Ground-Water Regions of the United States

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By RALPH C. HEATH

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PREFACE

Two of the primary responsibilities of the U.S. Geological Survey are to assess the Nation's water supply and to develop the understanding necessary to predict the environmental consequences of alternative means of developing and managing water resources. To carry out these responsibilities the Geological Survey conducts studies, many in cooperation with State and local agencies, to determine the quantity and quality of the Nation's water resources and the response of hydrologic systems to both natural and manmade stresses. The results of the studies are made available in numerous ways, including published reports, written and oral responses to specific requests, and presentations at scientific and public meetings.

Although most reports are designed to meet the technical needs of those engaged in the development, management, and protection of water supplies, the U.S. Geological Survey has long recognized the need to present the results of its studies in a form that is also understandable to those who are affected by and who benefit from water developments. To better meet this need, the Water Resources Division of the Geological Survey expanded the preparation of general-interest reports in 1980. The reports planned as a part of this program deal both with specific water-related problems, such as abrupt land subsidence that results in sinkholes and "water logging" of the land in urban areas due to a rising water table, and with general topics of broad public interest, such as this report which describes the ground-water resources of the Nation.

Ground water occurs in the rocks that form the Earth's crust and thus is in the domain of geology. Because the geology of the country is complex, the occurrence of ground water, in detail, is extremely complex. This complexity makes it difficult for many people to develop an understanding of ground-water occurrence and availability and has resulted in problems of ground-water depletion and ground-water pollution whose correction will be both difficult and expensive. Fortunately, such problems are not yet widespread and can, with intelligent application of existing ground-water knowledge, be avoided in most other areas. However, to realize this goal, those engaged in water-resources development and management and the general public need to become better informed on the Nation's ground-water resources. The purpose of this report is to help meet this need.

The report consists of sections that deal concisely with discrete parts of the overall subject. The sections are arranged in a sequence that begins with a discussion of the general aspects of geology and rocks and proceeds to a description of the ground-water systems in the 15 ground-water regions into which the United States, Puerto Rico, and the Virgin Islands are divided. An attempt has been made to illustrate most of the important concepts and topics covered in the discussions. It should be noted that the block diagrams used for illustration in the regional discussions are intended to show the major features of the ground-water system in the region rather than a specific part of a region.

The section entitled "Ground Water Regions of the United States" also warrants special mention. It includes maps that show the boundaries of the regions and tables that summarize the physical and hydrologic characteristics of the regions.

Thus, it serves as a bridge between the preceding sections which deal with the general aspects of geology, ground water, and classification of ground-water systems and the following sections which cover each of the 15 regions. The tables will be useful to those who wish to compare the characteristics of the different regions. Many readers may also find it useful to refer back to these tables from time to time as they read the regional descriptions.

Finally, metric units are used throughout the report but, as an aid to readers who are not familiar with some of these units, the equivalent values in inch-pound units are given at the back of the report. Also, definitions of certain technical terms are included at the end of the table of contents for the benefit of readers who are not familiar with some of the geologic and ground-water terms used in the report.

Ralph C. Heath

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DEFINITIONS OF TERMS

Alluvium. A general term for unconsolidated material deposited by a stream or other body of running water.

Aquifer. A water-bearing rock unit that will yield water in a usable quantity to a well or spring.

Bedrock. A general term for the consolidated (solid) rock that underlies soils or other unconsolidated surficial materials. (See **regolith.**)

Brecciated. A rock structure marked by angular fragments.

Capillary fringe. The zone above the water table in which water is held by surface tension. Water in the capillary fringe is under a pressure less than atmospheric.

Cone of depression. The depression of heads around a water-supply well caused by the withdrawal of water.

Confined aquifer. An aquifer saturated with water and bounded above and below by beds having a distinctly lower hydraulic conductivity than the aquifer itself.

Confining bed. A layer of rock adjacent to an aquifer that hampers the movement of water into or out of the aquifer.

Connate water. Water entrapped in the interstices of a sedimentary or extrusive igneous rock at the time of its deposition.

Crystalline rock. A general term used to refer to igneous and metamorphic rocks.

Discharge area. An area in which water is lost from the zone of saturation.

Drawdown. The decline in ground-water level at a point caused by the withdrawal of water from an aquifer.

