs in the bedrock and stripped weathered bedrock away from hills, thus increasing the original relief.

Streams that flowed northward or northwestward typically were blocked by the ice sheets that advanced from the north and northeast. Flow direction was reversed in some of the north-flowing streams; others resumed their northward flow after the ice retreated; and a few were overridden by thick ice and permanently obliterated. New channels were cut by meltwater streams in some places, and some of these new channels connected parts of separate preglacial streams. The present course of the Ohio River was formed during the Pleistocene Epoch as a composite of newly cut channel segments and connected, old channel segments. Some of the deeply cut meltwater stream valleys were later filled to their present levels with glacial deposits and alluvium.

In areas where streams drained away from the glacial ice, stratified glacial drift was deposited in the stream valleys, mostly when the ice was stagnant or when the ice sheet was melting. Sand and gravel were deposited (fig. 14) as deltas or fluvial deposits at the ice margins or in glacial lakes or as fluvial valley-train deposits downstream from the ice margin. The coarse sand and gravel form productive aquifers that commonly are interspersed with the clay and silt confining beds deposited in small lakes in the valleys. Some of the valley-train sand deposits extend for many miles, as in parts of the valleys of the Allegheny and the Susquehanna Rivers.

Sand and gravel deposited as alluvium along the valleys of major streams also form productive

aquifers. Some of the alluvium consists of reworked glacial deposits that were eroded and transported downstream during and following the last retreat of the ice. Reworked glacial material is most common in southward-flowing streams, such as the Allegheny and the Ohio Rivers, that have their headwaters in glaciated areas. Although some of the deposits of reworked glacial material are in dry terraces above the water table, most of them are saturated, and some, such as the gravel deposits along the upper reaches of the Ohio River, form highly productive aquifers. Alluvium in the valleys of northward-flowing streams consists of material that has been weathered and eroded from exposed consolidated sedimentary rocks. The alluvium along the northward-flowing rivers, such as the Kanawha in West Virginia and the Monongahela in Pennsylvania, generally is finer grained than that along the southward-flowing rivers and thus yields less water to wells.

GROUND-WATER FLOW

Most of the productive aquifers in the surficial aquifer system consist of valley-fill deposits of coarse-grained glacial or alluvial deposits, or both, and contain water under mostly unconfined conditions. In New Jersey, fine-grained glacial-lake sediments overlie aquifers in coarse-grained glacial sediments in many places and create confined conditions in the aquifers. The valley-fill aquifers receive most of their recharge from runoff of precipitation that falls on the surrounding uplands that are underlain by till or bedrock, both of which are less permeable than the valley-fill deposits. Some recharge is by infiltration of precipitation that falls directly on the valley-fill aquifers, and some is by inflow from adjacent bedrock (fig. 15A). Studies have concluded, however, that from 60 to 75 percent of the recharge to the valley-fill aquifers is from upland runoff, some of which is unchanneled, but most of which is in tributary streams and enters the aquifers as seepage through the streambeds. The higher recharge percentages are for aquifers in valleys that are less than one-half mile wide. The valley-fill aquifers discharge primarily to streams that flow in the valleys when the water level in the aquifer is higher than that in the stream (fig. 15A); during drought conditions, water levels in the aquifer can decline until the direction of flow is reversed and water moves from the stream to the aquifer (fig. 15B). The thickness and permeability of the bottom sediment in the stream determine the rate at which water can move between the stream and the aquifer. Some discharge from the valley-fill aquifers also is by outflow to adjacent bedrock, evapotranspiration, and withdrawals from wells (fig. 15B).

Base flow of a stream is maintained by ground-water discharge and is a good indication of the water-yielding capacity of the aquifer that provides the base flow. Base-flow characteristics in Segment 11 vary with the type of rocks or deposits through which the stream flows. Streams that flow on bedrock have minimal base flow and often become dry because the limited amount of fracture and pore space in the bedrock permits little water to be stored and subsequently released to the stream. In contrast, streams in valleys partly filled with glacial outwash and bordered by bedrock that is covered with till have large, sustained base flow because thick glacial deposits can store and slowly release large quantities of water even

where they consist of low-permeability till. Base flow has been estimated by some studies to account for more than 70 percent of the total runoff in the glaciated parts of the Appalachian Plateaus Province but accounts for only about 50 percent of the total runoff in the unglaciated parts of the province.

POTENTIAL WELL YIELDS

The considerable variation in potential yields of wells completed in the aquifers of the surficial aquifer system from place to place depends on the saturated thickness of the unconsolidated sediment, its coarseness, degree of sorting, and extent. Sustained well yields are dependent on recharge rates. Adequate recharge usually is not a problem because most of the aquifers are in the valleys of perennial streams from which flow to wells can be induced, especially if the wells are located near the streams.

The principal aquifers of the surficial aquifer system in New Jersey consist of glacial deposits of sand and gravel that partly fill bedrock valleys. Overlying till or glacial-lake deposits of silt commonly confine the aquifers, although they are unconfined in places. The combined thickness of coarse- and fine-grained valley-fill material is as much as 350 feet in some valleys. Yields of most large-diameter wells range from 130 to 800 gallons per minute, but some wells yield as much as 2,200 gallons per minute.

In northeastern Pennsylvania, yields from wells completed in glacial-deposit aquifers are about 400 to 750 gallons per minute near the confluence of the Lehigh and the Delaware Rivers. Elsewhere in the area, wells completed in the same type of material yield as much as 1,300 gallons per minute.

In western Pennsylvania, reported yields of wells completed in glacial gravels and alluvium along the Allegheny and the Ohio Rivers, stratified drift along other streams, and abandoned, filled channels within the glaciated area generally range from 200 to 1,200 gallons per minute. Locally, however, yields of as much as 2,000 gallons per minute have been reported, and along the West Branch of the Susquehanna River in west-central Pennsylvania, a few wells yield 1,000 to 3,000 gallons per minute. Wells located on alluvial terraces along north-flowing streams south of the limits of glaciation yield only 5 to 10 gallons per minute.

In West Virginia, the valleys of north-flowing tributaries of the Ohio River contain as much as 75 feet of alluvium; however, only the lower part of the alluvium is saturated. Yields

of wells completed in the alluvium are as much as 105 gallons per minute along the Little Kanawha River and 150 gallons per minute along the Kanawha River. Along the Ohio River, yields of 100 to 1,000 gallons per minute are reported from standard vertical wells completed in the alluvium. Yields from collector wells, which are bored or excavated horizontally, can be even higher.

GROUND-WATER QUALITY

The chemical quality of water in the aquifers of the surficial aquifer system is somewhat variable but generally is suitable for municipal supplies and most other purposes. Most of the water in the upper parts of the aquifers is not highly mineralized.

With the exception of local limestone and dolomite gravel in glacial deposits, the unconsolidated sand and gravel aquifers of the surficial aquifer system consist primarily of siliceous material, which is not very soluble. Furthermore, the aquifers are at or near the land surface and commonly are thin. Much of the recharge water enters the aquifers as runoff from adjacent highlands or directly from precipitation on the aquifers and the residence time of the water in the aquifer is generally short. The net effect of these factors is that the water contains little dissolved mineral material and has an average dissolved-solids concentration of about 250 milligrams per liter. Because hardness (caused principally by calcium and magnesium ions) averages about 140 milligrams per liter, the water is classified as hard. The median hydrogen ion concentration, which is measured in pH units, is 7.2. Thus, the water is slightly basic, because of the dissolution of calcium and magnesium carbonate, which raises the pH. The water is a calcium bicarbonate type (fig. 16).

Chloride concentrations average about 29 milligrams per liter but locally are as much as 1,200 milligrams per liter. Sulfate concentrations also average about 29 milligrams per liter but are as much as 670 milligrams per liter. Large concentrations of chloride and sulfate in the unconsolidated sand and gravel aquifers might be due to discharge from underlying bedrock aquifers that contain highly mineralized water.

The median iron concentration is 100 micrograms per liter, but concentrations of as much as 552,000 micrograms per liter have been measured. Locally, large concentrations of nitrate are probably the result of surface contamination by fertilizers, animal wastes, or sewage. Shallow aquifers, such as those of the surficial aquifer system, are particularly vulnerable to contamination.

FRESH GROUND-WATER WITHDRAWALS

Total freshwater withdrawals from unconsolidated sand and gravel aquifers of the surficial aquifer system in the Piedmont, the Blue Ridge, the Valley and Ridge, the Appalachian Plateaus, and the Central Lowland Provinces of Segment 11 were estimated to be 320 million gallons per day during 1985. About 140 million gallons per day was used for domestic and commercial purposes, and about 102 million gallons per day was withdrawn for public supply (fig. 17). Industrial, mining, and thermoelectric power uses accounted for withdrawals of about 62 million gallons per day. About 16 million gallons per day was withdrawn for agricultural use.

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that has been evaporated from the ocean is picked up by onshore winds and falls as precipitation when it reaches the shoreline.

Some of the precipitation returns to the atmosphere by evapotranspiration (evaporation plus transpiration by plants), but much of it either flows overland into streams as direct runoff or enters streams as base flow (discharge from one or more aquifers). The distribution of average annual runoff (fig. 2) is similar to the distribution of precipitation; that is, runoff is generally greatest where precipitation is greatest. Runoff rates range from more than 50 inches per year in parts of western North Carolina to less than 12 inches in parts of North Carolina, Virginia, and West Virginia.

Parts of the seven following physiographic provinces are in Segment 11: the Coastal Plain, the Piedmont, the Blue Ridge, the New England, the Valley and Ridge, the Appalachian Plateaus, and the Central Lowland. The provinces generally trend northeastward (fig. 3). The northeastern terminus of the Blue Ridge Province is in south-central Pennsylvania, and the southwestern part of the New England Province, the Reading Prong, ends in east-central Pennsylvania. The topography, lithology, and water-bearing characteristics of the rocks that underlie the Blue Ridge Province and the Reading Prong are similar. Accordingly, for purposes of this study, the hydrology of the Reading Prong is discussed with that of the Blue Ridge Province.

The Coastal Plain Province is a lowland that borders the Atlantic Ocean. The Coastal Plain is as much as 140 miles wide in North Carolina but narrows northeastward to New Jersey where it terminates in Segment 11 at the south shore of Raritan Bay. Although it is generally a flat, seaward-sloping lowland, this province has areas of moderately steep local relief, and its surface locally reaches altitudes of 350 feet in the southwestern part of the North Carolina Coastal Plain.

The Coastal Plain mostly is underlain by semiconsolidated to unconsolidated sediments that consist of silt, clay, and sand, with some gravel and lignite. Some consolidated beds of limestone and sandstone are present. The Coastal Plain sediments range in age from Jurassic to Holocene and dip gently toward the ocean.

The boundary between the Coastal Plain and the Piedmont Provinces is called the Fall Line (fig. 3) because falls and rapids commonly form where streams cross the contact between the consolidated rocks of the Piedmont (fig. 4) and the soft, semiconsolidated to unconsolidated sediments of the Coastal Plain. The increase in stream gradient at the Fall Line provided favorable locations for mills and other installations that harnessed water power during the early years of the Industrial Revolution, and on most major rivers, the Fall Line coincides with the head of navigation.

The Piedmont Province is an area of varied topography that ranges from lowlands to peaks

and ridges of moderate altitude and relief. The metamorphic and igneous rocks of this province range in age from Precambrian to Paleozoic and have been sheared, fractured, and folded. Included in this province, however, are sedimentary basins that formed along rifts in the Earth's crust and contain shale, sandstone, and conglomerate of early Mesozoic age, interbedded locally with basaltic lava flows and minor coal beds. The sedimentary rocks and basalt flows are intruded in places by diabase dikes and sills.

The mountain belt of the Blue Ridge Province forms the northwestern margin of the Piedmont in most of Segment 11. This belt consists mostly of igneous and high-rank metamorphic rocks but also includes low-rank metamorphic rocks of late Precambrian age and small areas of sedimentary rocks of Early Cambrian age along its western margin. In this report, the Reading Prong of the New England Province, which is an upland that extends from east of the Susquehanna River in Pennsylvania northeastward into New Jersey (fig. 3), is treated as part of the Blue Ridge Province. Part of the Reading Prong in Pennsylvania and New Jersey and a small part of the Piedmont Province in northeastern New Jersey have been glaciated. Glacial deposits completely or partly fill some of the valleys, and the eroding action of the glacial ice removed some of the rock from the ridges. Thus, the glaciated parts of the province have a smoother topography and less relief than other parts.

The Valley and Ridge Province is characterized by layered sedimentary rock that has been complexly folded and locally thrust faulted. As the result of repeated cycles of uplift and erosion, resistant layers of well-cemented sandstone and conglomerate form elongate mountain ridges and less resistant, easily eroded layers of limestone, dolomite, and shale form valleys. The rocks of the province range in age from Cambrian to Pennsylvanian. Parts of this province from central Pennsylvania into New Jersey have been glaciated, and glacial deposits fill or partially fill some of the valleys.

The Appalachian Plateaus Province is underlain by rocks that are continuous with those of the Valley and Ridge Province, but in the Appalachian Plateaus the layered rocks are nearly flat-lying or gently tilted and warped, rather than being intensively folded and faulted. The boundary between the two provinces is a prominent southeast-facing scarp called the Allegheny Front in most of the northern part of Segment 11 (fig. 5) and the Cumberland Escarpment in the southern part. The scarp faces the Valley and Ridge Province, and throughout most of the segment, the eastern edge of the Appalachian Plateaus Province is higher than the ridges in the Valley and Ridge. Like parts of the Reading Prong and the Valley and Ridge Province, the northern part of the Appalachian Plateaus Province in Pennsylvania has been glaciated. In the glaciated section, the surface is mantled by glacial drift, and the valleys are partly filled with glacial deposits.

The northwestern corner of Segment 11 contains a small part of the Central Lowland Province. This flat lowland is underlain by gently dipping sedimentary rocks, some of which are the same geologic formations as those of the Appalachian Plateaus Province. The two provinces

are separated by a northwest-facing scarp. Because of the small area of the Central Lowland Province within the segment and the similarity of aquifer properties with those of the glaciated part of the Appalachian Plateaus Province, the two provinces are discussed together in this report.

PRINCIPAL AQUIFERS

The rocks and unconsolidated deposits that underlie Segment 11 are divided into numerous aquifer systems, aquifers, and confining units. An aquifer system consists of two or more aquifers and can be of two types, both of which are in Segment 11. The first type consists of aquifers that are vertically stacked and hydraulically connected-that is, the ground-water flow systems in the aquifers function in the same fashion, and a change in conditions in one of the aquifers affects the others. The Northern Atlantic Coastal Plain aquifer system is of this type. The second type consists of several aquifers that are not connected, but share common geologic and hydrologic characteristics and, accordingly, can best be studied and described together. The surficial aquifer system is of this type. The areas where each principal aquifer or aquifer system is exposed at the land surface or is the shallowest major aquifer are shown in figures 6 and 7. For purposes of this Atlas, the principal aquifers in Segment 11 (some of which include many local aquifers) have been grouped by physiographic province. The Coastal Plain Province has six aquifers that consist mostly of semiconsolidated rocks. The Piedmont and the Blue Ridge Provinces have three types of aquifers in consolidated rocks, locally overlain by unconsolidated deposits of the surficial aquifer system. The surficial aquifer system also locally overlies aquifers in two types of consolidated rocks in each of the Valley and Ridge and the combined Appalachian Plateaus-Central Lowland Provinces. Some of the consolidated-rock aquifers are in more than one province; for example, limestone and dolomite aquifers are recognized in the Piedmont, the Blue Ridge, the Valley and Ridge, and the Appalachian Plateaus Provinces (fig. 7).

The aquifers and aquifer systems of Segment 11 can be grouped into three categories, depending on the degree of consolidation of the rocks and deposits that compose the aquifers. Rocks of Precambrian, Paleozoic, and early Mesozoic ages generally are consolidated; rocks of Cretaceous and Tertiary ages generally are semiconsolidated; and deposits of Quaternary age generally are unconsolidated. Some of the consolidated rocks, particularly those that underlie the Piedmont and the Blue Ridge Physiographic Provinces, are covered with unconsolidated material called regolith that is largely derived from weathering of the consolidated rocks.

Unconsolidated sand and gravel deposits that mostly occur as long, narrow bands in the northern and western parts of Segment 11 (fig. 6) compose the surficial aquifer system. Many of the sand and gravel deposits north of the limit of continental glaciation formed as glacial outwash that was deposited by meltwater from the ice sheets. Elsewhere, the sand and gravel

are stream-valley alluvium that was deposited adjacent to the principal streams in the segment. Some of the stream-valley alluvium consists of reworked glacial outwash. Unsorted, unstratified deposits called till, emplaced by the continental ice sheets, are not aquifers.

Aquifers in semiconsolidated to consolidated rocks underlie most of Segment 11 (fig. 7). These aquifers, along with confining units that separate them in some places, are described according to physiographic province. Aquifers in some of the provinces extend underground far beyond the areas where they are mapped at or near the land surface; for example, the Potomac aquifer is exposed as only a narrow band along the northwestern boundary of the Coastal Plain, but underlies most of the Coastal Plain.

The Northern Atlantic Coastal Plain aquifer system consists mostly of semiconsolidated sand aquifers separated by clay confining units. Unconsolidated sands compose the surficial aquifer, which is the uppermost water-yielding part of the aquifer system; the system also includes a productive limestone aquifer. The Coastal Plain sediments are thin near their contact with the rocks of the Piedmont Province and, in places, might not yield as much water as the underlying igneous and metamorphic rocks that are an extension of Piedmont rocks.

Aquifers in the Piedmont and the Blue Ridge Provinces and the Reading Prong are predominately in metamorphic and igneous rocks. In some topographically low areas of the Piedmont, aquifers are in carbonate rocks (limestone, dolomite, and marble) and in sandstone of early Mesozoic age that fills large basins that formed as deep rifts in the Earth's crust. The carbonate rocks are the most productive Piedmont and Blue Ridge aquifers.

Folded sedimentary rocks of Paleozoic age underlie the Valley and Ridge Physiographic Province. The strata consist mostly of sandstone, shale, and limestone; coal is present

in these rocks in Pennsylvania and Virginia, and they locally contain minor dolomite and conglomerate. Locally, the rocks have been metamorphosed into quartzite, slate, and marble. Carbonate rocks are the most productive Valley and Ridge aquifers.

The Appalachian Plateaus aquifers are in Paleozoic sedimentary rocks that are flat-lying or gently folded. The rocks consist mostly of shale, sandstone, conglomerate, and carbonate rocks; coal beds are in rocks of Pennsylvanian age. Most of the water-yielding beds are sandstones of Pennsylvanian and Mississippian age; Pennsylvanian coals and Permian sandstones yield water, but the Permian strata are mostly shale. Carbonate rocks of Mississippian age are also productive aquifers in many places. Small volumes of water are obtained locally from conglomerate beds of Pennsylvanian age.

GEOLOGY

Segment 11 contains two major rock types-consolidated crystalline rocks and consolidated to unconsolidated sedimentary rocks. The crystalline rocks consist of numerous kinds of igneous and metamorphic rocks and are mostly in the Piedmont and the Blue Ridge Provinces. Consolidated sedimentary rocks are mostly in the Valley and Ridge and the Appalachian Plateaus Provinces. Sedimentary rocks in the Coastal Plain Province are mostly semiconsolidated, but some are unconsolidated. The extent of the different rock types is shown in figure 8.

The igneous and metamorphic rocks in Segment 11 crop out in a band that trends northeastward, is widest in North Carolina, and narrows northeastward (fig. 8). The band includes much of the rock of the Piedmont Province and most of the rock of the Blue Ridge Province and the Reading Prong. The crystalline rocks generally are resistant to weathering and erosion. According to radiometric dating, the ages of the crystalline rocks range from more than 1,200 million to 196 million years before present (Precambrian to Jurassic). Even though these rocks vary greatly in mineral composition and texture, they have similar hydraulic characteristics in that they generally have almost no pore spaces between mineral grains and contain ground water in joints and fractures.

Most of the rocks that underlie Segment 11 are sedimentary rocks that can be grouped into three categories-well-consolidated rocks of Paleozoic age, variably consolidated rocks of Triassic and Early Jurassic age in early Mesozoic rift basins, and semiconsolidated to unconsolidated rocks of Cretaceous and younger age. Unconsolidated Quaternary deposits that overlie crystalline rocks or consolidated sedimentary rocks in the northern and western parts of the segment are shown in figure 6.

Paleozoic sedimentary rocks extend from western and central Virginia through all of West Virginia, western Maryland, western and northern Pennsylvania, and a small part of northern New Jersey. Most of these rocks are exposed in the folded and thrust-faulted Valley and Ridge Province and in gently warped to flat-lying beds of the Appalachian Plateaus Province (fig. 9), but some are in the Piedmont Province of northern Maryland, eastern Pennsylvania, and northern New Jersey. ThePaleozoic sedimentary rocks consist of conglomerate, sandstone, siltstone, mudstone, shale, coal, limestone, and dolomite. The sandstone and limestone beds are the most productive aquifers in these rocks.

Lower Mesozoic (Triassic and Lower Jurassic) sedimentary rocks are in deep, elongate basins in the Piedmont Province (figs. 8 and 9). The basins formed in rifts in the Earth's crust and are oriented roughly parallel to the modern coast. Some incompletely mapped basins are buried beneath Coastal Plain sediments. The Newark Basin in north-central New Jersey and adjacent parts of New York and Pennsylvania is the largest early Mesozoic basin in eastern North America. The sedimentary rocks in the basins have been tilted and faulted, but are not metamorphosed and deformed to the same extent as the older rocks that surround the basins.

The sedimentary rocks in the basins are primarily conglomerate, sandstone, shale, and siltstone, with minor limestone and coal. These rocks are interlayered with basalt flows and intruded by diabase dikes and sills. The conglomerate and sandstone are the most productive aquifers.

Semiconsolidated to unconsolidated sediments of Cretaceous and younger age in the Coastal Plain Province form a band that narrows toward the northeast and is parallel to the coast (fig. 8). The sediments, especially those of Cretaceous age, thicken greatly toward the coast in subsurface basins in Maryland, Delaware, and part of New Jersey but are much thinner on structurally high areas to the north and south. Most of the Coastal Plain sediments are sand, clay, and silt, with minor gravel and lignite; limestone is locally prominent, particularly in North Carolina. The sediments were deposited mostly in shallow marine environments when sea level was higher relative to the land surface than at present, or in the floodplains and deltas of rivers that drained the landmass to the north and west. The sands and limestones are the most productive aquifers.

All three categories of sedimentary rocks have been divided into numerous formations. The geologic and hydrogeologic nomenclature used in this report 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 names. Therefore, the nomenclature used in this report is basically a synthesis of that of the U.S. Geological Survey, the Delaware Geological Survey, the Maryland Geological Survey, the New Jersey Geological Survey, the North Carolina Geological Survey, the Pennsylvania Bureau of Topographic and Geologic Survey, the Virginia Division of Mineral Resources, and the West Virginia Geological and Economic Survey. Individual sources for nomenclature are listed with each correlation chart prepared for this report.

Quaternary deposits are in the extreme northern parts of all the physiographic provinces except the Coastal Plain (fig. 6). These deposits are predominately unsorted and unstratified glacial material (till) that ranges in size from clay to coarse gravel and boulders. Sand and gravel are present as outwash deposits that formed along the glacial front (the southern limit of glaciation) and as Holocene alluvium in major river valleys.

The area mapped in figure 8 contains four broad geologic categories (fig. 9). From northwest to southeast, these are: flat to gently folded Paleozoic sedimentary rocks that underlie the Appalachian Plateaus and the Central Lowland Physiographic Provinces; the same types of rocks folded into a series of anticlines and synclines in the Valley and Ridge Physiographic Province; metamorphic and igneous rocks of the Piedmont and the Blue Ridge Physiographic Provinces that contain large areas of tilted sedimentary rocks and lava flows in early Mesozoic basins, and smaller areas of faulted and folded blocks of Paleozoic sedimentary rocks that have undergone various degrees of metamorphism; and gently dipping, semiconsolidated to unconsolidated sediments of the Coastal Plain Physiographic Province. The combination of rock

type and geologic structure largely determines the hydraulic properties of the rocks. These factors, plus topography and climate, determine the characteristics of the ground-water flow system throughout the mapped area.

GROUND-WATER QUALITY

The concentration of dissolved solids in ground water provides a basis for categorizing the general chemical quality of the water. Dissolved solids in ground water primarily result from chemical interaction between the water and the rocks or unconsolidated deposits through which the water moves. Rocks or deposits composed of minerals that are readily dissolved will usually contain water that has large dissolved-solids concentrations. The rate of movement of water through an aquifer also affects dissolved-solids concentrations; the longer the water is in contact with the minerals that compose an aquifer, the more mineralized the water becomes. Thus, larger concentrations of dissolved solids commonly are in water at or near the ends of long ground-water flow paths. Aquifers that are buried to great depths commonly contain saline water or brine in their deeper parts, and mixing of fresh ground water with this saline water can result in a large increase in the dissolved-solids concentration of the freshwater. Contamination as a result of human activities can increase the concentration of dissolved solids in ground water; such contamination usually is local but can render the water unfit for human consumption or for many other uses.

The terms used in this report to describe water with different concentrations of dissolved solids are as follows:

Dissolved-solids concentration, in milligrams per liter

Freshwater	Less than 1,000
Slightly saline water	1,000 to 3,000
Moderately saline water	3,000 to 10,000
Very saline water	10,000 to 35,000
Brine	Greater than 35,000

FRESH GROUND-WATER WITHDRAWALS

Ground water is the source of public supply for almost 7 million people in Segment 11, or about 19 percent of the population in the seven-State area. About 2,600 million gallons per day was withdrawn from all the principal aquifers during 1985; 33 percent of this amount was withdrawn for public supply. Withdrawals by self-supplied industries and for mining accounted for 22 percent of the total water withdrawn.

Counties with the largest withdrawals in Segment 11 generally are those that contain large population centers. Such counties include those around Pittsburgh, Pa., the Philadelphia, Pa.-Camden, N.J. area; and the parts of New Jersey in the New York City metropolitan area (fig. 10). Large withdrawals are associated with mining activity in eastern North Carolina and with paper manufacturing in southeastern Virginia. Fresh ground-water withdrawals for most water-use categories increased through 1985, according to a nationwide compilation of water-use data by the U.S. Geological Survey.

The largest withdrawals of ground water, 1,029 million gallons per day, were from the Northern Atlantic Coastal Plain aquifer system, which accounted for about 40 percent of all ground-water withdrawals in the segment during 1985 (fig. 11). Withdrawals from aquifers in the Piedmont and the Blue Ridge Provinces during the same period were 634 million gallons per day. Withdrawals from aquifers in the Valley and Ridge Province were 371 million gallons per day, primarily in Pennsylvania and Virginia. Withdrawals from unconsolidated sand and gravel aquifers of the surficial aquifer system were 320 million gallons per day. In the Appalachian Plateaus Province, withdrawals were 282 million gallons per day, most of which was withdrawn in Pennsylvania and West Virginia.

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Northern Atlantic Coastal Plain aquifer system

INTRODUCTION

The Northern Atlantic Coastal Plain aquifer system consists of six regional aquifers in sedimentary deposits that range in age from Early Cretaceous to Holocene. The aquifer system underlies an area of about 50,000 square miles in Segment 11 and extends from the North Carolina-South Carolina State line northward to Raritan Bay, N.J. (fig. 18). The western limit of the aquifer system is the landward edge of water-yielding Coastal Plain strata where they pinch out against crystalline rocks of the Piedmont Physiographic Province at the Fall Line. Although the aquifers included in the aquifer system extend beneath the Atlantic Ocean and, in places, contain brackish water or freshwater under nearshore parts of the Continental Shelf, the eastern limit of the aquifer system is, for all practical purposes, the shoreline. The Northern Atlantic Coastal Plain aquifer system grades southward into the Southeastern Coastal Plain aquifer system, which is described in Segments 5 and 6 of this Atlas; the part of the coastal plain that underlies Long Island is described in Segment 12.

The northern part of the Atlantic Coastal Plain is underlain by a wedge-shaped mass of semi-consolidated to unconsolidated sediments that thickens toward the ocean and restson a surface of crystalline rock (fig. 19). The thickness of the sediments shown in figure 19 at the New Jersey coastline is about 4,000 feet, but the sediments attain thicknesses of as much as 8,000 feet along the coast of Maryland and 10,000 feet along the coast of North Carolina. The sediments consist of lenses and layers of clay, silt, and sand, with minor amounts of lignite, gravel, and limestone. The sand, gravel, and limestone compose aquifers of varying extent;

some are traceable over long distances, whereas others are local. The aquifers are separated by confining units of clay, silt, and silty or clayey sand. Although water moves more readily through the aquifers than through the confining units, water can leak through the confining units, especially where they are thin or where they contain sand; the aquifers, therefore, are hydraulically interconnected to some degree.

The aquifers and confining units that underlie the Coastal Plain vary considerably in thickness (fig. 20). Much of this variation is because the sediments that contain these hydrologic units were deposited on an irregular crystalline-rock surface that was warped by tectonic forces so as to form arches that alternate with troughs or embayments. The three areas where the crystalline rock is arched upward in figure 20 are, from left to right, the Cape Fear Arch and the Norfolk and the South New Jersey Highs. The intervening downwarped areas, from left to right, are the Albemarle and the Salisbury Embayments. The arches were not always upwarped, however, nor were the embayments always downwarped. For example, the sediments that compose the Peedee-upper Cape Fear aquifer are thicker atop the Cape Fear Arch than in the Albemarle Embayment. This indicates that the Cape Fear Arch was downwarped during the time that the sediments that compose this aquifer were deposited. Likewise, thinning of the sediments of the Severn-Magothy aquifer into the Salisbury Embayment indicates that the embayment was not downwarped while these sediments were accumulating. Potomac aquifer sediments thin across all the arches and thicken into all the embayments shown in figure 20, which indicates that the crystalline-rock surface had the same configuration when those sediments were deposited as it has now.

The sediments that compose the Northern Atlantic Coast-al Plain aquifer system were deposited in nonmarine, marginal marine, and marine environments. Lower Cretaceous sediments were deposited mostly by streams in alluvial and deltaic environments. From Late Cretaceous through early Ter-tiary time, a series of marine transgressions covered most of the Atlantic Coastal Plain, and shallow marine to marine environments prevailed. A general regression of the sea began during late Tertiary time, when nonmarine Miocene sediments were deposited in New Jersey and parts of Maryland. Post-Miocene sediments are mostly Quaternary nonmarine clastic rocks.

Interbedding of fine- and coarse-grained Coastal Plain sediments is complex because of shifting deltaic and alluvial deposition sites and because of repeated transgressions and regressions of the sea. Sediment types and textures, accordingly, can change greatly within short horizontal or vertical distances. Bodies of sand, gravel, or limestone can change facies laterally and become clayey or silty and, thus, less permeable. Therefore, many local aquifers can be identified, but these local aquifers can be grouped on the basis of similar hydrologic characteristics and treated as regional aquifers. Six regional aquifers separated by four regional confining units make up the Northern Atlantic Coastal Plain aquifer system (fig. 21).

Except for the surficial aquifer, which is named for its location at the land surface, the name

applied to each regional aquifer is taken from one or more of the geologic formations or groups that compose the aquifer. The names chosen are taken from the geologic units that are the most widespread and (or) compose the more productive aquifers. Use of an aquifer name in a given State does not necessarily mean that the geologic formation from which the name is derived is recognized in that State. For example, the Potomac aquifer (fig. 21) is named for permeable sediments that are part of the Potomac Formation (or Group), which is a geologic name used in Virginia, Maryland, Delaware, and New Jersey. The Potomac aquifer also is mapped in North Carolina even though equivalent sediments there are called by different names. Combined aquifer names couple the name of the youngest, most extensive water-yielding formation with that of the oldest, most extensive water-yielding formation. An example is the Castle Hayne-Aquia aquifer in sediments of Oligocene through Paleocene age (fig. 21). The Castle Hayne Formation of North Carolina and the Aquia Formation of Virginia and Maryland form the most productive, most extensive parts of this regional aquifer.

VERTICAL SEQUENCE OF AQUIFERS

The Coastal Plain aquifers in Segment 11 are, in descending order, the surficial aquifer (fig. 22), the Chesapeake aquifer (fig. 23), the Castle Hayne-Aquia aquifer (fig. 24), the Severn-Magothy aquifer in the northern part of the segment (fig. 25), the Peedee-upper Cape Fear aquifer in the southern part (fig. 25), and the Potomac aquifer (fig. 26). The boundaries of the aquifers are irregular, as shown in these figures, and none of the aquifers extends over the whole Coastal Plain. The regional aquifers consist of various geologic formations and, in most places, are vertically separated by clayey or silty confining units that retard the vertical flow of ground water. The aquifers contain saline water in places, especially near the modern coastline, but they are mapped wherever the sediments that compose them are permeable, regardless of the chemical quality of the water in the sediments. The Castle Hayne-Aquia aquifer is absent in part of the Delmarva Peninsula (fig. 24) because the sand beds of the aquifer contain more clay and are less permeable toward the coast.

The surficial aquifer is the uppermost aquifer in the aquifer system (fig. 22). This aquifer consists of unconsolidated, locally gravelly sand, mostly of Quaternary age. Although a thin blanket of unconsolidated sediments makes up the uppermost Coastal Plain beds over wide areas, these sediments mostly are unsaturated or else yield little water to wells. The aquifer is mapped in figure 22 only in those areas where wells completed in the aquifer can be expected to yield at least 50 gallons per minute.

The Chesapeake aquifer (fig. 23) underlies the surficial aquifer in most places, but the two aquifers are separated by a clayey confining unit. The Chesapeake aquifer consists mostly of sand beds of Miocene age. Phosphate of mineable concentration is in sands of the aquifer in North Carolina.

The Castle Hayne-Aquia aquifer (fig. 24) underlies the Chesapeake aquifer; a clayey confining unit separates the two aquifers everywhere. In North Carolina, the Castle Hayne-Aquia aquifer is mostly limestone of the Castle Hayne Formation that produces large volumes of water. Further northward, the aquifer is mostly glauconitic sand.

The Severn-Magothy aquifer underlies the Castle Hayne-Aquia aquifer from New Jersey southward to the Delmarva Peninsula (fig. 25). The Peedee-upper Cape Fear aquifer, which is the southern equivalent of the Severn-Magothy aquifer, is present from southeastern Virginia to the North Carolina-South Carolina border. Both aquifers consist of fine to medium sand, and are overlain by a silt and clay confining unit. The Peedee-upper Cape Fear and the Severn-Magothy aquifers are absent in most of Virginia.

The Potomac aquifer (fig. 26) is the lowermost and most widespread aquifer of the aquifer system. The Potomac aquifer consists of fine to coarse sand beds and is separated from overlying aquifers everywhere by a confining unit of clay and sandy clay.

SURFICIAL AQUIFER

The surficial aquifer extends over large parts of the Del-marva Peninsula and the eastern coastal plain of North Carolina. Although thin surficial deposits yield small volumes of water to rural and domestic wells in a large part of the Coastal Plain, the surficial aquifer is defined as a principal Coastal Plain aquifer in this report only where it is capable of yielding at least 50 gallons of water per minute to wells or where the use of underlying aquifers is restricted because the deeper aquifers contain saline water. The surficial aquifer consists of unconsolidated sand and gravel of marine and nonmarine origin, depending on the locality. Many small-scale aquifers constitute the surficial aquifer.

The surficial aquifer consists of sand of Pleistocene age and beach and dune deposits of Holocene age on the Cape May Peninsula at the southern tip of New Jersey where the aquifer is underlain by a clay confining unit that separates it from the deeper Chesapeake aquifer. The surficial aquifer attains its greatest thicknesses in buried channels in the Del-marva Peninsula. Elsewhere in Segment 11, the average thickness of the aquifer is generally 50 feet or less. Near the Delaware-Maryland State boundary, the surficial aquifer directly overlies water-yielding beds of the Chesapeake aquifer. In that area, the combined beds act as a single aquifer.

The surficial aquifer contains water predominately under unconfined conditions, but clay beds locally create confined conditions. Almost all the flow within the aquifer is local; that is, water moves from recharge areas along short flow paths to discharge to the nearest stream or other surface-water body. Some water, however, percolates downward to recharge the underlying aquifers.

The transmissivity of the surficial aquifer (the rate at which water will move through the aquifer) is variable. Transmissivity values for the aquifer are generally less than 1,000 feet squared per day except on the Delmarva Peninsula where they are commonly 8,000 feet squared per day. Locally, the transmissivity of the aquifer is as much as 20,000 feet squared per day in buried channels in Delaware and 53,000 feet squared per day in a paleochannel in Maryland. The aquifer is very thick in the places where the transmissivity values are largest.

The quality of water in the surficial aquifer is variable and partly reflects the chemistry of the precipitation that recharges the aquifer. In precipitation, dissolved sodium and chloride concentrations tend to be greater, and dissolved sulfate concentrations tend to be less, nearer the coastline than inland. The chemical composition of the precipitation is modified as the water percolates downward through the soil zone and then moves through the aquifer where it reacts chemically with aquifer minerals. Because the water follows short flow paths, its residence time is short in the surficial aquifer, and the dissolution of minerals is limited.

Where the surficial aquifer adjoins the coast or saltwater estuaries and where it occurs on offshore islands, it is usually hydraulically connected to saline water. Hydraulic heads (water levels) in the aquifer are only slightly above sea level in these low-lying land areas, and the depth to saline water may be shallow as a result. The same low-lying areas tend to be natural discharge areas for the aquifers that underlie the surficial aquifer. The water that is discharged upward from the deeper aquifers tends to be hard and highly mineralized. In these areas, only water in the upper part of the surficial aquifer might be suitable for use.

Water in the surficial aquifer is especially susceptible to contamination by human activities because the aquifer is exposed at the land surface. For example, nitrogen and lime that are added to the soil during crop production can enter the water. Livestock wastes and septic-tank fields also produce nitrogen, the end product of which is nitrate in the ground water. Local contamination also can result from seepage from landfills, leakage from underground storage tanks, chemical spills, and infiltration of urban contaminants.

Ground-water withdrawals from the surficial aquifer in Segment 11 are greatest on the Delmarva Peninsula where sands of Holocene to Pliocene age and some gravel beds of Miocene age constitute the aquifer. The distribution of major pumping centers during 1979 and 1980, excluding irrigation, is shown in figure 27. The aquifer is used locally in Virginia for domestic and agricultural supplies, and withdrawals from the aquifer in North Carolina are principally for the same uses. South of Chesapeake Bay, the surficial aquifer is typically thinner or contains more clay than in the Delmarva Peninsula. In North Carolina, the surficial aquifer is near the coast and in several counties near the South Carolina border. Throughout much of the coastal area, the surficial aquifer is recognized as a principal aquifer not because of its potential to yield large volumes of water, but because the underlying aquifers commonly contain saline water and their use is thus restricted.

Total fresh ground-water withdrawals from the surficial aquifer were about 120 million gallons per day during 1985. The largest withdrawals of water were concentrated near Salisbury, Md., and Dover, Del. (fig. 27). Water from the aquifer was used principally for agricultural supplies and domestic and commercial purposes, but substantial quantities also were used for public supply and for industrial, mining, and thermoelectric power supplies (fig. 28).