Extrusive igneous rock. An igneous rock that has been ejected onto the surface of the Earth, including lava and volcanic ash.

Freshwater. Water containing only small quantities (generally less than 1,000 mg/L) of dissolved minerals.

Gaining stream. A stream or reach of a stream that receives water from the zone of saturation.

Glacial drift. A general term for material transported by glaciers or icebergs and deposited directly on land or in the sea.

Ground water. Water in the saturated zone that is under a pressure equal to or greater than atmospheric pressure.

Hydraulic conductivity. The capacity of a rock to transmit water; expressed as the volume of water that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

Hydraulic gradient. Change in head per unit of distance measured in the direction of the steepest change.

Hydraulic head. In ground water, the height above a datum plane (such as sea level) of the column of water that can be supported by the hydraulic pressure at a given point in a ground-water system. For a well, the hydraulic head is equal to the distance between the water level in the well and the datum plane.

Igneous rock. A rock that solidified from molten or partly molten material.

Intrusive igneous rock. A rock that solidified below the Earth's surface from molten or partly molten material.

Joint. A planar parting or fracture in a rock.

Lava tube. A hollow space beneath the surface of a solidified lava flow, formed by the withdrawal of molten lava after formation of the surficial crust.

Loess. An unconsolidated, commonly nonstratified, surficial deposit, consisting predominantly of silt- and clay-size particles, that appears to have been deposited by the wind.

Losing stream. A stream or reach of a stream that contributes water to the zone of saturation.

Metamorphic rock. A rock formed at depth in the Earth's crust from preexisting rocks by mineralogical, chemical, and structural changes caused by high temperature, pressure, and other factors.

Mineralized water. Water containing dissolved minerals in concentrations large enough to affect use of the water for some purposes. A concentration of 1,000 mg/L of dissolved solids is commonly used as the lower limit for mineralized water.

Mining. A term used in connection with withdrawals that deplete ground-water storage in arid and semiarid regions in which the opportunity for natural replenishment of storage is insignificant.

pH (hydrogen-ion activity). A number used by chemists to express the acidity of solutions, including water. A pH value lower than 7 indicates an acidic solution, a value of 7 is neutral, and a value higher than 7 indicates an alkaline solution. Most ground waters in the United States have pH values ranging from about 6.0 to 8.5.

Phreatophyte. A deep-routed plant that obtains its water supply from the zone of saturation.

Playa. The central vegetation-free areas in the lowermost part of closed or undrained desert basins in which water accumulates for short periods after rains.

Porosity. The volume of openings in a rock. When expressed as a fraction, porosity is the ratio of the volume of openings in the rock to the total volume of the rock.

Potentiometric surface. An imaginary surface representing the level to which water will rise in wells.
Primary porosity. The openings or pores in a rock at the time it was formed.
Recharge area. An area in which water reaches the zone of saturation from surface infiltration.
Regolith. A general term for the layer of unconsolidated (soil-like) material of whatever origin that nearly everywhere forms the surface of the land and that overlies or covers the more coherent bedrock.
Saprolite. A soft, clay-rich material formed in place by chemical weathering of igneous and metamorphic rocks.
Saturated zone. The subsurface zone in which all openings are full of water.
Sedimentary rock. A layered rock formed at or near the Earth's surface (1) from fragments of older rocks, (2) by precipitation from solution, or (3) from the remains of living organisms.
Shrinkage cracks. Small cracks formed in a rock during a decrease in volume, as during the loss of water (drying) of mud or the cooling of lava.
Specific retention. The ratio of the volume of water retained in a rock after gravity drainage to the volume of the rock.
Specific yield. The ratio of the volume of water that will drain under the influence of gravity to the volume of saturated rock.
Storage coefficient. The volume of water released from storage in a unit prism of an aquifer when the head is lowered a unit distance.
Till. An unsorted and unstratified mixture of clay, silt, sand, gravel, and boulders deposited directly by glaciers.
Transmissivity. The capacity of an aquifer to transmit water; equal to the hydraulic conductivity times the aquifer thickness.
Unconfined aquifer. An aquifer that contains both an unsaturated and a saturated zone (i.e., an aquifer that is not full of water).
Underground water. A general term for all water beneath the land surface.
Unsaturated zone. The subsurface zone, usually starting at the land surface, that contains both water and air.
Water budget. An accounting of the inflow to, outflow from, and storage in a hydrologic unit such as a drainage basin, aquifer, soil zone, lake, or reservoir.
Water table. The level in the saturated zone at which the water is under a pressure equal to the atmospheric pressure.