CHESAPEAKE AQUIFER

The Chesapeake aquifer is the uppermost regional aquifer of the Northern Atlantic Coastal Plain aquifer system. The aquifer consists of permeable beds in the Chesapeake Group of Oligocene to Pliocene age and their approximate stratigraphic equivalents. The top of the Chesapeake aquifer is mostly above sea level in New Jersey but is nearly 300 feet below sea level on the Outer Banks of North Carolina (fig. 29).

The Chesapeake aquifer in New Jersey includes the Cohansey Sand and most of the Kirkwood Formation, along with local terrace gravels. The local name of the Chesapeake aquifer is the Kirkwood-Cohansey aquifer system (fig. 21). In its thicker parts, confining units divide the Chesapeake aquifer into three local aquifers. The upper part of the aquifer is predominately fine to coarse sand that contains water mostly under unconfined conditions. The lower part is typically fine to medium sand that contains two thick clay beds near the coast. The maximum thickness of the Chesapeake aquifer in New Jersey is about 960 feet, but this includes about 450 feet of clay that forms local confining units in the lower part of the aquifer.

On the Delmarva Peninsula, the regional Chesapeake aquifer comprises six local sand aquifers, which consist of layers of medium to coarse, silty sand, and locally contain grav-el or shell fragments. The sands are separated by confining units of silty sand and clay. On the northwestern Delmarva Peninsula, the local aquifers are successively truncated and overlain from southwest to northeast by the surficial aquifer. Where the surficial and Chesapeake aquifers are in direct contact, they form a composite aquifer that contains water under unconfined, or water-table, conditions. The Chesapeake aquifer generally dips gently and thickens oceanward. Its total thickness exceeds 600 feet along the coast, but much of the thickening is due to clayey and silty sediments. The deeper and more southeasterly parts of the aquifer contain slightly saline to saline water. Only the upper part of the aquifer is important as a source of water in the Virginia part of the peninsula.

The Chesapeake aquifer in Maryland is not mapped west of Chesapeake Bay; sediments equivalent to the lower part of the aquifer extend west of the bay but consist mostly of clay and silt. The upper part of the Chesapeake aquifer west of the bay in Virginia is the local Yorktown-Eastover aquifer (fig. 21).

The Chesapeake aquifer in North Carolina is restricted to the northeastern part of the Coastal Plain. It consists of two local aquifers (fig. 21)-the upper (Yorktown) aquifer extends farther

west than the lower (Pungo River) aquifer. The Yorktown aquifer consists of fine shelly sand, silty sand, and shell beds, whereas the Pungo River aquifer consists of fine to medium phosphatic sand. Where both local aquifers are present, the maximum thickness of the Chesapeake aquifer is about 1,000 feet; the average thickness is about 330 feet.

Much of the water in the upper part of the Chesapeake aquifer is under unconfined conditions. The aquifer is closely connected to streams, and before pumping began, most of the water that entered the aquifer as recharge from precipitation moved only a few miles or less along flow paths to discharge to the streams (fig. 30). Some of the water, however, moved along longer flow paths to discharge to estuaries or the ocean. Where the water table was close to the land surface, some ground water discharged to the atmosphere through evaporation and transpiration. Where hydraulic heads (water levels) in the Chesapeake aquifer were higher than those in the underlying Castle Hayne-Aquia aquifer, a small part of the water in the Chesapeake aquifer moved downward across a confining unit and into the lower aquifer. In some areas, mostly near the coast, the hydraulic head in the Castle Hayne-Aquia aquifer was greater than that in the Chesapeake aquifer, and water moved upward from the deeper aquifer into the Chesapeake aquifer.

The Chesapeake aquifer is considered to be a principal aquifer only where the transmissivity of the aquifer is greater than 500 feet squared per day (fig. 29). In these areas, wells completed in the aquifer commonly yield 50 gallons per minute or more. Elsewhere, the aquifer may yield water, but not in quantities sufficient for most uses; therefore, it is considered to be a minor aquifer. The transmissivity of the aquifer generally increases toward the coast and reaches a maximum near the southern border of Delaware and in a small area of coastal New Jersey. The coastward increase in transmissivity reflects an increase in the thickness of the aquifer in these areas.

After withdrawals began, ground water continued to flow regionally in the same directions as before development, but some of the water that would have discharged to surface-water bodies or to the atmosphere under natural conditions was intercepted by wells. Flow paths shifted as water moved toward cones of depression that formed around pumping centers (fig. 31). By 1980, the potentiometric surface had been lowered over wide areas, which resulted in reduced evaporation and transpiration and increased recharge to the aquifer.

Withdrawals caused the potentiometric surfaces of the upper and lower parts of the aquifer to be different in parts of New Jersey, Delaware, and North Carolina. This is because thick confining beds within the aquifer impede vertical ground-water flow in these areas between the upper and lower parts of the aquifer. The lowering of the potentiometric surface induced saline water intrusion locally on the Cape May Peninsula and other coastal areas in New Jersey.

Water in the aquifers of the Northern Atlantic Coastal Plain aquifer system can be classified according to dominant dissolved cations and anions into the following hydrochemical facies

typical of ground water in the Northern Atlantic Coastal Plain: variable composition, calcium plus magnesium bicarbonate, sodium bicarbonate, and sodium chloride. To demonstrate the facies classification used, a sodium bicarbonate water is one in which sodium ions account for more than 50 percent of the total cations in the water and bicarbonate ions account for more than 50 percent of the total anions. Waters classified as variable composition have no ions that exceed 50 percent.

The hydrochemical facies in water from the upper part of the Chesapeake aquifer in Virginia and North Carolina follow a general coastward, or downdip, sequence from a variable-composition facies in aquifer outcrop areas to a calcium plus magnesium bicarbonate facies, then to a sodium bicarbonate facies, and finally to a sodium chloride facies (fig. 32). This sequence is generally characteristic of waters in the Coastal Plain aquifers. Also, the concentration of dissolved solids in the ground water increases in a seaward direction. The distribution of hydrochemical facies with respect to areas where the Chesapeake aquifer crops out and with respect to the coast, and the seaward increase in dissolved-solids concentration, are largely the result of natural (prepumping) ground-water flow patterns. The same sequence of hydrochemical facies occurs with increasingdepth in the aquifers and is accompanied by an increase in the dissolved-solids concentration in the water.

Over most of its extent in New Jersey, the Chesapeake aquifer is exposed at the land surface and contains water of the variable-composition facies (fig. 32). In a narrow band parallel to the coast, the mixing of that water with saline water resulted in a sodium chloride facies. Dissolved-solids concentrations are generally less than 250 milligrams per liter, except along the coast. Sulfate is present locally in water from the aquifer in central New Jersey, probably as a result of the oxidation of sulfide minerals, such as pyrite, in the aquifer.

The hydrochemical facies pattern on the Delmarva Peninsula (fig. 32) is, for the most part, the result of ground water movement from aquifer recharge areas in the central part of the peninsula toward the Atlantic Ocean and the Delaware Bay on the east and northeast and toward the Chesapeake Bay on the west. The water changes northwestward and southeastward from a variable-composition facies to a calcium plus magnesium bicarbonate facies. Some of the change in facies also is due to northwestward truncation of local aquifers that contain water of differing character.

In the western parts of the coastal plain of North Carolina and Virginia, the hydrochemical facies of water in the Chesapeake aquifer cannot be identified conclusively because data are too sparse. Accordingly, the water is designated as "variable composition." Dissolved-solids concentrations in water from this area are generally less than 250 milligrams per liter. Seaward of this area in North Carolina, dissolved-solids concentrations increase to more than 2,000 milligrams per liter near the Albemarle Sound and the coast. Fossil shell material in the aquifer is a source of dissolved calcium and magnesium in the broad area mapped as calcium plus magnesium bicarbonate facies. Further eastward, clayey material in the aquifer acts as a

natural softening agent, exchanging sodium ions for calcium to produce the sodium bicarbonate facies. The mixing of fresh ground water with saline water in the low-lying coastal area causes an increase in the dissolved-solids concentration of the water and a change to sodium chloride facies.

Total freshwater withdrawals from the Chesapeake aquifer during 1985 were estimated to be 195 million gallons per day. The distribution of major pumping centers, excluding irrigation, during 1979 and 1980 is shown in figure 33. The largest withdrawals of water were in New Jersey, although pumping centers on the Delmarva Peninsula also withdrew large volumes of water. Withdrawal centers in eastern North Carolina and southeastern Virginia pumped only small to moderate volumes of water.

About one-half of the freshwater withdrawn from the Chesapeake aquifer during 1985 (about 95 million gallons per day) was used for public supply (fig. 34). About 45 million gallons per day was withdrawn for domestic and commercial use. Agricultural withdrawals accounted for about 39 million gallons per day during 1985, and only about 16 million gallons per day was withdrawn for industrial, mining, and thermoelectric power uses.

CASTLE HAYNE-AQUIA AQUIFER

The Castle Hayne-Aquia aquifer extends from New Jersey southward to southeastern North Carolina (fig. 35). The aquifer consists mostly of permeable strata of Eocene and Paleocene age but locally includes rocks of Oligocene age. The top of the aquifer is about at sea level in most places near its northwestern limit and slopes seaward to depths of more than 750 feet below sea level in New Jersey and more than 1,250 feet below sea level on the Outer Banks of North Carolina. The aquifer is absent in the southwestern one-third of the Delmarva Peninsula, where its permeable beds grade eastward into clay. A clayey confining unit overlies the aquifer almost everywhere and is thickest on the western shore of the Chesapeake Bay in Maryland where it consists of as much as 250 feet of diatomaceous clay.

In New Jersey, the regional Castle Hayne-Aquia aquifer consists of the local Piney Point and Vincentown aquifers (fig. 21), which are thin sand aquifers within a thick confining unit of silt and clay. The name "Piney Point aquifer" is applied in this chapter to permeable, fine to coarse, glauconitic sand (fig. 36) that was formerly correlated in New Jersey as the Eocene Piney Point Formation but is now (1996) considered to be a separate, younger, unnamed sand that is hydraulically connected to permeable sands of the Piney Point Formation in Maryland. The underlying Vincentown aquifer consists of sparsely glauconitic quartz sand and fossiliferous, calcareous, quartz sand. In Burlington, Ocean, and Monmouth Counties, N.J., moderately permeable sand of the Vincentown aquifer grades southeastward into silt and clay within a few miles of the outcrop area of the aquifer. In this area, the Vincentown aquifer is laterally separated from the Piney Point aquifer by less permeable sediments (fig. 35). The maximum thickness of the Castle Hayne-Aquia aquifer in New Jersey is 220 feet, and the

average thickness is about 90 feet.

The regional Castle Hayne-Aquia aquifer in Delaware, Maryland, and Virginia is subdivided into two local aquifers (fig. 21). The upper aquifer, which is called the Piney Point-Nanjemoy aquifer in Delaware and Maryland and the Chickahominy-Piney Point aquifer in Virginia, consists of medium to coarse glauconitic sand mainly in the Piney Point and the Nanjemoy Formations. The lower aquifer, which is called the Aquia-Rancocas aquifer in Delaware and Maryland and the Aquia aquifer in Virginia, consists of glauconitic sand of the Aquia Formation or the Rancocas Group. The upper aquifer consists predominately of Eocene sands, but contains some sands of Oligocene age; the lower aquifer consists of Paleocene sands. The aquifers are separated by a silt and clay confining unit that ranges in thickness from a few feet in southern Virginia to as much as 210 feet in northeastern Maryland. The maximum thickness of the Castle Hayne-Aquia aquifer in Delaware, Maryland, and Virginia exceeds 460 feet, and the average thickness is about 140 feet.

In North Carolina, the regional Castle Hayne-Aquia aquifer consists of two local aquifers-the Castle Hayne aquifer (a major aquifer) and the underlying, less important Beaufort aquifer. The Castle Hayne aquifer is limestone, sandy marl, and fine to coarse limey sand. It includes most of the Eocene Castle Hayne Formation and the lithologically similar Oligocene River Bend Formation. This aquifer is restricted to the eastern one-half of the North Carolina Coastal Plain, and its average thickness is about 185 feet. The Beaufort aquifer, which is fine to medium glauconitic sand, contains thin beds of shell and limestone. It extends farther north and south than the Castle Hayne aquifer, but its thickness is generally less than 50 feet. The two aquifers are separated by a confining unit of silt, clay, and sandy clay that is generally less than 50 feet thick but is as much as 180 feet thick along the coast.

The Castle Hayne-Aquia aquifer is considered to be a major aquifer except for areas where the transmissivity of the aquifer is less than 1,000 feet squared per day (fig. 35). In these areas of low transmissivity, which are mostly in Virginia, Maryland, and Delaware, the aquifer is thin. It thins westward because it pinches out as a result of erosion, but the eastward thinning is the result of a change in facies from sand to clay. The transmissivity of the aquifer is highest in southeastern North Carolina, where it is mostly a thick section of highly permeable limestone.

Before ground-water withdrawals began, water moved from recharge areas of higher altitude along the western limit of the aquifer toward rivers, estuaries, bays, and the Atlantic Ocean (fig. 37). In New Jersey, flow was generally toward the ocean, the Delaware River, and the Delaware Bay. Flow in the western shore of Maryland was from the northwestern limit of the aquifer toward both the Potomac River and Chesapeake Bay. A ground-water divide on the Delmarva Peninsula separated flow to Chesapeake Bay from flow to Delaware Bay. In Virginia, flow was generally along shorter flow paths from recharge areas toward the major rivers. The regional movement of water in North Carolina was eastward, along long flow paths from recharge areas that are less than 50 feet above sea level (except for local areas in Bertie,

Lenoir, and Duplin Counties) toward sounds and the ocean.

In addition to lateral flow, water also entered and left the Castle Hayne-Aquia aquifer from overlying and underlying aquifers by vertical leakage through confining units. Because the Castle Hayne-Aquia aquifer is buried throughout most of its extent, it does not receive recharge directly from precipitation and does not discharge by evapotranspiration. Nevertheless, where the aquifer is near the surface, most of the ground water moved through local flow systems in which water entered the aquifer by downward leakage through a confining unit and discharged a short distance away by upward leakage to another aquifer or to a stream.

Ground-water withdrawals lowered the hydraulic head in the aquifer and formed cones of depression in its potentiometric surface (fig. 38). The direction of ground-water flow was changed in and around the pumping centers, and was reversed from the prepumping flow direction in some places (compare figs. 37 and 38). Heads have declined in small areas in New Jersey and the western shores of Maryland and Virginia as a result of withdrawals at pumping centers. The most prominent areas of decline in hydraulic head are in the central Del-marva Peninsula, where water is withdrawn from the local Piney Point and Aquia-Rancocas aquifers for public supply and in the southern part of the North Carolina Coastal Plain, where large volumes of water have been withdrawn from the local, highly productive Castle Hayne aquifer for mining uses and public supply.

Water in the Castle Hayne-Aquia aquifer changes in a seaward direction from a calcium plus magnesium bicarbonate hydrochemical facies along most of the western margin to a sodium bicarbonate facies in the middle parts and then to a sodium chloride facies near the coast (fig. 39). Dissolved-solids concentrations in the water increase seaward from the landward margins of the aquifer. These distributions are mostly the result of natural ground-water flow patterns. Whole or broken fossil shell material characterizes the aquifer from New Jersey southward through Virginia; in North Carolina, the aquifer is mostly limestone. Chemical reactions between ground water and the shell material or limestone minerals within the aquifer near its western limit are predominately dissolution and precipitation of calcareous material, which results in a calcium plus magnesium bicarbonate hydrochemical facies. This facies is especially widespread in North Carolina because of the abundant calcium and magnesium carbonate in the Castle Hayne aquifer.

The band of sodium bicarbonate facies in the aquifer is broader from New Jersey through Virginia than in North Caroina. In this band, ion-exchange reactions predominate. Glauconite is abundant in the aquifer north of North Carolina and is the principal agent in the exchange of sodium for calcium ions, a process that produces a sodium bicarbonate type water. The sodium chloride facies is in much of the low-lying coastal area, particularly in North Carolina, where the mixing of freshwater with saline water is the most important chemical process.

A small area of variable-composition facies is situated along the outcrop of the aquifer in Anne Arundel County, Md. Because the hydraulic gradient is steep, the ground water moves rapidly and is in contact with aquifer minerals for only a brief time. Accordingly, the water does not assume a distinctive chemical type.

The distribution of major pumping centers that withdrew water from the Castle Hayne-Aquia aquifer during 1979 and 1980 for all purposes except irrigation is shown in figure 40. The largest withdrawals were in North Carolina. During 1980, 67 million gallons per day were pumped from the aquifer in Beaufort County, N.C., to lower the pressure in the aquifer under open-pit phosphate mines and to wash and process the phosphate ore. Large volumes of water also were withdrawn in North Carolina for public supplies for the cities of New Bern, Jacksonville, and Wilmington. Most of the water withdrawn from the aquifer in pumping centers in Virginia and northward was used for public supplies and domestic and commercial uses.

Total fresh ground-water withdrawals from the Castle Hayne-Aquia aquifer were estimated to be 164 million gallons per day during 1985. The amount of water withdrawn was much greater in North Carolina than in the other Segment 11 States combined, and the use of the water also was much different (fig. 41).

About 76 percent of the total withdrawals, or about 125 million gallons per day, were in North Carolina (fig. 41A). Most of the water withdrawn in North Carolina was used for mining, industrial, and thermoelectric power purposes, with about 88 million gallons per day being pumped for this use; most of this water was used by the mining industry. Withdrawals in North Carolina for domestic and commercial, public supply, and agricultural uses were about 21, 13, and 4 million gallons per day, respectively.

About 24 percent of the total withdrawals, or about 39 million gallons per day, were in Virginia, Maryland, Delaware, and New Jersey (fig. 41B). About 46 percent of the water withdrawn, or about 18 million gallons per day, was pumped for domestic and commercial uses. Withdrawals for public supply were about 14 million gallons per day. About 5 million gallons per day was withdrawn for mining, industrial, and thermoelectric power use, and about 2 million gallons per day was withdrawn for agricultural purposes.

SEVERN-MAGOTHY AQUIFER

The Severn-Magothy aquifer underlies most of the New Jersey Coastal Plain and the Delmarva Peninsula and is on the Maryland part of the western shore of Chesapeake Bay (fig. 42). The aquifer consists of permeable sand beds of Late Cretaceous age. The top of the aquifer is slightly above sea level along its northwestern limit and slopes southeastward to depths of more than 2,000 feet below sea level. Except where it crops out near its western limit, the aquifer is overlain by a confining unit of silt and clay.

The Severn-Magothy aquifer in New Jersey consists of three local aquifers (fig. 21), which are named for the geologic units that compose the aquifers. From top to bottom, these are the Wenonah-Mount Laurel aquifer, the Englishtown aquifer, and the upper (Magothy) part of the Potomac-Raritan-Magothy aquifer. The Wenonah-Mount Laurel aquifer is predominately fine to medium glauconitic sand; the Englishtown aquifer is fine to medium sand and has some beds of clay and silt; and the Magothy aquifer typically consists of well-stratified to crossbedded, fine to medium sand. Each of the local aquifers is separated from the underlying aquifer by a confining unit of clay and silt. The confining unit between the Wenonah-Mount Laurel and the Englishtown aquifers is generally from 25 to 70 feet thick; the one that underlies the Englishtown aquifer is generally from 100 to 400 feet thick and effectively isolates the deep Magothy aquifer from the overlying aquifers. The maximum thickness of the Severn-Magothy aquifer in New Jersey exceeds 720 feet, and the average thickness is about 340 feet.

In Delaware, Maryland, and the Eastern Shore of Virginia, the Severn-Magothy aquifer consists of sand beds in the Severn Formation, the Mount Laurel Sand, the Matawan Formation (or Group), and the Magothy Formation. The sands are generally similar in lithology to their equivalents in New Jersey, except that the sands of the Severn, the Mount Laurel, and the Matawan are thinner, finer grained, and contain more clay than those in New Jersey; the Magothy Formation, therefore, contains the principal water-yielding sands. Confining units of finer grained, and contain more clay than those in New Jersey; the Magothy Formation, therefore, contains the principal water-yielding sands. Confining units of clay and silt separate the local Severn and Matawan aquifers and the local Matawan and Magothy aquifers. Each of the confining units is generally from 50 to 75 feet thick in Delaware but is thinner in Maryland and Virginia. The maximum thickness of the Severn-Magothy aquifer in Delaware, Maryland, and Virginia is about 385 feet; the average thickness is about 185 feet.

In a few local areas, the transmissivity of the Severn-Magothy aquifer is less than 1,000 feet squared per day (fig. 42). The aquifer is thin in these areas and generally yields less than 50 gallons per minute to wells. Throughout most of its area, the aquifer has a transmissivity of less than 5,000 feet squared per day, but transmissivity values exceed 10,000 feet squared per day in two local areas in New Jersey.

Before development of the aquifer began, water levels in the upper part of the regional Severn-Magothy aquifer were more than 100 feet above sea level in places along a ground-water divide in the central part of the New Jersey Coastal Plain and in aquifer outcrop areas in Anne Arundel and Prince Georges Counties, Md. (fig. 43). Water levels were less than 50 feet above sea level on the Delmarva Peninsula. Regional ground-water movement was toward the Atlantic Ocean and Chesapeake, Delaware, and Raritan Bays. Before pumping began, the configuration of the potentiometric surface of the local Magothy aquifer (the lower part of the regional Severn-Magothy aquifer) was generally similar to that shown in figure 43. However, because recharge to the local Magothy aquifer in New Jersey was impeded by the substantial

thickness of the overlying clay and silt confining unit, water levels in the local Magothy aquifer were as much as 50 feet lower than those in the upper part of the regional Severn-Magothy aquifer. For the upper and lower parts of the Severn-Magothy aquifer, regional flow was along intermediate to long flow paths, and the water moved from outcrop recharge areas toward discharge areas at lowlands, major bays, and the Atlantic Ocean. In addition to the lateral flow, water also moved vertically into and out of the Severn-Magothy aquifer from overlying and underlying aquifers by leakage across confining units. Except in aquifer outcrop areas along its northwest ern boundary, the Severn-Magothy aquifer is covered by a confining unit and thus does not receive direct recharge by precipitation, nor does it discharge water by evapotranspiration.

Ground-water withdrawals caused a general decline in the potentiometric surface throughout the aquifer, created cones of depression in the potentiometric surface (fig. 44), and changed the directions of ground-water movement near pumping centers. In the upper part of the regional Severn-Magothy aquifer, withdrawals lowered the potentiometric surface to more than 150 feet below sea level in northeastern New Jersey. Hydraulic heads were lowered below sea level over much of the extent of the aquifer in eastern New Jersey, most of the Delmarva Peninsula, and part of the western shore of Maryland as a result of pumping. The lowered heads resulted in intrusion of saline water into the aquifer along Raritan Bay. The lowered hydraulic head in the Severn-Magothy aquifer in central Delaware is attributed in part to withdrawals from the overlying Castle Hayne-Aquia aquifer (local Piney Point aquifer), which caused water to move upward into the shallower aquifer through a leaky confining unit.

By 1980, water-level declines in response to withdrawals in southwestern New Jersey were larger in the lower part (local Magothy aquifer) of the regional Severn-Magothy aquifer than in the upper part. Much more water was pumped from the lower part of the regional aquifer than from the upper part, and the thick confining unit that overlies the lower part of the aquifer retarded recharge from above. The potentiometric surface was more than 75 feet below sea level in 1980 (fig. 44) in an area of central Camden County, New Jersey, where the predevelopment potentiometric surface of the upper part of the aquifer was more than 100 feet above sea level (fig. 43). Withdrawals loweredthe potentiometric surface below sea level throughout most of the lower part of the regional aquifer in New Jersey and resulted in saline water encroachment into the aquifer in Salem County, N.J., and along Raritan Bay.

Hydrochemical facies in the upper part of the Severn-Magothy aquifer show the same coastward sequence that is typical of water in aquifers of the northern Atlantic Coastal Plain-variable composition at the western margin, grading eastward to calcium plus magnesium bicarbon ate, grading, in turn, to sodium bicarbonate, and, finally, to sodium chloride in downdip parts of the aquifer (fig. 45). The facies generally appear vertically in the same sequence downward in the aquifer. Predevelopment ground-water flow patterns largely determine the distribution of hydrochemical facies and the seaward increase in dissolved-solids concentrations in the water. Local intrusion of saline water as a result of withdrawals is not

shown at this map scale.

The upper part of the regional Severn-Magothy aquifer contains glauconite in most places. Glauconite is active in base-exchange reactions-the mineral exchanges sodium ions for calcium ions, which naturally softens the water. This proc-ess is reflected by the broad band of sodium bicarbonate facies across the Delmarva Peninsula and New Jersey (fig. 45). Because the lower part of the Severn-Magothy aquifer on the western shore of Maryland does not contain glauconite, the base exchange process is less active, and the band of sodium bicarbonate facies is narrower. The dissolved-solids concentration in water from the upper part of the Severn-Magothy aquifer increases downdip to more than 2,000 milligrams per liter in southern New Jersey and the eastern Delmarva Peninsula (fig. 45). Mixing of freshwater with saline water in low-lying coastal areas is responsible for the large increase in dissolved solids and the change to a sodium chloride facies.

Major pumping centers that withdrew water from the Severn-Magothy aquifer during 1979 and 1980 were located mostly near its western limit (fig. 46). The greatest rate of withdrawal, by far, was in New Jersey; however, numerous pumping centers also withdrew water in Maryland. Total fresh ground-water withdrawals from the aquifer were estimated to be 173 million gallons per day during 1985 (fig. 47). Withdrawals in New Jersey were 151 million gallons per day during this period. Of the water withdrawn, 80 percent, or about 138 million gallons per day, was used for public supply. About 17 million gallons per day was withdrawn for industrial, mining, and thermoelectric power purposes. Withdrawals for domestic and commercial uses were about 14 million gallons per day, and only about 4 million gallons per day was withdrawn for agricultural use.

PEEDEE-UPPER CAPE FEAR AQUIFER

The regional Peedee-upper Cape Fear aquifer underlies most of the North Carolina Coastal Plain and extends into a small part of southeastern Virginia (fig. 48). The aquifer consists of permeable sands of the Peedee Formation, the Black Creek Formation, and the upper part of the Cape Fear Formation, all of Late Cretaceous age, and their stratigraphic equivalents in Virginia. The Peedee-upper Cape Fear aquifer is the lateral equivalent of the Severn-Magothy aquifer, but the two aquifers are not known to be connected. A clayey confining unit overlies the Peedee-upper Cape Fear aquifer in most places. The top of the aquifer is above sea level over much of the western part of the North Carolina Coastal Plain and slopes eastward to a depth of more than 3,000 feet below sea level at Cape Hatteras. The entire aquifer contains saline water in a large area in eastern North Carolina, approximately where the top of the aquifer is 1,000 feet below sea level or deeper. No fresh ground water circulates in the aquifer east of the line that represents water with 10,000 milligrams per liter chloride concentration (fig. 48).

The regional Peedee-upper Cape Fear aquifer in North Carolina consists of the local Peedee,

Black Creek, and upper Cape Fear aquifers (fig. 21), which are separated by confining units of clay and silt that generally range from 20 to 70 feet in thickness. The Peedee aquifer consists of fine tomedium glauconitic sand of the Peedee Formation, and contains shell material and calcareous sandstone beds. The Black Creek aquifer consists of very fine to fine lignitic, glauconitic, and shelly sand interbedded with clay of the Black Creek Formation, and fine to medium sand, with lenses of coarse sand and clay of the underlying Middendorf Formation. The Black Creek aquifer is the thickest and most productive of the three local aquifers. The upper Cape Fear aquifer consists mostlyof alternating beds of fine to medium sand and clay of the upper part of the Cape Fear Formation. The maximum thickness of the regional Peedee-upper Cape Fear aquifer is about 1,200 feet; the average is about 570 feet. The greater thicknesses are along the coast, but the aquifer contains saline water there.

In Virginia, sand beds equivalent to the upper part of the Cape Fear Formation have been assigned to the local upper Potomac aquifer (fig. 21). Beds equivalent to the local Peedee and Black Creek aquifers are mostly absent in Virginia. The average thickness of the regional Peedee-upper Cape Fear aquifer in Virginia is about 95 feet.

Where the transmissivity of the Peedee-upper Cape Fear aquifer is less than 1,000 feet squared per day (fig. 48), the aquifer is considered to be a minor aquifer. Wells completed in the aquifer in this low-transmissivity area yield less than 50 gallons per minute. By contrast, in some areas, the transmissivity of the aquifer is greater than 10,000 feet squared per day; in such areas, yields of 1,000 gallons per minute or more are obtained from properly constructed wells.

The potentiometric surface of the Peedee-upper Cape Fear aquifer was more than 400 feet above sea level in the southwestern corner of the North Carolina Coastal Plain before ground-water withdrawals began (fig. 49). The high areas on the potentiometric surface coincide with the high altitude of the land surface. By contrast, the potentiometric surface in Virginia was less than 50 feet above sea level throughout the aquifer. Ground water moved regionally from areas of high hydraulic head, generally along the western limit of the aquifer, toward areas of low head along the coast and beneath sounds and estuaries. The direction of regional movement was eastward and southeastward along long flow paths. Locally, some water moved from recharge areas along short to intermediate flow paths and discharged to streams. In addition to the lateral flow indicated by the arrows in figure 49, water also leaked through confining units vertically into and out of the Peedee-upper Cape Fear aquifer from overlying or underlying aquifers that had hydraulic heads greater than those in the aquifer. Where the heads in the Peedee-upper Cape Fear aquifer were higher than those in adjacent aquifers, the leakage was reversed. Direct recharge by precipitation or discharge by evapotranspiration took place where the aquifer is exposed at the land surface.

The potentiometric surface of the aquifer has been lowered in and around pumping centers where large volumes of water are withdrawn. The direction of ground-water movement has

been changed or, in places, reversed so that flow is toward the pumping centers. Cones of depression (fig. 50) have formed in the potentiometric surface of the upper part of the aquifer around the areas where withdrawals are greatest. One large area of decline in southeastern Virginia is the result of pumping for public supply. Another area of decline in Beaufort County, N.C., is the result of large withdrawals from the Castle Hayne-Aquia aquifer. The withdrawals from this shallower aquifer, which are primarily for mining purposes, have induced upward leakage of water from the Peedee-upper Cape Fear aquifer through the confining unit that overlies it. The hydraulic head in the middle part of the Peedee-upper Cape Fear aquifer (the local Black Creek aquifer) has declined in the area of Kinston and Greenville, N.C. (fig. 50), but the decline is not evident in the potentiometric surface of the upper part of the aquifer. The decline is the result of withdrawals for public supply. Water levels in the local Black Creek aquifer have been drawn down more than those in the overlying local Peedee aquifer because most of the pumping wells are completed in the Black Creek aquifer and the confining unit that overlies the Black Creek aquifer is thicker and retards flow more effectively than the one above the Peedee aquifer.

The water in the upper part of the Peedee-upper Cape Fear aquifer is of variable composition over a large area in the western part of the North Carolina Coastal Plain (fig. 51). The processes of dissolution of shell material and precipitation of carbonate minerals predominate in the area where the water is a calcium plus magnesium bicarbonate type. In the southwestern part of the aquifer, the sodium bicarbonate facies is adjacent to the variable-composition facies; because the aquifer contains glauconitic sand and little or no shell material, the calcium plus magnesium bicarbonate facies is absent. A band of sodium bicarbonate facies is west of the widespread area of sodium chloride facies that is the result of mixing of saltwater and freshwater. The coastward progression of hydro-chemical facies is typical of that in other aquifers of the Northern Atlantic Coastal Plain and is mostly the result of predevelopment ground-water flow patterns.

In the areas of variable-composition and calcium plus magnesium bicarbonate facies, dissolved-solids concentrations in water from the upper part of the aquifer are generally less than 250 milligrams per liter. Dissolved-solids concentrations increase coastward to more than 2,000 milligrams per liter, mostly in the area of sodium chloride facies. In the easternmost part of the North Carolina Coastal Plain, water in the aquifer contains more than 10,000 milligrams per liter chloride (fig. 48) and probably as much as 20,000 milligrams per liter dissolved solids in some places.

Numerous pumping centers withdrew water from the Peedee-upper Cape Fear aquifer during 1979 and 1980 (fig. 52). Use of the aquifer was widespread during this period, especially toward its western margin. The largest withdrawals, however, were in the central parts of the aquifer, where several cities withdrew water for public supplies.

Total fresh ground-water withdrawals from the Peedee-upper Cape Fear aquifer were

estimated to be 126 million gallons per day during 1985 (fig. 53). Most of the water (about 58 million gallons per day) was withdrawn for public supply. Domestic and commercial withdrawals were about 40 million gallons per day, and about 28 million gallons per day were withdrawn for industrial, mining, and thermoelectric power uses.

POTOMAC AQUIFER

The regional Potomac aquifer underlies the entire Northern Atlantic Coastal Plain except for small areas near the Fall Line in Virginia, Maryland, and Delaware, and a multicounty area in the western part of the North Carolina Coastal Plain (fig. 54). The aquifer is the lowermost, and most widespread, aquifer of the Northern Atlantic Coastal Plain aquifer system. The Potomac aquifer consists mostly of permeable sands in the Potomac Formation (or Group) and their stratigraphic equivalents but includes younger, hydraulically connected, permeable sediments. The top of the aquifer is above sea level only in a narrow band near its western limit from New Jersey southward to Northampton County, N.C. The aquifer is more than 2,500 feet below sea level in southern New Jersey and on the easternmost part of the Delmarva Peninsula and more than 4,500 feet below sea level in easternmost North Carolina. A confining unit of clay and sandy clay overlies the aquifer in most places and is particularly effective in retarding vertical flow near Cape May, N.J., where its thickness is greater than 700 feet.

The regional Potomac aquifer in New Jersey includes the middle and lower aquifers of the Potomac-Raritan-Magothy aquifer system (fig. 21). The middle aquifer consists mostly of permeable beds of the Raritan Formation and the undifferentiated Potomac Formation and is mostly lenticular sand bodies interbedded with clay and silt, predominately of fluvial origin. The lower aquifer of the Potomac-Raritan-Magothy aquifer system is similar in lithology to the middle aquifer but contains more sand. The two local aquifers are separated by an indistinctly defined confining unit of clay and sandy clay that is generally from 50 to 150 feet thick where the regional Potomac aquifer contains freshwater but is more than 1,000 feet thick at the southeastern tip of New Jersey, where the aquifer contains saline water. The maximum thickness of the regional Potomac aquifer in New Jersey is about 3,400 feet, and the average thickness is about 630 feet. These thicknesses, as well as the those described below for the other States, include clay between the deepest permeable sand and bedrock and sands that contain saline water and effectively are not part of the aquifer.

The regional Potomac aquifer in Delaware and Maryland consists of the local Patapsco aquifer and the underlying local Patuxent aquifer, both named for sand and gravel formations of the Potomac Group that crop out in the northern part of the Maryland Coastal Plain. The Patapsco aquifer typically is lenses of fine to medium sand that range in length and width from a few feet to several miles, contain some gravel, and are separated by clay beds. The Patuxent aquifer typically is medium to coarse gravelly sand, and also is lenticular. A clayey confining unit that separates the two local aquifers generally is from 50 to 300 feet thick in northern Delaware and the western shore of Maryland, where the regional Potomac aquifer contains

freshwater, but is more than 900 feet thick at the mouth of Delaware Bay where the water in the aquifer is saline. The regional Potomac aquifer thickens and contains more clay to the southeast. The sediments that make up the Poto-mac aquifer are predominately of fluvial and deltaic origin. The maximum thickness of the aquifer in Delaware and Maryland is about 5,000 feet, and the average thickness is about 1,600 feet.

The regional Potomac aquifer in Virginia consists of the local middle and lower Potomac aquifers, which are approximately equivalent to the Patapsco and the Patuxent aquifers, respectively, of Maryland and Delaware, and consist of fine to coarse gravelly sand. The local middle and lower Potomac aquifers are separated by a clayey confining unit that generally is from 15 to 100 feet thick in the western part of the Coastal Plain where the regional Potomac aquifer contains freshwater and as much as 175 feet thick on the Delmarva Peninsula where the aquifer contains saline water. The maximum thickness of the regional Potomac aquifer in Virginia is about 4,600 feet, and the average thickness is about 800 feet.

The regional Potomac aquifer in North Carolina consists of two local aquifers-the lower Cape Fear aquifer and the Lower Cretaceous aquifer (fig. 21). The lower Cape Fear aquifer consists of fine to medium sand (interbedded with clay) of the lower part of the Cape Fear Formation and other hydraulically connected permeable sediments. The Lower Cretaceous aquifer is predominately fine to medium sand with a few beds of coarse sand and limestone, all of which are in Lower Cretaceous strata. These Lower Cretaceous beds are not exposed at the surface, are known only through data from a few wells, and have no formal stratigraphic names. The Lower Cretaceous aquifer has been defined only in the northern part of the North Carolina Coastal Plain; farther south along the coast, equivalent beds contain saline water. The maximum thickness of the regional Potomac aquifer in North Carolina is about 4,900 feet, and the average thickness is about 500 feet.

The Potomac aquifer is considered to be a major aquifer except for local areas in North Carolina where the transmissivity of the aquifer is less than 1,000 feet squared per day (fig. 54); in these low-transmissivity areas, the aquifer is thin. The aquifer thins westward because it has been partly eroded away, but the eastward thinning is due to a facies change from sand to clay. The coastward increase in clay and decrease in sand also is shown by the distribution of transmissivity in Virginia and northward. Transmissivity values increase eastward from the western limits of the aquifer to its central parts, mostly because the thickness of the aquifer steadily increases seaward. East of the high-transmissivity areas, the transmissivity of the aquifer decreases due to the eastward change in facies from sand to clay, even though the total thickness of the aquifer continues to increase.

The potentiometric surface of the regional Potomac aquifer was highest along its western limit and in a small area along the South Carolina-North Carolina State line before withdrawals began (fig. 55). The potentiometric surface was higher at or near the higher land altitudes and lowest where ground water discharged to major rivers, bays, and the Atlantic Ocean. Regional

ground-water movement was eastward and southeastward except in North Carolina where regional movement was toward the central part of the Coastal Plain. Water that contains concentrations of 10,000 milligrams per liter or more chloride marks the limit of the fresh ground-water flow system. Flow in North Carolina was effectively diverted by this saltwater body so that the ground water discharged to major streams in the central Coastal Plain. Only lateral flow is shown by the arrows in figure 55, but water also leaked vertically into and out of the Potomac aquifer from the overlying aquifers. The Potomac aquifer mostly is covered by confining units and thus receives little direct recharge by precipitation or discharges little water by evapotranspiration.

After withdrawals from the regional Potomac aquifer began, much of the flow was diverted toward major pumping centers, and large cones of depression formed in the potentiometric surface (fig. 56). A composite cone has developed over most of the New Jersey Coastal Plain and part of northern Delaware. By 1980, hydraulic heads in this area had declined to more than 25 feet below sea level throughout the area of the cone and to more than 100 feet below sea level in a small area in Delaware. Saline water has encroached into the aquifer along Raritan Bay, along the lower Delaware River in New Jersey, and around the harbor at Baltimore, Md., because of the lowered hydraulic heads. A prominent composite cone more than 100 feet below sea level around Franklin, Va., and more than 50 feet below sea level in much of southern Virginia also extends into North Carolina. The cone reflects large withdrawals for industrial use, primarily to supply paper mills at Franklin and West Point, Va.