Ground-Water Regions of the United States

By Ralph C. Heath

GROUND WATER— AN INVALUABLE RESOURCE

The importance of ground water to mankind is difficult to overestimate. It is an important source of water in nearly all inhabited places on Earth—and the only dependable source of water in most arid and semiarid regions. Much of the economic development of Third World countries, especially since World War II, has been made possible by the development of readily available ground water. But even in the more advanced countries, ground water has been, and continues to be, an important factor in economic growth. For example, ground-water withdrawals in the United States in 1980 amounted to about 124 km^3 (cubic kilometers) (29.7 cubic miles, or 3.27×10^{13} gallons). This represents about 40 percent of the freshwater used for all purposes except hydropower generation and electric-powerplant cooling.

Ground water is available in at least small amounts at nearly every point on the Earth's surface, making it one of the most widely available of all natural resources. Consequently, it serves as the only, or the dominant, source of domestic water in all rural areas, as the largest source of water for irrigation and other purposes in arid and semiarid regions, and as an important source of water for urban and industrial purposes in humid areas. The importance of ground water is readily apparent from data on ground-water use in the United States. The estimated use in 1980, by State, is shown in figure 1 and is summarized in table 1.

The widespread use of ground water results not only from its general availability, but also from economic and public-health considerations. From the standpoint of economics, ground water is commonly available at the point of need at relatively little cost and thus does not

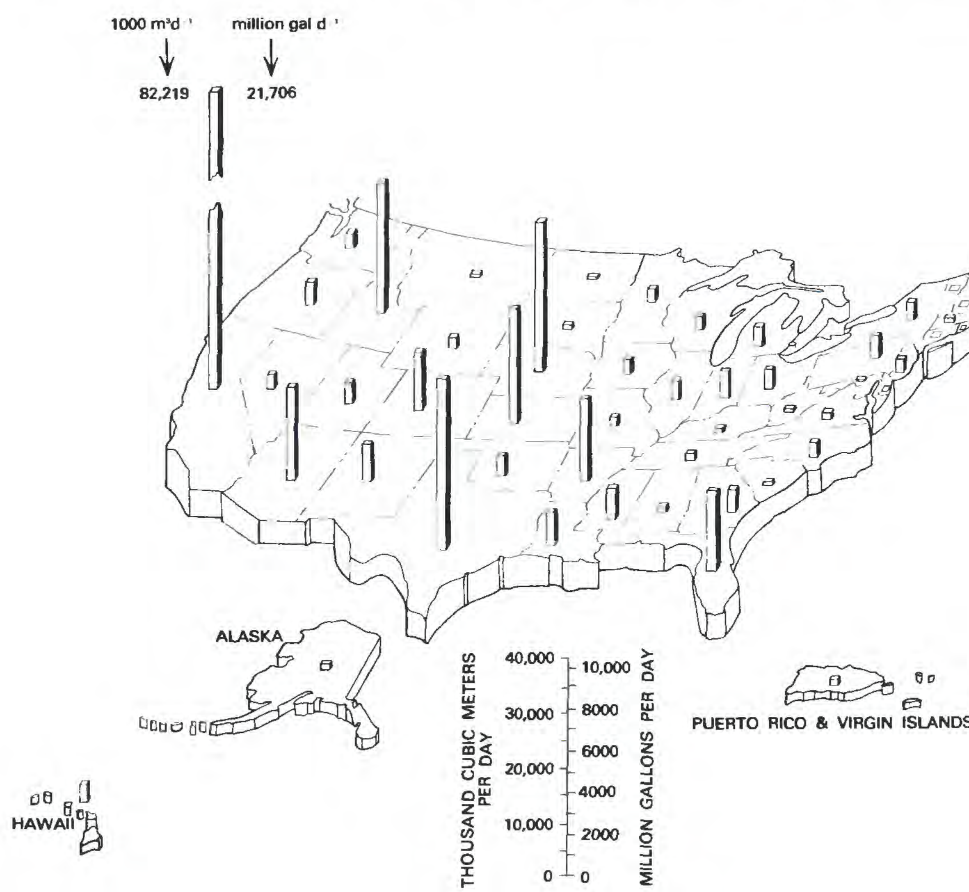


Figure 1. Ground-water withdrawals, by State, in 1980.