Hydrochemical facies of water in the regional Potomac aquifer show the same general seaward progression from variable composition to sodium chloride facies as other Coastal Plain aquifers (fig. 57). The variable-composition facies, however, is only in small areas where the aquifer crops out in New Jersey and Maryland. Along much of the western boundary of the aquifer in Delaware, southwestern Maryland, and northern Virginia, the calcium plus magnesium bicarbonate facies prevails. This facies might be the result of recharge by downward leakage from overlying aquifers that contain carbonate minerals in the form of shell material. The predominance of sodium bicarbonate water in large areas of the aquifer results partly from ion-exchange reactions that take place in water that percolates downward through overlying aquifers and confining units to the regional Potomac aquifer and partly from ion-exchange reactions within the Potomac aquifer. Freshwater mixes with saline water in near-coastal areas of the aquifer and produces the sodium chloride facies.

Most of the major pumping centers that withdrew water from the Potomac aquifer during 1979 and 1980 were near its western margin (fig. 58). However, large withdrawals were made in Virginia in the central parts of the Coastal Plain. The pumping centers in Virginia mostly supplied water for industrial, mostly paper-manufacturing, uses; those farther northward mostly provided public supplies.

Total fresh ground-water withdrawals from the Potomac aquifer were estimated to be 251

million gallons per day during 1985 (fig. 59). Of this amount, about 54 percent, or about 135 million gallons per day, was withdrawn for public supply. Withdrawals for industrial, mining, and thermoelectric power uses were the second largest withdrawal category; about 90 million gallons per day was pumped for those uses. Domestic and commercial withdrawals were about 23 million gallons per day, and only about 3 million gallons per day was pumped for agricultural use.

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Piedmont and Blue Ridge aquifers

INTRODUCTION

Most of the Piedmont and the Blue Ridge Physiographic Provinces (fig. 60) is underlain by dense, almost impermeable bedrock that yields water primarily from secondary porosity and permeability provided by fractures. The bedrock in both provinces is partly covered by glacial deposits, which include productive sand and gravel aquifers that are part of the surficial aquifer system in northeastern Pennsylvania and northern New Jersey. The principal differences between the two provinces are relief, altitude, and geographic position. The Piedmont Province is characterized by lower altitudes and more subdued topography than the adjacent Blue Ridge, which is a province of mountain ridges to the northwest (fig. 61). In this report, the hydrology of the Reading Prong, a physiographic feature that is part of the New England Physiographic Province, but whose topography and rock types are similar to those of the Blue Ridge Province, is discussed with the latter.

The Piedmont Province is bounded on the southeast by the Fall Line (fig. 60), which is a zone of rapids or waterfalls that marks the position where streams flow from the consolidated rocks of the Piedmont onto semiconsolidated to unconsolidated rocks of the Coastal Plain. The western and northwestern boundaries of the Piedmont Province are, for most of their length, the base of a mountain ridge. This ridge is the highlands of the Reading Prong from northern New Jersey to northeastern Pennsylvania and the Blue Ridge Mountains from southern Pennsylvania to North Carolina. In the gap between the two mountain ridges, the Piedmont Province is adjacent to the Valley and Ridge Province, and the boundary between the

provinces is the northwestern edge of the early Mesozoic Gettysburg and Newark Basins (fig. 60).

The Piedmont Province can be subdivided topographically into lowland and upland areas. The lowlands are underlain by carbonate rocks (limestone, dolomite, and marble) and by clastic sedimentary rocks in early Mesozoic rift basins; these rocks are easily eroded. Extensive areas of carbonate rocks are concentrated in Pennsylvania; smaller areas are in Maryland. Locally, the early Mesozoic basins contain bodies of igneous rocks, such as basalt flows and diabase dikes and sills collectively called traprock. These igneous rocks are resistant to erosion and form low knobs and ridges (fig. 62) in the lowlands. Most of the province is uplands which are typically low, rounded hills and shallow valleys underlain by a complex assortment of metamorphic and igneous rocks of Paleozoic and Precambrian age. Locally, in such places as Washington, D.C., and Philadelphia, Pa., these crystalline rocks are at low altitudes and have low relief. Major structural lineaments and stratigraphic units strike predominately northeastward, but these alignments are not necessarily reflected by drainage patterns.

The Piedmont surface rises gradually westward to the Blue Ridge Mountain front, the highlands of the Valley and Ridge, or the Reading Prong. The western boundary of the Piedmont is at an average altitude of from 300 to 400 feet in New Jersey and is from 350 to 700 feet above sea level in Pennsylvania. The boundary rises to 700 or 800 feet above sea level in northern Virginia and farther south rises to about 1,500 feet above sea level near the Virginia-North Carolina State line.

The Blue Ridge Province (including the Reading Prong) in New Jersey and northern Pennsylvania consists of a narrow belt of rounded, gentle knobs of diverse altitude slightly higher than the adjacent Piedmont Province. From southern Pennsylvania to North Carolina, the eastern boundary of the Blue Ridge Province is the Blue Ridge front, which is a single, abrupt slope and commonly is marked by faulting. The Blue Ridge front rises more than 1,700 feet above the Piedmont surface near the North Carolina-Virginia State line and reaches a maximum height of nearly 2,500 feet in central North Carolina. The Blue Ridge Province contains the tallest mountains, highest altitudes (greater than 6,000 feet), and the most rugged topography in eastern North America (fig. 63). The southern part of the province is characterized by steep, forest-covered slopes cut by numerous stream valleys. The valleys of the major rivers include broad, gently rolling areas, as well as narrow gorges. In Segment 11, the province reaches a maximum width of 70 miles in North Carolina. Altitudes are much lower in the northern portion of the province.

Rocks of the Blue Ridge Province and the Reading Prong are, for the most part, many types of metamorphic and intrusive igneous rocks. In New Jersey, Pennsylvania, and North Carolina, however, sedimentary rocks (limestone, dolomite, conglomerate, sandstone, and shale) also are included in the province. In all these rocks, except limestone, dolomite, and marble, which contain solution openings, joints and fractures are the only openings that store and transmit

water. The main body of rock between the joints and fractures is almost impermeable.

HYDROGEOLOGIC UNITS

The Piedmont and Blue Ridge Provinces are underlain by three principal types of bedrock aquifers. In order of decreasing area, these are crystalline-rock and undifferentiated sedimentary-rock aquifers, aquifers in early Mesozoic basins, and carbonate-rock aquifers (table 1). Unconsolidated aquifers that are part of the surficial aquifer system overlie the bedrock aquifers locally in Pennsylvania and northern New Jersey.

Crystalline-Rock and Undifferentiated Sedimentary-Rock Aquifers

The most widespread aquifers in the Piedmont and Blue Ridge Provinces in Segment 11 are the crystalline-rock and undifferentiated sedimentary-rock aquifers. These aquifers extend over about 49,000 square miles, or about 86 percent of the area, of these provinces (table 1). Similar aquifers ex-tend southward into Segments 6 and 10 and northward into Segment 12 of this Atlas and are briefly discussed in the chapters describing these segments.

Most of the rocks that compose the crystalline-rock and undifferentiated sedimentary-rock aquifers are crystalline metamorphic and igneous rocks of many types. The main types of crystalline rocks are coarse-grained gneisses and schists of various mineral composition; however, fine-grained rocks, such as phyllite and metamorphosed volcanic rocks, are common in places. Most of the metamorphic rocks were originally sediments; some, however, were igneous rocks or volcan-ic tuff, ash, and lava flows. The degree of heat and pressure to which the original rocks were subjected, the nature of the fluids that have been in contact with the rocks, and the degree of folding and shearing that they have undergone have produced their present texture and mineralogy. Most of the metamorphic rocks have undergone several periods of metamorphism. Locally, they contain highly mineralized zones, some of which are ore bearing. During and after metamorphism, igneous rocks intruded the metamorphic rocks and are present as dikes, sills, and large to small plutons.

The undifferentiated sedimentary-rock aquifers consist of tightly cemented, predominately clastic rocks, many of which grade into metamorphic rocks. Undifferentiated sedimentary rocks are a minor component of the Blue Ridge Physiographic Province and are mainly along the western border of the province in North Carolina. Some of the sedimentary formations are in fault blocks. Most of the undifferentiated sedimentary rocks are of late Precambrian or early Paleozoic age, but in New Jersey, some are as young as middle Paleozoic.

Unconsolidated material called regolith (fig. 64) overlies the crystalline-rock and undifferentiated sedimentary-rock aquifers almost everywhere. The regolith consists of saprolite, colluvium, alluvium, and soil. Saprolite is a blanket of decomposed or partially decomposed rock that is usually thick and clayey, and whose texture varies depending on the

type of parent bedrock from which the saprolite is derived. Colluvium is weathered rock material that has slumped downward from hillsides. Alluvium consists mostly of water-transported sediment in stream valleys and channels. Because the regolith material varies greatly in thickness, composition, and grain size, its hydraulic properties also vary greatly. However, the regolith is everywhere more permeable than the underlying bedrock. Water in the bedrock is stored in and moves through fractures, which form the only effective porosity in the unweathered rock.

Aquifers in Early Mesozoic Basins

Aquifers in early Mesozoic rift basins are all within the Piedmont Province and occupy about 9 percent of the combined area of the Blue Ridge and the Piedmont Provinces (table 1). An additional 2 percent of the area of the combined provinces is occupied by the early Mesozoic Durham, Sanford, Wadesboro, and Davie County Basins in North Carolina (fig. 60), but the rocks in these basins are not considered to be significant aquifers. Aquifers in early Mesozoic basins are primarily in three major basins-the Newark Basin in New Jersey and Pennsylvania (fig. 60) is the largest basin and the one from which the most ground water is withdrawn; second largest is the Gettysburg Basin of Pennsylvania and Maryland; and third is the Culpeper Basin of Virginia. The Richmond Basin in Virginia and the Dan River-Danville Basin in Virginia and North Carolina are of intermediate size. Nine smaller early Mesozoic basins are in Virginia.

The early Mesozoic basins formed by downfaulting that accompanied rifting of the Earth's crust in the Triassic and Jurassic Periods during incipient stages of continental breakup and are filled mostly with thick sequences of sedimentary rocks (fig. 65). For the most part, major faults border the basins on the west and northwest, and the predominant direction of dip of the sedimentary rocks in the basins is toward these major border faults. Exceptions are the Durham and the Sanford Basins in North Carolina, which are bounded on the east by major faults; the dip of the beds in these basins is to the east or the southeast.

The lower Mesozoic rocks lie unconformably on Precambrian and Paleozoic crystalline rocks, and locally on Paleozoic sedimentary rocks in New Jersey. Sedimentary rocks in the basins consist predominately of interbedded shale, sandstone, and siltstone, all typically red, reddish brown, or maroon but locally gray or black. Conglomerate, dolomite, lacustrine black mudstone, and coal are present locally. In many places, the sedimentary rocks are interbedded with basalt flows (figs. 65 and 66) or have been intruded by diabase dikes and sills. Thicknesses of Triassic and Jurassic rocks in the larger basins have been calculated to be more than 20,000 feet.

Deposition of sediments in the early Mesozoic basins was controlled by a combination of intermittent faulting and subsidence of the basins, altitude of the bordering highlands, climate, and drainage patterns. A tropical climate prevailed in the basins during Triassic and Jurassic time. Temperatures were high and rainfall varied, but tended to be low. Sediments deposited

in lakes later became siltstone and mudstone, those deposited in swamps became black mudstone and coal, and river deposits and alluvial fans became sandstone and conglomerate. Lake levels varied; some lakes dried up seasonally, and the exposed sediment was oxidized and turned red. The sediments show evidence of cyclic repetition, which has been attributed to periodic changes in the Earth's climate.

The Newark Basin (fig. 60) extends from the Hudson River Valley to the divide between the Schuylkill and the Susquehanna Rivers in Pennsylvania. The Newark Basin contains three principal stratigraphic units. From oldest to youngest, these are the Stockton Formation of Triassic age, which is mainly soft feldspathic sandstone, shale, and some conglomerate; the Lockatong Formation of Triassic age, which is predominately gray and black siltstone and shale; and the Brunswick Group of Jurassic and Triassic age, which contains argillite, shale, siltstone, sandstone, conglomerate, and three basalt units. The igneous rocks that occur as sills and flows parallel to and interbedded with the sedimentary beds and as dikes and stocks that cut across them are resistant to erosion, and form hills. The Lockatong Formation, which is the least productive water-yielding sedimentary rock in the basin, is more resistant to erosion than the other sedimentary rocks and also underlies low hills.

The Gettysburg Basin stretches from the narrow neck that connects it to the Newark Basin about 80 miles westward and southward to near Frederick, Md. (fig. 60). The New Oxford Formation of Triassic age, which is composed of feldspathic sandstone, siltstone, and shale, is the lowermost formation in the Gettysburg Basin and is overlain in most places by red shale, siltstone, and fine sandstone of the Gettysburg Formation of Triassic and Jurassic age. The conglomeratic Hammer Creek Formation of Triassic age overlies the New Oxford Formation in the narrow neck between the Newark and the Gettysburg Basins. Basalt flows occur in the upper part of the Gettysburg Formation.

The Culpeper Basin of northern Virginia and adjacent Maryland (fig. 60) is an elongate, fault-bounded trough that trends north-northeast from the southern border of Madison County, Va., about 90 miles to Frederick County, Md. All the formations in the basin are part of the Culpeper Group. The lower part of the group consists of sandstone, siltstone, and conglomerate of Late Triassic age; the upper part consists of Lower Jurassic sedimentary rocks and interbedded basaltic lava flows.

The Richmond Basin stretches from just north of Richmond, Va., 35 miles south to the Dinwiddie-Amelia County border (fig. 60). The lowest stratigraphic unit in the basin is the Middle Triassic Tuckahoe Group, which contains siltstone, shale, and coal beds. It is overlain by the Upper Triassic Chesterfield Group, which consists of black shale and sandstone of the Vinita beds and the Otterdale Sandstone. The sedimentary rocks are cut by a few Late Jurassic diabase dikes. Small outliers near the Richmond Basin may have been connected to the original basin because they consist of similar rocks.

The Dan River-Danville Basin extends from southern Appomattox County, Va., about 100 miles southwest into Stokes County, N.C. In Virginia, the basin is named Danville, and in North Carolina, Dan River. The basin contains sedimentary rocks of the Upper Triassic Dan River Group; in Virginia, the Dry Fork Formation is also present. The sedimentary rocks consist of sandstone, siltstone, mudstone, shale, and local conglomerate and are locally cut by diabase dikes.

Rocks in the four southernmost early Mesozoic basins in North Carolina contain water sufficient only for domestic supplies in the upper 300 feet. The rocks are similar in composition but are more compact and tightly cemented than those in the basins to the north and do not yield sufficient quantities of water to be considered a principal aquifer.

Carbonate-Rock Aquifers

Limestone, dolomite, and marble of Paleozoic and Precambrian age form carbonate-rock aquifers that extend over about 3 percent of the Piedmont and the Blue Ridge Provinces in Segment 11. Although these carbonate rocks are of small extent, they are significant local sources of water. Carbonate-rock aquifers are in five areas of the Piedmont and the Blue Ridge Provinces of Segment 11 (fig. 60). In addition to these areas, small, isolated elongate stringers of limestone and marble form minor aquifers locally, particularly in Virginia, and generally trend parallel to the Blue Ridge front.

In northern New Jersey and eastern Pennsylvania (fig. 60, Area 1), Precambrian and lower Paleozoic carbonate rocks are interspersed with granite and gneiss of the Reading Prong and locally have been juxtaposed by faults with lower Mesozoic rocks of the Newark Basin in Pennsylvania. These carbonate rocks form a series of long, narrow blocks in the noncarbonate rocks that surround them. The major faults and other geologic structures generally trend northeast-southwest but have been tilted or rotated in some areas so that they trend northwest-southeast. The principal water-yielding units are listed in table 2. A large area of carbonate rocks is centered in the Hanover-York-Lancaster Valley area of Pennsylvania (fig. 60, Area 2). The lithology and water-yielding characteristics of the principal carbonate-rock formations are listed in table 3. Three carbonate-rock formations (table 4) are present in Area 3, which encompasses the Frederick Valley in Frederick County, Md., and extends northward into Pennsylvania (fig. 60). Small areas of carbonate rock in Area 4 (fig. 60) include those underlain by the Cockeysville Marble of Ordovician and Cambrian age in southern Chester County, Pa., in Baltimore and Howard Counties, Md., and New Castle County, Del. Carbonate rocks of Cambrian age in North Carolina are exposed mostly in two windows, or openings, that were eroded through major thrust sheets to expose the underlying rock in Area 5 (fig. 60). The exposed rocks are the Shady Dolomite and the Rome Formation in the Hot Springs Window in Madison County and the Shady Dolomite in the Grandfather Mountain Window in northern McDowell County. An elongated outcrop of the Cambrian or Precambrian Murphy Marble in Cherokee County, N.C., is in a structural fold.

GROUND-WATER FLOW AND WELL YIELDS

Recharge is highly variable in the Blue Ridge and the Piedmont Provinces because it is determined by local precipitation and runoff, which are highly variable and are influenced by topographic relief and the capacity of the land surface to accept infiltrating water. The greatest annual precipitation and runoff in Segment 11 are in the Blue Ridge Province, notably in southwestern North Carolina. Because the western part of the Piedmont Province from North Carolina to central Virginia is in the rain shadow of the Blue Ridge Mountains, it receives less precipitation than areas on either side.

Most of the Piedmont and the Blue Ridge Provinces are covered by regolith. Compared to the Blue Ridge, the gentler topographic relief of the Piedmont and less precipitation make the Piedmont less subject to rapid denudation than the Blue Ridge and thus favor the accumulation of a thicker regolith. The combination of large areas of thin regolith and dense bedrock with minimal permeability in the Blue Ridge Province do not favor large amounts of ground-water recharge.

Most of the recharge in the Piedmont and the Blue Ridge Provinces takes place in interstream areas. Almost all recharge is from precipitation that enters the aquifers through the porous regolith. Much of the recharge water moves laterally through the regolith and discharges to a nearby stream or depression during or shortly after a storm or precipitation event. Some of the water, however, moves downward through the regolith until it reaches the bedrock where it enters fractures in crystalline rocks and sandstones or solution openings in carbonate rocks.

Crystalline-Rock Aquifers

In crystalline-rock areas, the regolith and fractures in the bedrock serve as the principal places for the storage transmission of water, and ground-water movement is generally along short flow paths from interstream recharge areas to the nearest stream. This situation applies to most of the Piedmont and the Blue Ridge Provinces. Where bedrock fractures have one or more preferred directions of orientation, as is often the case, ground water will tend to flow more readily in the direction of the fractures; this is a condition called anisotropy.

An example of anisotropy is shown by the results of an aquifer test performed on wells completed in crystalline rocks of the Piedmont Province near Greensboro, N.C. (fig. 67). The contours in the figure are lines of equal water-level decline measured in numerous observation wells after a production well with a 6-inch diameter had been pumped for 57 hours at a rate of about 39 gallons per minute. This well was completed in fractured gneiss; the joints and fractures in the rock trend northeast. The contours that show water-level decline form an oval shape that is elongated to the northeast, which indicates that the bedrock is more permeable in that direction.

Aquifers in Early Mesozoic Basins

The rocks of the early Mesozoic basins include beds of sandstone, arkose, and conglomerate that originally had considerable effective porosity between the grains. However, due to compaction and cementation, the pores in most of these strata are now reduced in size and poorly interconnected, so that only a small part of the ground water moves between pores. The diabase and basalt that intrude the sedimentary rocks had very low primary porosity. The ground water in the lower Mesozoic rocks moves primarily along joints, fractures, and bedding planes. The water-bearing fractures and bedding planes in each tabular aquifer are more or less continuous, but the hydraulic connection across the confining units between individual aquifers is poor (fig. 68). Because of preferential alignment of these openings, the aquifers are anisotropic; most of the water movement is parallel to the strike of the beds.

Because some sedimentary rocks contain more interconnected openings than others, the ground-water system in the early Mesozoic basins consists of a series of aquifers of tabular form that alternate with confining units that are several tens of feet thick. The aquifers and confining units dip toward the border faults that bound the basins at angles that range from 10 to 15 degrees. The aquifers generally extend downdip for a few hundred, rarely for a few thousand, feet but are continuous along strike for thousands of feet. Wells drilled perpendicular to the strike of the beds might penetrate separate aquifers (fig. 69), depending on the angle of the dip of the aquifers and the spacing of the wells. Consequently, well fields designed with wells aligned perpendicular to the strike would likely have minimum interference between wells. Wells B and C in figure 69 are completed in the same local aquifers, and each well, when pumped, will interfere with the other. By contrast, wells C and D are not completed in the same aquifer, and pumping either well will not affect water levels or well yields in the other well.

The aquifers in the early Mesozoic basins north of North Carolina generally yield more water than other noncarbonate aquifers in the Piedmont and the Blue Ridge Provinces, possibly because the original, intergranular pore space in the Meso-zoic rocks may be sufficient to store and transmit appreciable quantities of water. The lower Mesozoic rocks make up some of the few aquifers in the Piedmont and the Blue Ridge Provinces in which the yield per foot appears to increase with depth. In the Pennsylvania part of the Newark Basin, wells between 200 and 550 feet deep are most likely to obtain maximum yields; the average yield of wells deeper than about 200 feet is distinctly higher than that of shallower wells. This may be the result of a rather abrupt change in the nature of rock weathering at depth. In Pennsylvania, the zone of greatest decomposition of the rock-the zone where the original void spaces are believed to be partly plugged with residual clay-apparently is above 200 feet. In Maryland, some water-yielding zones are at depths of between 600 and 900 feet in aquifers of the early Mesozoic basins.

The dikes in the early Mesozoic basins resemble walls of diabase that are nearly vertical

through the sedimentary rocks into which they are intruded. The dikes themselves generally yield little water, but in many places, the strata adjacent to the dikes have been made brittle by baking from the heat of the dike and have been fractured by the intrusion. The dikes also function as dams because they block ground-water flow and tend to impound water in the sediments on their upgradient sides. In many places, wells drilled near dikes produce more water than wells drilled elsewhere in lower Mesozoic strata.

Typical yields of large-diameter wells in the Newark and the Gettysburg Basins of Pennsylvania are generally greatest (about 80 gallons per minute) from wells completed in massive sandstones and 0 conglomerates and are least (about 5 gallons per minute) from wells completed in diabase. Yields of wells completed in shale or argillite are typically about 12 gallons per minute. Although limestone and dolomite conglomerate is the largest-yielding aquifer (median yield 30 gallons per minute from wells 250 to 500 feet deep) in the Culpeper Basin of Maryland and Virginia, noncarbonate conglomerates tend to be mediocre aquifers (median yield 8 gallons per minute for the same depth range), probably because they are tightly cemented. Thin-bedded siltstone tends to yield more water than sandstone (75 gallons per minute versus 15 gallons per minute).

Many wells completed in aquifers in the early Mesozoic basins yield large quantities of water during pumping tests that range from 24 to 48 hours but fail to maintain large yields over long periods of time. The yields of several wells that were tested at 75 gallons per minute soon after completion declined in a few years to about 15 gallons per minute. These wells might have been completed in aquifers that did not contain much water in storage and had low rates of recharge. Another possibility is that after a period of pumping, some of the fractures in the aquifers might have been partly closed by clay and silt that were disturbed and transported by the pumping action or by the precipitation of minerals from the water.

Carbonate-Rock Aquifers

Carbonate rocks are soluble in weak acid solutions compared to rocks of other composition. Water that percolates downward through the soil contains small amounts of dissolved carbon dioxide and organic acids, which make the water weakly acidic and thus capable of dissolving carbonate minerals. Dissolution commonly begins along pre-existing openings, such as fractures or bedding planes, and enlarges these openings to form a network of interconnected openings, which greatly increases the porosity and permeability of the rock. A well that intersects a water-filled solution channel or cavern will produce an abundant supply of water. However, where the water table is deep, the cavities are mostly drained. Not all carbonate rocks form productive aquifers. The water-yielding character of these rocks depends on the degree of fracturing and dissolution of the rocks.

The carbonate rocks of the Piedmont and the Blue Ridge Provinces have virtually no primary permeability or porosity, and water in these rocks moves through secondary openings, such as

bedding planes, joints, faults, and other partings, within the rock that have been enlarged by dissolution. In rocks that have a large content of sand, clay, or other noncarbonate minerals, dissolution is inhibited and enlargement of openings might not be extensive. In such rocks, all the water might occur in fracture openings similar to those in unweathered crystalline rocks.

Ground water in carbonate rocks is under unconfined to confined conditions. The water is confined or semiconfined in the regolith and in the zone of fractured rock that immediately underlies it. Deep fractures and solution channels in the unweathered rock contain semiconfined to confined water and, in some places, transmit water several tens of miles from recharge areas to discharge areas.

Data on the regional hydraulic properties of the carbonate-rock aquifers are not available. From the observed behavior of pumped wells completed in confined carbonate-rock aquifers and the effects of the pumping on adjacent wells, however, it appears that a decline of artesian pressure in response to pumping generally is transmitted rapidly to distant points, but the decline is seldom equal in all directions. In fact, closely spaced wells might encounter different systems of rock openings, in which case pumping from one well will not affect the water levels in an adjacent well.

Even though cavities in carbonate rocks commonly contain an abundant supply of water, they also might contain large amounts of exceedingly fine mud that must be removed or stabilized before clear water can be obtained from the cavities. Solution cavities also can act as channels for the transmission of sewage, surface contaminants, or other types of pollution.

RELATION OF HYDROGEOLOGIC SETTING AND WELL YIELD

Several factors affect the yields of wells completed in the rocks of the Piedmont and the Blue Ridge Provinces. Variations in yield depend on the type of rock in which a well is completed; the thickness of the regolith; the number, size, and spacing of bedrock fractures and the degree to which the fractures are connected; and the topographic setting of the well.

The largest sustained well yields can be obtained from carbonate-rock aquifers, whereas the smallest sustained yields generally are from crystalline-rock and undifferentiated sedimentary-rock aquifers. Aquifers in early Mesozoic basins yield intermediate volumes of water. Well yields for all types of crystalline rocks generally are small; a recent study showed an average yield of 18 gallons per minute for wells completed in these rocks in North Carolina. Coarse-textured crystalline rocks, such as gneiss and schist, generally yield more water than fine-grained, metavolcanic rocks.

Crystalline bedrock is covered by a thick to thin layer of regolith almost everywhere in the Piedmont and the Blue Ridge Provinces. Although the porosity of the regolith varies, depending mostly on the type of bedrock, it is everywhere more porous than the bedrock. The

porosity of the regolith ranges from about 20 to 30 percent, but the porosity of the bedrock ranges from only about 0.01 to 2 percent. Accordingly, the regolith has the capacity to store a much larger volume of water than the bedrock, which contains water only in fractures, as shown in figure 70. The cylinder-and-rod sketch on the right of the figure illustrates this concept. Most of the water is stored in the regolith reservoir, which is represented by the cylinder, from which a small part of the water moves downward and is stored in bedrock fractures, which are represented by the interconnected rods. The size, number, and interconnection of the fractures decrease with depth. The thicker the regolith, the greater the volume of water in storage and the more likely well yield can be sustained. Where the regolith is thin, crystalline-rock wells are more likely to go dry during the summer months or periods of drought.

Most of the fractures in crystalline rocks or consolidated sedimentary rocks are steeply inclined, intersecting openings that are more numerous at shallow depths. Examples of some of the possible distributions of fractures with respect to wells that are completed in crystalline rocks are shown in figure 71. Only about 3 percent of wells encounter no fractures (fig. 71A) and are either dry or will not have a sustained yield. Where the rock is fractured only near the surface (figs. 71B and C), wells will yield from 10 to 20 gallons per minute for a short time until the fractures are drained, when well yield suddenly declines. Where several fractures connected to the regolith are penetrated by a well (fig. 71D), moderate sustained yields are possible, whereas a well that encounters numerous closely spaced fractures (fig. 71E) is most likely to have a high sustained yield. Where only a few fractures exist (fig. 71F), sustained yields are likely to be low. When the water level in a well that was completed in rocks with intergranular porosity is lowered by pumping, the hydraulic gradient toward the well is increased, and the flow toward the well also is increased. However, if the water level is lowered below the deepest fracture in the examples shown, then there is no effect on the gradient, and flow toward the well will not increase.

The Piedmont and the Blue Ridge Provinces contain many faults, most of which show only small displacement. The fault zones themselves commonly have low permeability because they can be filled with clay gouge, recemented breccia, or recrystallized rock, all of which impede the flow of ground water. Most of the water-bearing fractures in the Piedmont and the Blue Ridge are joints, stress-relief fractures, or cleavage planes and are not directly associated with a fault. Some fracture zones appear as lineaments that can be identified on aerial photographs.

Wells in valleys, draws, and depressions tend to have higher-than-average yields for the following reasons: (1) valleys and draws commonly coincide with fracture zones in the rocks, (2) the water table is nearer the surface in topographically low areas and thus provides greater available drawdown for a given well depth in a valley than on a hill, (3) the water table ordinarily slopes toward wells in valleys from at least two directions, whereas it slopes away from wells on hilltops in at least two directions, and water levels in wells on hilltops, therefore, are more likely to decline rapidly than those in wells in valleys, and (4) seasonal fluctuations of

the water table are greater on hilltops where well yields are likely to be reduced during dry seasons. Draws on the sides of the valleys of per-ennial streams where a thick blanket of regolith underlies the adjacent ridges are the best sites for wells with large yields. A statistical analysis that related well yield to topographic setting in the Piedmont and the Blue Ridge Provinces of North Carolina indicated that wells drilled in valleys or draws have average yields that are three times those of wells located on hills or ridges. Solution openings in carbonate rocks are usually more abundant in valleys, depressions, and draws, which are, therefore, favorable sites for wells in this type of rock.

Ground-water discharge to a stream (base flow) is an indi-cation of the maximum sustained ground-water yield. The per-centage of streamflow composed of base flow is determined by the infiltration capacity of the soil and the capacity of the underlying aquifers to store and transmit water. In part of the Piedmont Province in southeastern Pennsylvania, base flow ranges from 57 to 66 percent of streamflow in drainage basins that are underlain predominately by crystalline rocks and 77 percent in a typical basin that is underlain by carbonate rocks. Base flow ranges from 33 to 67 percent of streamflow in three drainage basins that are underlain by crystalline rocks in the Piedmont and the Blue Ridge of Maryland and from 32 to 65 (average 44) percent in 10 crystalline-rock drainage basins in the Piedmont of North Carolina. The average base flow in the early Mesozoic Culpeper Basin of Maryland and Virginia is 68 percent of streamflow.

GROUND-WATER QUALITY

The quality of water from aquifers in the different rock types of the Piedmont and the Blue Ridge Provinces is similar (fig. 72). The water generally is suitable for drinking and other uses, but iron, manganese, and sulfate locally occur in objectionable concentrations. Large iron concentrations can be caused by corrosion or the action of iron-fixing bacteria on iron and steel casings and well fittings. Some crystalline rocks and some sedimentary rocks in early Mesozoic basins contain minerals that, when weathered, can contribute iron and manganese to ground water, particularly if the water is slightly acidic. Treatment of the water usually will alleviate problems of excessive iron and manganese concentrations.

The crystalline-rock and undifferentiated sedimentary-rock aquifers consist primarily of metamorphic and igneous rocks but include small areas of sedimentary rocks, principally conglomerate, sandstone, and shale. These rocks consist mostly of silica and silicate minerals that are not readily dissolved. Dissolved-solids concentrations in water from these aquifers average about 120 milligrams per liter. The water is soft; hardness averages about 63 milligrams per liter. The median hydrogen ion concentration, which is measured in pH units, is 6.7; consequently, the water is slightly acidic. The median iron concentration is 0.1 milligram per liter, but concentrations as large as 25 milligrams per liter have been reported. The water is mostly a calcium plus magnesium bicarbonate type (fig. 72A).

The aquifers in early Mesozoic basins are mostly sandstone, siltstone, and shale, with some limestone and conglomerate. The minerals that compose these rocks are slightly more soluble than those of the rocks that compose the crystalline-rock and undifferentiated sedimentary-rock aquifers. Dissolved-solids concentrations in water from the aquifers in early Mesozoic basins average about 230 milligrams per liter, and hardness averages about 160 milligrams per liter, which is considered to be hard. The median hydrogen ion concentration, which is measured in pH units, is 7.6. The dissolution of calcium and magnesium carbonate raises the pH of the water and renders it less acidic. Chloride and sulfate concentrations average about 12 and 29 milligrams per liter, respectively, but chloride concentrations as large as 1,400 milligrams per liter and sulfate concentrations as large as 1,200 milligrams per liter have been reported in water from deep wells. The median iron concentration is 0.1 milligram per liter, but concentrations as large as 5.3 milligrams per liter have been reported. The water from the aquifers in early Mesozoic basins is mostly a calcium bicarbonate type (fig. 72B).

The dominance of soluble calcium and magnesium carbonate minerals in the carbonate-rock aquifers is reflected in the composition of the water from the aquifers. Dissolved-solids concentrations in the water average about 330 milligrams per liter, and hardness (caused principally by calcium and magnesium ions) averages about 280 milligrams per liter, which is considered to be very hard. The median hydrogen ion concentration, which is measured in pH units, is 7.5. The median iron concentration is 0.1 milligram per liter, but concentrations as large as 8 milligrams per liter have been reported. The water is mostly a calcium bicarbonate type (fig. 72C).

FRESH GROUND-WATER WITHDRAWALS

Total freshwater withdrawals from the bedrock aquifers of the Piedmont and the Blue Ridge Provinces were about 634 million gallons per day during 1985. About 52 percent of the otal, or about 329 million gallons per day, was withdrawn from the crystalline-rock and undifferentiated sedimentary-rock aquifers. Withdrawals from the aquifers in early Mesozoic basins were about 223 million gallons per day, or about 35 percent of the total. The remaining 13 percent, or about 82 million gallons per day, was withdrawn from the carbonate-rock aquifers.

The distribution of withdrawals from the three types of bedrock aquifers varies greatly from State to State (fig. 73). More than one-half of the water withdrawn from the crystalline-rock and undifferentiated sedimentary-rock aquifers during 1985 was pumped in North Carolina (fig. 73A). The aquifers in early Mesozoic basins (fig. 73B) were important sources of supply in Pennsylvania and New Jersey during the same period. Withdrawals from the carbonate-rock aquifers during 1985 were greatest in Pennsylvania (fig. 73C). The withdrawals are directly proportional to the area underlain by each bedrock aquifer type in each State.

Withdrawals for different uses during 1985 varied among the bedrock aquifer types (fig. 74).

Most of the water withdrawn from the crystalline-rock and undifferentiated sedimentary-rock aquifers was used for domestic and commercial supplies. By contrast, most of the water withdrawn from the aquifers in early Mesozoic basins and the carbonate-rock aquifers was used for public supply. The percentage of water withdrawn for industrial, mining, and thermoelectric power uses was nearly the same for all three aquifer types. Agricultural withdrawals were the smallest use category for each of the three aquifer types.

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Valley and Ridge aquifers

INTRODUCTION

Aquifers in the Valley and Ridge Physiographic Province consist of permeable rocks within a sequence of folded and faulted sedimentary formations of Paleozoic age. The upper strata were folded into anticlines and synclines as they slid over underlying beds along large, nearly horizontal faults. The folded rocks form a series of parallel valleys separated by steep to well-rounded ridges that rise from about 100 to 2,000 feet above the valley floors. The province is named for these al-ternating valleys and ridges that trend northeastward from southwestern Virginia to east-central Pennsylvania and then eastward toward northern New Jersey (fig. 75) in Segment 11. The province extends southwestward through Tennessee (Segment 10 of this Atlas) into northern Georgia and Alabama (Segment 6 of this Atlas) and is briefly discussed in the chapters that describe aquifers in these segments. The province also is called the Folded Appalachians because folded strata dominate the topography (fig. 76). The same Paleozoic formations of the Valley and Ridge Province are present in the Appalachian Plateaus Province to the west, where they are much more gently folded and nearly flat-lying in places. The rocks of the Valley and Ridge Province are chiefly sandstone, shale, and carbonate rocks; locally, coal-bearing beds are present. A thick cover of regolith has developed on the rocks, particularly in the valleys.

The Valley and Ridge Province reaches a maximum width of about 80 miles in central Pennsylvania and is bounded by the higher land surfaces of the Blue Ridge and the Piedmont Provinces on the southeast and the Appalachian Plateaus Province on the northwest. In most places, the Valley and Ridge is separated from the Appalachian Plateaus by an escarpment

called the Allegheny Front in Pennsylvania, Maryland, and West Virginia and the Cumberland Escarpment in Virginia (fig. 75).

The Great Valley is the most pronounced and persistent valley in the Valley and Ridge Province. It is floored with easily eroded rock, such as shale, slate, or carbonate rocks. The valley generally ranges from 10 to 20 miles wide but is much narrower in and near Roanoke County, Va. Part of the eastern boundary of the Great Valley is a zone of thrust faulting; crystalline rocks of the Blue Ridge Province have been shoved northwestward tens of miles over Paleozoic sedimentary rocks in places. The western boundary of the valley is the first persistent mountainous ridge of resistant sedimentary rock. The part of the Valley and Ridge northwest of the Great Valley consists of persistent mountain ridges underlain by resistant sandstone, conglomerate, and quartzite, which alternate with valleys floored with shale or slate and carbonate rocks.

Drainage patterns in the Valley and Ridge Province directly reflect the alternating bands of resistant and easily eroded rocks in the folded strata of the province. Major streams and their tributaries intersect at right angles to form a rectangular stream network called a trellis drainage pattern (fig. 77). For example, in the Shenandoah Valley, which is part of the Great Valley in Virginia and West Virginia, the Shenandoah River flows northward to join the Potomac River. The Shenandoah River follows a band of weak and soluble rocks as the course of least resistance, as do most of the other rivers in the Valley and Ridge. Such streams are called subsequent streams and their courses are determined by regional geologic structure as expressed by the patterns of resistant and weak rocks.

A few major rivers, however, such as the Lehigh and the Susquehanna Rivers in Pennsylvania, the Delaware River between Pennsylvania and New Jersey, and part of the Potomac River in West Virginia, Maryland, and Virginia, cut directly across the ridges and valleys (fig. 75). Such streams are called superimposed streams. The Susquehanna River, for example, crosses six major ridges within 50 miles upstream from Harrisburg, Pa.. The notch carved through a resistant ridge by a river is called a water gap (fig. 78). When a stream no longer flows through a water gap, usually because the stream has been captured by headward erosion of a larger stream, the abandoned water gap is called a wind gap (fig. 79).

GEOLOGIC STRUCTURE

The geologic structure of the Valley and Ridge Province is complex, but the process principally responsible for the present configuration of the rock layers was displacement to the northwest. Some movement took place along low-angle reverse faults; rocks of the Blue Ridge Province and the Reading Prong were thrust northwestward over layered sedimentary rocks of the Valley and Ridge Province for tens of miles, and the layered rocks, in turn, were broken into slices that slid over each other. At and near the land surface, the beds were folded into nearly parallel, northeast-trending anticlines and synclines. In some areas, the folded beds are

bounded below by nearly horizontal thrust faults. At the time of deformation, slippage occurred along bedding planes; accordingly, the folded beds above were detached from those below.

Folding is most intense in the parts of the Valley and Ridge Province in New Jersey and central to northeastern Pennsylvania. Because of the intense deformation, cleavage in places is more prominent than bedding, and some of the rocks have undergone low-grade metamorphism. In the Valley and Ridge Province in southwestern Virginia and farther to the southwest in Tennessee, folding is less intense, but major faults are common, and vertical to overturned beds appear in many places, particularly on the northwestern sides of anticlines. The western boundary of the Valley and Ridge Province is marked by a rather abrupt reduction in the deformation of the beds. This corresponds approximately with the Allegheny Front, which marks the boundary between the Valley and Ridge and the Appalachian Plateaus Province. Faults occur at the boundary in some places, but have not been identified everywhere.

The present Appalachian Mountains are merely the roots of ancient mountains. Only parts of the original folds remain, and the mountain ridges are the eroded edges of resistant rock layers, principally hard sandstone, conglomerate, or quartzite. Axes of anticlines commonly are valleys, especially where the rock that forms the center of the upfold has little resistance to erosion. Axes of synclines commonly coincide with ridges or mountains where the rock at the center of the downfold is resistant. Formations that have been eroded away elsewhere might be preserved in synclines. Broad folds, whether syn-clines or anticlines, can appear as a series of narrow ridges and valleys produced by the differences in erodability of their rock layers.

HYDROGEOLOGIC UNITS

The principal aquifers in the Valley and Ridge Province from Virginia through New Jersey are carbonate rocks and sandstones that range in age from early to late Paleozoic (fig. 80). Not all the geologic formations recognized in each of the States are shown; some formations that are thin or are of small extent are omitted. Most of the more productive aquifers are in carbonate rocks, primarily limestone, and most are in valleys. Although the water-yielding character of the carbonate rocks depends on the degree of fracturing and development of solution cavities in the rock, the limestone formations generally yield moderate to large volumes of water. Sandstone formations also can yield large quantities of water to wells where the sandstone is fractured. Locally, fractured shale beds form productive aquifers. Because the rocks change in lithology, thickness, water-yielding character, and formation name from place to place, it is difficult to make statements about the water-yielding character of any of the named stratigraphic units that apply throughout Segment 11. Generally, however, limestone aquifers predominate in rocks of Cambrian, early Ordovician, late Silurian, and early Devonian age (fig. 80), whereas sandstone aquifers are prominent in rocks of middle and late Ordovician, middle Devonian, and younger age.

The sedimentary formations of the Valley and Ridge Province are commonly thick and steeply tilted; thus, a water well usually penetrates only the consolidated rock formation exposed at the surface. Therefore geologic maps are good guides to the type of rock from which a well can withdraw water.

The Great Valley makes up most of the Valley and Ridge Province in New Jersey and is floored with shale and carbonate rock of early Paleozoic age. A thick sequence of carbonate rocks that consist of the Leithsville Formation, the Allentown Dolomite, and the Beekmantown Group contains the most productive aquifers. Yields of as much as 850 gallons per minute have been reported for wells that obtain water from combinations of these geologic units. West of the Great Valley, predominately Silurian and Devonian rocks (mostly shale, sandstone, and conglomerate) are exposed. Wells completed in these clastic rocks and in thin limestone units interbedded with them yield 15 to 100 gallons per minute.

The Valley and Ridge Province is widest in Pennsylvania and contains more geologic units than elsewhere in Segment 11 (fig. 80). The Great Valley in Pennsylvania is floored with ower Paleozoic carbonate rocks and shale. Principal water-yielding geologic units are limestone and dolomitic limestone of the Waynesboro Formation through the St. Paul Group (Cambrian and Ordovician ages), with well yields reported to range from 25 to 210 gallons per minute. Yields from sandstone of the Martinsburg Formation, by contrast, only range from 10 to 30 gallons per minute. Northwest of the Great Valley, the uppermost Paleozoic rocks in central to northeastern Pennsylvania are coal-bearing beds of Pennsylvanian age mostly associated with the anthracite coal fields where deeply infolded beds of coal were preserved from erosion. The processes of folding and deep burial drove off most of the volatile content of the bituminous coal in the more intensely folded areas and converted it to anthracite. This conversion did not take place everywhere, however. For example, in south-central Pennsylvania, Pennsylvanian rocks range from 1,000 to 1,500 feet thick in a synclinal mountain in parts of Huntingdon, Bedford, and Fulton Counties (fig. 75), but the coals they contain are closer in rank to bituminous than anthracite. Pennsylvanian rocks consist of sandstone, which is coarse or conglomeratic in some places; gray and black shale and claystone; thin beds of limestone; and coal. Sandstone is more abundant in the Pottsville Group than other geologic units, and yields of wells completed in the Pottsville commonly range from 50 to 100 gallons per minute.

Mississippian rocks in Pennsylvania have a distribution pattern similar to that of Pennsylvanian rocks but have a somewhat wider extent. They consist primarily of shale, sandstone, and conglomerate; yields of wells completed in sandstones of the Mississippian parts of the Mauch Chunk and the Pocono Formations range from 20 to 90 gallons per minute. Devonian rocks are extensively exposed west of the Great Valley in southern Pennsylvania and north and east of the Susquehanna River. The ridges of the province are typically formed on the upturned edges of layers of hard Silurian sandstone and quartzite, but the Silurian section also includes shale and limestone. Yields from limestones of Silurian and Devonian age (Mifflintown Formation through Onondaga Group, fig. 80) commonly range from 20 to 120 gallons per minute to

wells; local yields of as much as 1,400 gallons per minute have been reported. Wells completed in sandstones of the Keefer Formation and Oriskany Group yield as much as 120 gallons per minute.

The Valley and Ridge Province extends throughout most of the Maryland Panhandle, but the Great Valley part of the province is restricted to Washington County (fig. 75). The Great Valley in Maryland is floored with predominately carbonate-rock and shale formations of Cambrian and Ordovician age. The principal water-yielding units in the Great Valley are the Tomstown Formation through the Beekmantown Group (fig. 80); well yields commonly range from 25 to 400 gallons per minute. West of the Great Valley, sandstones of Ordovician to Devonian age are the principal aquifers but commonly yield less than 120 gallons per minute; locally, yields of as much as 100 gallons per minute are reported for wells in limestone of late Silurian and early Devonian age.

In West Virginia, the Great Valley part of the Valley and Ridge Province is only in Jefferson and Berkeley Counties (fig. 75) and is underlain mostly by carbonate rocks of Cambrian and Ordovician age (Tomstown Dolomite through Black River Limestone, fig. 80) that typically yield about 35 gallons per minute to wells. Locally, wells completed in these rocks yield as much as 600 gallons per minute, however, and some springs that issue from the rocks discharge from 1,000 to 5,000 gallons per minute. Fractured shale of the Martinsburg Formation in the Great Valley locally yields 20 gallons per minute to wells. Elsewhere in the province, yields of wells com-pleted in Silurian and lower Devonian limestones commonly only range from 10 to 20 gallons per minute; some springs that issue from these rocks discharge as much as 15,000 gallons per minute. Devonian and Mississippian sandstones commonly yield 15 gallons per minute or less to wells.

The Valley and Ridge Province in western Virginia extends from Clark and Frederick Counties to the North Carolina State line (fig. 75). The Great Valley in Virginia is floored primarily by carbonate rocks and shale of Cambrian and Ordovician age, which commonly yield from 150 to 1,000 gallons per minute to wells. Locally, wells completed in fractured shale of the Martinsburg Formation yield up to 155 gallons per minute. Limestone beds of late Silurian and early Devonian age west of the Great Valley typically yield only 20 gallons per minute or less to wells.

GROUND-WATER FLOW

Water in the Valley and Ridge aquifers moves mostly along fractures and bedding planes in all rock types, and in solution openings in the carbonate rocks. These types of openings are secondary porosity that formed after the rocks were deposited and lithified; almost all the original primary pore space between individual mineral grains or rock particles was filled with fine-grained material or mineral cement during the process of lithification of the rocks.

Circulating, slightly acidic ground water that moves along fractures and bedding planes in the carbonate rocks has partly dissolved these rocks in places and has created a network of large, interconnected openings that yield substantial quantities of water to wells. The alternating sequences of upfolded and downwarped rocks in the Valley and Ridge Province, coupled with the stream network that has developed in the folded rocks, create a series of shallow, isolated, local ground-water flow systems. Most of the ground water under the ridges flows across the strike of the rocks, but in the valleys, it usually moves along the strike. The flow within these local ground-water systems is predominately within a few hundred feet of the land surface, but circulation in some of the systems is deep enough for the water to become geothermally heated. The regolith that covers the consolidated rocks in most places has some primary porosity. The local flow systems receive recharge mostly to the regolith on the tops or flanks of ridges. The water then moves into the underlying bedrock or flows within the regolith downgradient toward the intervening valleys and discharges to streams or springs. Although the hard sandstone, conglomerate, and quartzite that typically cap the ridges have low permeability, the steep gradient provided by the dip of the beds and the relief usually is sufficient to move ground water into the adjoining valleys (fig. 81). Thick wedges of colluvium that locally cover the lower flanks of the ridges can temporarily store large quantities of water that later move into bedrock aquifers in the valleys. Perched water tables can over-lie local clayey zones in the colluvium and commonly are expressed by permanent to intermittent ponds. The perched water can be as much as 400 feet above the regional water table in the underlying consolidated rock.

The carbonate rocks that are mostly in the valleys receive recharge from precipitation that falls directly on the valley floors (fig. 82), as well as from runoff from the adjacent ridges. Highly permeable solution zones that have developed by the enlargement of joints and other openings collect and channel the water. Sinkholes, which are closed depressions in the land surface that form where part of the roof of a solution cavity has collapsed, form a direct connection from the land surface to a carbonate aquifer. Surface runoff can move directly into a sinkhole, as can ground water in the regolith that overlies the carbonate rocks. Recharge to the aquifer through sinkholes takes place very quickly, and any contaminants at or near the land surface can move directly into the aquifer. Surface water that is channeled into small streams in the valleys can leak downward through the streambed to recharge the aquifer in places where the water table of the aquifer is lower than the water level in the stream.

The flow paths of ground water in the Valley and Ridge Province are generally short, except for those in carbonate-rock aquifers where networks of solution openings prevail. Water can flow through connected solution conduits, such as those mapped in figure 83, for distances that range from thousands of feet to several miles. As it moves downgradient from recharge areas, the water tends to be concentrated in ever-larger conduits until it typically discharges as flow from a large spring. The larger solution channels, including caves, generally form at or near the water table, but some dissolution takes place as deep as 100 feet below the top of the zone of saturation. The orientation of the solution openings is parallel to that of the joints and fractures in the carbonate rocks. Secondary openings, such as joints in noncarbonate

rocks, also have preferred orientations. As a result, wells completed in fractures or solution openings and wells completed in the intervening bedrock can have dissimilar heads and specific capacities, and the pumping of one well will have little effect on water levels in the other.

Although springs issue from some of the aquifers in all the physiographic provinces in Segment 11, large springs are most characteristic of the Valley and Ridge Province. Spring-flow is particularly large for springs that issue from the carbonate rocks. Three types of springs are common, and all result from ground-water movement driven by the force of gravity. Contact springs (fig. 84, center) form where water-saturated permeable material overlies less-permeable material. The water comes to the land surface at the contact of the two types of material, and the springs might issue where the contact intersects a sloping land surface. Contact springs are common in the Valley and Ridge Province but generally discharge only small volumes of water. Impermeable-rock springs (fig. 84, right) are fed by fractures, joints, or bedding planes in rocks that have low intergranular permeability. Small springs of this type that issue where a vertical joint intersects a bedding plane and that generally discharge only small volumes of water are typical of parts of the Appalachian Plateaus Province, but are also in the Valley and Ridge. Tubular springs (fig. 84, left) issue from solution channels in carbonate rocks. The largest magnitude springs are of this type because the catchment basins of networks of solution openings are likely to be more extensive than those of intersecting fractures, and the large solution openings in the carbonate rocks are able to transmit large quantities of water. For example, in Pennsylvania, 90 percent of the springs that discharge 100 gallons per minute or more issue from Ordovician and Cambrian limestones and dolomites; most of those that discharge more than 2,000 gallons per minute issue from limestone.

Water in the aquifers from which the springs issue can be either confined or unconfined. Springs that issue from aquifers that contain water under confined conditions are called artesian springs, whereas those that issue from unconfined aquifers are called gravity springs.

Spring location is related to geologic structure and topography. In the Valley and Ridge Province, many springs are located on or near anticlinal axes and around the noses of plunging anticlines. Open tension fractures tend to be concentrated in these places, and in the case of plunging anticlines, water-yielding beds may drain in the direction of plunge. Large springs are common where water gaps have been cut through anticlinal ridges because water-yielding geologic formations are commonly exposed at the lowest altitudes in these gaps. The bases of sandstone ridges are, in general, the sites of major springs. The largest springs tend to be in valleys, and some form the headwaters of streams.

Some of the springs in the Valley and Ridge Province discharge water that is distinctly warmer than the average air temperature. Most of the thermal springs in the Eastern United States are in the Valley and Ridge Province. The spring waters have become naturally heated by deep circulation of the water to levels where the rocks are substantially warmer than the average

surface temperature of the Earth. This increase in temperature with depth is called the geothermal gradient. The normal geothermal gradient for the Eastern United States is sufficient to warm the circulating water appreciably. For water to reach the temperatures observed in thermal springs of Segment 11, circulation to minimum depths of from 800 to 5,200 feet is required. Conditions for a thermal spring require that the flow of ground water be concentrated, channeled to depths sufficient to heat the water, and then channeled back to the land surface. Folding, faulting, and fracturing of confined aquifers provide the necessary paths and barriers to channel the flow of the water (fig. 85). Water enters fractured rocks at topographically high recharge areas, and the cold water moves deeply enough to become heated and subsequently rise. Thermal springs commonly issue in valleys that have developed on or near the crest of anticlines, but generally a variety of geologic structures combine to form the deep flow system that results in the thermal springs.

Deeply circulating waters might have a long residence time in the aquifer, and as the water is heated, it can become exposed to emanations of gases and vapors from deeper in the Earth. This exposure and the heat of the water facilitates the dissolution of minerals from the surrounding rock by the ground water. Generally, the water in thermal springs that discharge from limestone is mineralized and commonly contains hydrogen sulfide. The water from thermal springs that discharge from the Oriskany Sandstone is reported to contain more dissolved minerals than water from cold springs that issue from the same formation. Waters from many thermal springs have been thought to have medicinal properties because of the mineralization.

RELATION OF GEOLOGY AND WELL YIELD

Several geologic factors influence well yields in the Valley and Ridge Province. Some geologic structural factors affect the yield of wells completed in carbonate and noncar-bonate aquifers. Wells located along fracture traces in any type of rock usually yield much more water than wells that do not penetrate fractures. Fold hinges represent areas where fractures are more abundant and rock cleavage can be well developed, which enhances secondary permeability. Also, the dip of strata in the area of a fold hinge tends to be less, a factor associated with higher well yields. Wells completed in beds that dip at angles of less than 15 degrees generally yield more water than those completed in beds that are inclined more steeply because more bedding-plane partings are penetrated by a well of a given depth in the nearly horizontal strata than one of the same depth in steeply dipping beds. Wells located on anticlines yield more water than those on synclines because the fractures on anticlines are tensional and, thus, more apt to be open than the compressional fractures on synclines. Thin-bedded rocks generally have more closely spaced fractures than thick-bedded rocks and, therefore, are likely to have higher fracture permeability and to yield more water.

Topographic location affects well yield; wells in valley bottoms generally are more productive than those on ridges or uplands because fracture zones in noncarbonate rocks and solution

channels in carbonate rocks tend to be concentrated in valleys. Regolith is generally thicker in valleys and, thus, stores more water for gradual release to the underlying bedrock aquifers.

Noncarbonate rocks interbedded with carbonate rocks are typically more permeable than noncarbonate rocks with no intervening carbonate strata. In noncarbonate rocks, friable sandstone probably is potentially the most productive aquifer. Shale, massive mudstone, and claystone are the least productive rock types.

Some factors influence well yields only in carbonate aquifers. Well yields are generally proportional to the thickness of the regolith that overlies a carbonate aquifer. The regolith acts as a sponge and stores water for gradual release to solution openings in the underlying carbonate rock. The continual release of this water contributes to the continued dissolution of the carbonate rock and expansion and enlargement of the solution openings. Well yield varies with carbonate rock type; the best- to worst-yielding carbonate lithologies are, in order, sandy dolomite, coarse-grained dolomite, limestone, and fine-grained dolomite.

GROUND-WATER QUALITY

The chemical quality of water in the aquifers of the Valley and Ridge Province is somewhat variable but is generally suitable for municipal supplies and other purposes. Most of the water in the upper parts of the aquifers is not greatly mineralized and is suitable for drinking and most other uses. However, the deep parts of the aquifers contain saline water in many places and brackish water has been reported locally from zones as shallow as 90 feet below the land surface in valleys near the West Branch of the Susquehanna River in Pennsylvania. The large dissolved-solids concentrations in the saline and brackish water might result from the dissolution of halite (rock salt) at greater depths by deeply-circulating water. Abandoned or improperly plugged boreholes drilled for oil and gas exploration provide paths for upward movement of mineralized water in some areas.

The carbonate-rock aquifers consist mainly of calcium and magnesium carbonate, which are readily dissolved and thus affect the chemical composition of ground water. Waters from these aquifers have dissolved-solids concentrations that average about 330 milligrams per liter and hardness that averages about 280 milligrams per liter, which is considered to be very hard. The median hydrogen ion concentration, which is measured in pH units, is 7.4 (slightly basic); dissolution of calcium and magnesium carbonate minerals raises the pH of the water and increases the hardness. The median iron concentration is 0.1 milligram per liter, which is considered to be low, but concentrations as large as 8 milligrams per liter have been reported. Water in the carbonate-rock aquifers is mostly a calcium plus magnesium bicarbonate type (fig. 86A).

The undifferentiated sedimentary-rock aquifers consist principally of fractured sandstone but locally include fractured shale. The minerals that compose these rocks are chiefly silicates,

which are much less soluble than those that compose the carbonate-rock aquifers. The water is mostly a calcium bicarbonate type (fig. 86B). Dissolved-solids concentrations are small and average only about 150 milligrams per liter. Hardness averages about 100 milligrams per liter, and the water is considered to be moderately hard. The median hydrogen ion concentration, which is measured in pH units, is 7.4. The median iron concentration is about 0.1 milligram per liter, but concentrations as large as 14 milligrams per liter have been reported. In some coal-mining areas, the ground water is mixed with acidic mine water, which can contain large concentrations of iron, manganese, sulfate, and dissolved solids.

FRESH GROUND-WATER WITHDRAWALS

Total freshwater withdrawals from consolidated-rock aquifers in the Valley and Ridge Province in Segment 11 were about 371 million gallons per day during 1985. With-drawals from carbonate-rock aquifers were estimated to be 249 million gallons per day (fig. 87). Slightly more than one-half of this water was used for domestic and commercial supplies. Withdrawals from undifferentiated sedimentary-rock aquifers, primarily sandstone aquifers, in the Valley and Ridge Province were estimated to be 122 million gallons per day. About two-thirds of this water was used for domestic and commercial supplies.

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Appalachian Plateaus aquifers

INTRODUCTION

The Appalachian Plateaus Physiographic Province in Segment 11 extends over most of West Virginia, more than one-half of Pennsylvania, and small parts of westernmost Virginia and Maryland (fig. 88). The province is bounded on the east and southeast by the Valley and Ridge Province and by a narrow strip of the Central Lowland Province in Erie County, Pa. The Appalachian Plateaus Province extends into Segments 6, 10, and 12 of this Atlas but is most extensive in Segment 11. In most places, the eastern boundary of the Appalachian Plateaus is marked by an escarpment called the Cumberland Escarpment in Virginia and the Allegheny Front in West Virginia, Maryland, and Pennsylvania. A northward-facing erosional escarpment forms the boundary between the Appalachian Plateaus and the Central Lowland Provinces. The altitude of the Appalachian Plateaus Province is higher than that of the Valley and Ridge Province, as well as the Central Lowland Province.

Aquifers in consolidated sedimentary rocks in the Appalachian Plateaus Province are divided into the following categories-Mississippian aquifers and Permian and Pennsylvanian aquifers (fig. 88). Most of the water-yielding rocks are sandstones (fig. 89), but carbonate rocks of Mississippian age locally yield water in parts of Virginia and West Virginia. Coal beds and seams yield water because they commonly are fractured along joint systems (cleat) that store and transmit water. Devonian siltstone, shale, and thin-bedded sandstone in Pennsylvania, Maryland, and West Virginia locally yield sufficient water for domestic and commercial supplies, especially where the rocks are fractured, but are not considered to be principal

aquifers in this report. Unconsolidated glacial and alluvial deposits, discussed in the Surficial aquifer system section of this chapter, are productive aquifers in large areas in Pennsylvania and smaller areas in West Virginia.

The consolidated rocks of the Appalachian Plateaus Province are almost flat-lying to gently folded; the regional dip of the beds rarely exceeds 25 feet per mile. Elongate, gentle folds form alternating anticlines and synclines in Pennsylvania and West Virginia. These gentle warps are surface expressions of small displacements along deep-seated faults in many cases. Deformation of strata in the Appalachian Plateaus is extremely subtle compared to the folding in the Valley and Ridge Province. The Central Lowland Province is similar to the Appalachian Plateaus in the nearly flat-lying attitude of its rock layers and in the geologic formations present, but the formations of Pennsylvanian and Mississippian age have been eroded away in the Central Lowland.

HYDROGEOLOGIC UNITS

Consolidated sedimentary rocks that compose the Appalachian Plateaus aquifers in Segment 11 range in age from Devonian to Permian (fig. 89). Not all the geologic formations recognized in each of the States are shown in the figure. Some formations are thin or are of local extent; as a result, they are not important in the hydrogeologic framework and are omitted. Most of the productive aquifers consist of sandstone or conglomerate, but limestone formations locally yield significant volumes of water. The water-yielding character of the geologic units shown as aquifers in figure 89 varies because the units change in lithology and thickness from place to place.

In southwestern Pennsylvania, the consolidated rocks nearest the surface are mostly Pennsylvanian in age. Pennsylvanian rocks are the principal coal-bearing formations and consist of cyclic sequences of sandstone, shale, conglomerate, clay, coal, and minor limestone. The sandstones are the most productive aquifers, although coal beds and limestones also yield water; the limestones, however, are thin compared to those of the Valley and Ridge Province. Rocks of Permian age cover most of Greene and Washington Counties in the southwestern corner of the State. Permian rocks are similar in lithology and water-yielding characteristics to the Pennsylvanian rocks, but were not deposited in cycles; they contain only thin coal beds and consist of more shale and less sandstone and conglomerate than the Pennsylvanian strata. Mississippian rocks consist mostly of shale, sandstone, and siltstone with minor conglomerate and limestone and are exposed north and east of the Pennsylvanian rocks where the beds of Pennsylvanian age have been removed by erosion. The principal water-yielding geologic units are sandstones of the Permian and Pennsylvanian Dunkard Group through the Mississippian and Devonian Pocono Formation (fig. 89). Reported typical yields of wells completed in all these units range from 30 to 300 gallons per minute, but some wells yield as much as 600 gallons per minute. Rocks of Devonian age are exposed north of the Mississippian strata in the Appalachian Plateaus Province and in the small part of the Central

Lowlands Province in Segment 11. Devonian strata consist mostly of fine grained sandstone, siltstone, and shale, and are not considered to be principal aquifers, although these beds locally yield as much as 200 gallons per minute where they are fractured.

The Appalachian Plateaus Province in Maryland is only in Garrett County and the adjoining western one-third of Allegany County (fig. 88). Rocks of Pennsylvanian age cover most of the Plateaus area, but Mississippian and Devonian rocks are exposed along the crests of northeast-trending anticlines and in some of the deeper valleys. The Pennsylvanian and upper Mississippian geologic formations and their water-yielding characteristics are similar to those of Pennsylvania (fig. 89). Yields of wells completed in Pennsylvanian rocks range from 20 to 430 gallons per minute, but yields of wells completed in Mississippian strata only range from 20 to 180 gallons per minute. Devonian rocks in Maryland locally yield only small quantities of water.

The water-yielding geologic units of West Virginia are similar to those of Pennsylvania (fig. 89), except that the sandstones of the Mauch Chunk Group yield little water, and the Mississippian Greenbrier Limestone locally is a productive aquifer. The Greenbrier is exposed primarily in parts of Tucker, Randolph, Pocohontas, Greenbrier, and Monroe Counties in the southeastern part of the State. Yields of wells completed in Permian and Pennsylvanian sandstones range from 5 to 400 gallons per minute. Yields from the Greenbrier Limestone range from 5 to 100 gallons per minute to wells, but some springs that issue from the Greenbrier discharge 1,000 gallons per minute or more. Yields of wells completed in sandstone of the Pocono Group range from 5 to 120 gallons per minute, but the water in the deeper parts of the Pocono is highly mineralized.

The Appalachian Plateaus Province in Virginia covers Buchanan and Dickenson Counties and parts of four adjoining counties in the southwestern corner of the State. The principal water-yielding geologic units are sandstones of the Harlan, the Wise, and the Lee Formations of Pennsylvanian age and the Mississippian Greenbrier Limestone (fig. 89). Water from these aquifers is used mainly for domestic supply because well yields are generally less than 12 gallons per minute from the Pennsylvanian aquifers and less than 50 gallons per minute from the Greenbrier Limestone. Many of the sandstone beds in the Pennsylvanian rocks are tightly cemented and are less permeable than the coal beds, which tend to be highly fractured and thus yield water. Some deep coal mines in this area are reported to be dry, which suggests that water-bearing fractures in all the rocks extend only a few hundred feet below land surface.

GROUND-WATER FLOW

Bedrock aquifers in the unglaciated part of the Appalachian Plateaus Province accept less recharge than those in the Valley and Ridge Province. This is because the unglaciated part of the Appalachian Plateaus is highly dissected, much of the area is sloping, and the slopes are covered with only thin accumulations of regolith. Accordingly, most of the precipitation that

falls on the area runs rapidly off the slopes. However, a small part of the precipitation infiltrates the Earth's surface and moves downward through the unsaturated zone to infiltrate weathered bedrock and shallow fractures in unweathered bedrock. The general movement of the water is from areas of high head, usually at high altitude, toward areas of low head, usually in lowlying areas. The water generally moves vertically downward in areas of recharge, then horizontally in the aquifers, and finally upward in discharge areas as it follows paths of least resistance. The movement of the water is steplike because it moves vertically through fractures, then horizontally through sandstone or coal beds, and vertically again when it encounters other fractures. The water will follow permeable beds or a zone of fractures laterally for considerable distances. Saline water or brine is near the surface in much of the area because circulation of fresh ground water generally extends no more than a few hundred feet below the land surface. Most of the ground water moves through local or intermediate-scale flow systems; no regional flow occurs.

Circulation of ground water in the more dissected parts of the Appalachian Plateaus can be envisioned as the drainage of "hydrologic islands" into bounding valleys underlain by older rocks; these "islands" consist of younger rocks at higher altitudes. The edges of two such "islands" with an intervening valley are shown in figure 90. Water moves down tributary valleys toward major rivers, partly as surface water through gaining streams and partly as ground water in alluvial or bedrock aquifers. Saline water or brine at shallow depths is virtually stagnant.

Springs commonly mark the intersection of the water table with a valley wall (fig. 90). Low-permeability rocks, such as shale or siltstone, or ironstone layers, retard the vertical movement of water. The water moves laterally in permeable strata atop the low-permeability rocks until it discharges as springflow. Most of the water that discharges from springs and much that discharges to surface streams is in the aquifers under unconfined conditions.

Water that leaks downward across shale or other low-permeability confining units is present under confined conditions. Water in wells that penetrate an artesian aquifer rises above the top of the aquifer and can flow at the land surface. Confined conditions frequently occur in the troughs of the gently warped synclines that characterize parts of the Appalachian Plateaus (fig. 91). The figure shows an aquifer that is overlain and underlain by less-permeable material with recharge areas at a higher altitude than the central, down-folded part of the aquifer; thus, the water is under pressure. The potentiometric surface, which represents this pressure, is defined as the height to which water will rise in tightly cased wells that penetrate the aquifer. The potentiometric surface is drawn down around a flowing well or a well that is being pumped because of the release of part of the pressure.

Fresh ground water generally circulates only to shallow depths in the Appalachian Plateaus Province. In much of the area, saline water or brine is not far below the land surface with only a thin transition zone between the freshwater and saltwater. In the Pittsburgh, Pa., area, wells

drilled deeper than 100 feet below the level of the nearest major stream might yield saline water. The discovery of saltwater springs in the 18th century led to a flourishing salt industry in West Virginia. The origin of the brine that feeds the springs is uncertain, but one possible explanation is that salt has been leached from deposits of rock salt and other evaporites. Such deposits are in the Upper Silurian Salina Group, which underlies much of western Pennsylvania, and in the Wills Creek Shale of Maryland, West Virginia, and Virginia. The brine might move upward along deep-seated fractures.

The presence of brine in the Appalachian Plateaus Province compared to its near-absence in the Valley and Ridge Province also might be attributed to the following factors that determine the relative effectiveness of flushing of the brine by freshwater:

° In the Appalachian Plateaus, extensive, almost flat-lying confining units of shale, siltstone, clay, and dense limestone effectively impede the vertical movement of water. This is especially true of the Pennsylvanian rocks, which cover a large part of the area.

° The aquifers and confining units are not as intensely fractured in the Appalachian Plateaus as in the Valley and Ridge. The fractures also decrease in number with depth, and the circulation of water likewise decreases with depth.

° Most of the Appalachian Plateaus lacks the thick, solution-riddled carbonate-rock aquifers of the Valley and Ridge; such aquifers are conduits for the vigorous circulation of water.

The rocks of the Appalachian Plateaus are only mildly deformed compared to those of the Valley and Ridge. The lower part of the geologic section is, therefore, not brought near the land surface by thrust faults or overturned folds and is unable to receive freshwater as recharge or to readily discharge entrapped fluids, such as brine.

In the Central Lowland Province, very saline water is at shallow depths in the consolidated rocks below the glacial drift. The bedrock is generally low-permeability Devonian shale and is an extension of deeply buried formations that contain saline water in the Appalachian Plateaus Province. The younger, more permeable bedrock formations that contain most of the freshwater circulation system in the Appalachian Plateaus Province have been eroded away in the Central Lowland Province.

FACTORS THAT AFFECT GROUND-WATER FLOW

Underground mining of coal disturbs the natural ground-water flow system when the mines are active because artificial drains are constructed to dispose of unwanted water and mining activities can create new fractures and thus increase permeability. The regional water table can be lowered when the drains are effective, and ground-water flow directions can be changed in some cases until flow moves across former ground-water divides into adjoining

basins. Ground water tends to flow toward mines, which are usually dewatered by pumping. Adverse effects of mine drainage on well yields are greatest where the mines are not much deeper than the bottoms of the wells and where vertical fractures connect the aquifers and the mines. Abandoned mines can collapse, which causes fracturing of the rocks that overlie the mine and might be accompanied by an appreciable depression on the land surface. These conditions are likely to enhance recharge to the ground-water system and to reduce surface runoff and evapotranspiration.

Uncased boreholes that penetrate several aquifers, which might have different heads, provide artificial interconnections, or "short circuits," between the aquifers. The water that enters the borehole from aquifers with higher heads moves up the borehole and then laterally into aquifers with lower heads so that the composite head in the well is different than that in each of the aquifers. Flow within the borehole will continue, even when the well is not being pumped, until the head in the two aquifers becomes equal. The freshwater flow system of an area can be significantly altered where numerous uncased wells exist and may result in a change in the potentiometric surface.

Although bedrock formations in the Appalachian Plateaus Province can be traced over many miles, the distribution of lo-cal aquifers within these formations depends, in most cases, on the distribution of fracture permeability. Erosion is one factor that controls the distribution of fractures. Local aquifers, in some cases, are in valleys (fig. 92). Near-vertical tensile fractures and horizontal fractures are associated with slumping that takes place along valley walls, and recharge tends to be concentrated by the fractures. Under the valley floors, the most significant fractures are parallel to bedding, or nearly horizontal. Relief of compressional stress results when the weight of the rock that overlies a valley is reduced, because part of the rock is removed by erosion. This causes the remaining rock to separate along bedding planes and also results in the formation of vertical fractures. Fractures that underlie the valley are interconnected with those along the valley walls, and the interconnected fracture set enhances the permeability of the rock. Away from the valley walls, fractures are scarce and less likely to be interconnected; accordingly, wells in these areas will tend to have lower yields than those in the valleys. Furthermore, water in the shallow fractures on hilltops tends to drain in dry seasons, and yields of some wells might accordingly decline. In general, well yields are directly proportional to the number of interconnected fractures.

GROUND-WATER QUALITY

The chemical quality of water in the freshwater parts of the bedrock aquifers of the Appalachian Plateaus Province is somewhat variable but generally is satisfactory for municipal supplies and other purposes. Most of the water in the upper parts of the aquifers is not greatly mineralized and is suitable, or can be treated and made suitable, for most uses. Saline water commonly is in the aquifers at depths of only a few hundred feet below the land surface.

The undifferentiated sedimentary-rock aquifers consist principally of sandstone and fractured shale and coal. Most of the minerals that compose these aquifers do not readily dissolve, and the water is a calcium sodium bicarbonate type (fig. 93A). Dissolved-solids concentrations are small and aver-age only about 230 milligrams per liter. Hardness averages about 95 milligrams per liter, which is considered to be moder-ately hard. Water from predominately shale aquifers in Pennsylvania is reported to be hard, whereas that from predominately sandstone aquifers is reported to be soft. The median hydrogen ion concentration, which is measured in pH units, is 7.3. The median iron concentration is about 0.1 milligram per liter, but concentrations as large as 38 milligrams per liter have been reported.

Carbonate-rock aquifers consist mostly of calcium and magnesium carbonate minerals, which are readily soluble and affect the chemical composition of the ground water. Limited data show that dissolved-solids concentrations in water from carbonate-rock aquifers in the Appalachian Plateaus Province average about 180 milligrams per liter, and hardness averages about 170 milligrams per liter, which is considered to be hard. The median hydrogen ion concentration, which is measured in pH units, is 7.5 (slightly basic). The median iron concentration is near zero. Water in these aquifers is mostly a calcium bicarbonate type (fig. 93B).

Contamination of ground water by the improper construction or plugging of oil and gas wells is a common problem in the Appalachian Plateaus Province. The area is the cradle of the oil industry in the United States; drilling for oil began in the 1860's, and drilling for brine began even earlier. Natural brines are associated with accumulations of oil and gas and are at shallow depths in many places. Wells that penetrate aquifers that contain brine, if not properly cased and cemented, can provide conduits for the brine to enter shallower freshwater aquifers. It was once a common practice for brine produced with oil and gas to be discharged into open pits from which it seeped downward to contaminate fresh ground-water bodies. Such practices are generally prohibited now, but effects of the past remain.

In coal-mining areas, which in the Appalachian Plateaus Province are generally within the limits of Pennsylvanian rocks (fig. 88), ground water commonly includes water that has been in contact with mine workings or that has infiltrated and leached mine spoil piles (fig. 94). Water affected by coal-mining operations is usually acidic. Sulfur-bearing minerals, such as pyrite, that are present in the coal are exposed to air in mines and spoil piles, and the oxidized sulfur combines with water to form sulfuric acid. The acid water commonly contains large concentrations of iron, manganese, sulfate, and dissolved solids and is highly colored (fig. 95). An exception is in the southern coal fields of West Virginia where the coal is low in sulfur, mine drainage tends to be alkaline, and water from working or abandoned mines is commonly used for public supply.

FRESH GROUND-WATER WITHDRAWALS

Total freshwater withdrawals from consolidated sedimentary-rock aquifers in the Appalachian Plateaus and the Central Lowland Provinces were estimated to be 282 million gallons per day during 1985. About 47 percent of this amount, or about 133 million gallons per day, was withdrawn for domestic and commercial supplies (fig. 96). About 116 million gallons per day, or about 41 percent of the total withdrawals, was pumped for industrial, mining, and thermoelectric power purposes; most of this water was used in coal mining operations.

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Table 1. Crystalline-rock and minor, undifferentiated sedimentary-rock aquifers underlie most of the Piedmont and the Blue Ridge Provinces in Segment 11.

Aquifer	Rock types	Percentage of Piedmont and Blue Ridge area underlain
Crystalline-rock and undifferentiated sedimentary-rock aquifers	Granite, mafic and felsic volcanic rocks, gneiss, schist, slate, phyllite, quartzite; minor conglomerate, sandstone, shale	86
Aquifers in early Mesozoic basins	Sandstone, shale, diabase dikes, basalt flows	[1]9
Carbonate-rock aquifers	Limestone, dolomite, marble	3

[1] An additional 2 percent of the area is underlain by early Mesozoic basins whose rocks are not productive aquifers

Table 2. Carbonate-rock aquifers in the Piedmont and Blue Ridge Provinces of New Jersey carbonate-rock aquifers in the Piedmont and Blue Ridge Provinces of New Jersey and eastern Pennsylvania generally yield volumes of water to wells.

[—, no data]

Eraithem	System	Stratigraphic unit	Principal lithology	Thickness (feet)	Typical well yield (gallons per minute)	Remarks
Paleozoic	Ordovician	Beekmantown Group	Cherty limestone and dolomite	1,400–1,800	—	Upper part not as reliable an aquifer; lower part crops out, contains cavities
	Cambrian	Allentown Dolomite	Cherty dolomite	1,700	60–210	Contains cavities; locally might yield 1,000 gallons per minute
		Leithsville Formation	Dolomite	800	100	Highly cavernous, underlies low areas
Precambrian		Franklin Marble	Marble	—	80–800	

Table 3. The carbonate-rock aquifers in the Hanover–York–Lancaster Valley area yield small to large volumes of water

Subarea	System	Stratigraphic unit	Principal lithology	Thickness (feet)	Typical well yield (gallons per minute)	Remarks
Northern	Ordovician	Beekmantown Group	Limestone and dolomite	1,400–2,300	50	
	Cambrian	Conococheague Group	Dolomite	1,000	25	Moderate yields
		Buffalo Springs Formation	Limestone and dolomite	1,000	10	Generally yield little water, but Zooks Corner Formation locally yields more than 1,000 gallons per minute
		Zooks Corner Formation	Sandy dolomite	1,600	6	
		Ledger Dolomite	Dolomite	1,000	100–200	Locally yields up to 1,100 gallons per minute
		Kinzers Formation	Limestone and dolomite	820	17	
		Vintage Dolomite	Dolomite	650	30–650	
Southern	Ordovician and Cambrian	Conestoga Limestone	Limestone	500–800	65	Large yields possible from solution cavities
		Cockeysville Marble	Marble	750	10–15	Locally yields up to 1,000 gallons per minute
	Cambrian	Elbrook Formation	Limestone and dolomite	900	75	
		Ledger Dolomite	Dolomite	1,000	100–200	Locally yields up to 1,100 gallons per minute
		Kinzers Formation	Limestone and dolomite	900	17	
		Vintage Dolomite	Dolomite	650	30–650	

Table 4. Three carbonate-rock aquifers are in the Frederick Valley, Maryland, area, but only the Grove and Frederick Limestones yield large volumes of water to wells

[—, no data]

System	Stratigraphic unit	Principal lithology	Thickness (feet)	Typical well yield (gallons per minute)	Remarks
Ordovician and Cambrian	Grove Limestone	Limestone	600	70–215	Forms ridges, but contains solution cavities
Cambrian	Frederick Limestone	Limestone	500	120–170	Locally yields up to 275 gallons per minute
	Tomstown Dolomite	Dolomite	200	—	Present only as a narrow strip along western edge of valley