Table 1. Summary of water use in the United States in 1980
[All purposes except hydroelectric power and condenser and reactor cooling of thermoelectric power plants]

State	Land area (km^2)	Population in 1980 (1,000's)	Total water use (1,000 m^3d^{-1})	Ground-water use			
				Amount (1,000 m^3d^{-1})	Percentage of total	Per unit area ($m^3day^{-1}km^{-2}$)	Per capita (m^3day^{-1})
Alabama	131,334	3,890.1	9,558	1,335	14	10.2	0.34
Alaska	1,475,264	402.6	728	152	21	.1	.38
Arizona	293,750	2,717.7	29,795	15,818	53	53.8	5.82
Arkansas	134,538	2,289.9	22,534	15,028	67	111.7	6.56
California	404,975	23,668.6	161,381	76,913	48	189.9	3.25
Colorado	268,754	2,888.8	58,190	10,609	18	39.5	3.67
Connecticut	12,593	3,107.6	2,681	522	19	41.4	.17
Delaware	5,133	595.0	1,977	290	15	56.5	.49
Dist. of Columbia	158	638.0	793	3	0	19.2	.00
Florida	140,093	9,740.0	20,878	14,156	68	101.0	1.45
Georgia	150,409	5,464.3	8,852	4,389	50	29.2	.80
Hawaii	16,641	965.0	4,417	2,507	57	150.7	2.60
Idaho	214,133	943.9	68,596	23,990	35	112.0	25.42
Illinois	144,387	11,418.4	14,871	3,652	25	25.3	.32
Indiana	93,491	5,396.0	15,475	4,843	31	51.8	.90
Iowa	144,487	2,913.0	4,452	2,863	64	19.8	.98
Kansas	211,828	2,363.0	23,570	20,983	89	99.1	8.88
Kentucky	102,694	3,661.4	3,545	906	26	8.8	.25
Louisiana	116,369	4,199.2	26,222	6,590	25	56.6	1.57
Maine	80,083	1,124.7	3,038	303	10	3.8	0.27
Maryland	25,618	4,216.0	4,650	581	12	22.7	.14
Massachusetts	20,269	5,737.0	4,659	1,225	26	60.4	.21
Michigan	147,156	9,258.4	14,310	3,589	25	24.4	.39
Minnesota	205,359	4,061.2	5,225	2,525	48	12.3	.62
Mississippi	122,497	2,520.6	7,235	5,641	78	46.0	2.24
Missouri	178,697	4,888.0	5,057	1,789	35	10.0	.37
Montana	377,070	786.2	41,051	994	2	2.6	1.26
Nebraska	198,091	1,570.0	36,973	26,958	73	136.1	17.17
Nevada	284,613	799.2	13,241	2,684	20	9.4	3.36
New Hampshire	23,380	920.6	1,175	247	21	10.6	.27
New Jersey	19,479	7,360.0	11,211	2,748	25	141.1	.37
New Mexico	314,457	1,299.9	14,472	6,874	48	21.9	5.29
New York	123,882	17,556.7	15,427	3,014	20	24.3	.17
North Carolina	126,387	5,874.4	14,804	2,913	20	23.0	.50
North Dakota	179,417	652.4	1,443	445	31	2.5	.68
Ohio	106,125	10,797.0	13,673	3,663	27	34.5	.34
Oklahoma	178,145	3,025.1	6,135	3,967	65	22.3	1.31
Oregon	249,117	2,614.2	25,740	4,281	17	17.2	1.64
Pennsylvania	116,462	11,824.5	20,981	3,861	18	33.2	0.33
Rhode Island	2,717	947.2	654	139	21	51.1	.15
South Carolina	78,283	3,119.3	3,762	868	23	11.1	.28
South Dakota	196,723	695.3	2,607	1,242	48	6.3	1.79
Tennessee	107,040	4,590.7	9,722	1,686	17	15.8	.37
Texas	678,927	14,013.5	48,126	30,286	63	44.6	2.16
Utah	212,629	1,462.0	17,128	3,936	23	18.5	2.69
Vermont	24,002	511.5	437	172	39	7.2	.34
Virginia	103,030	5,377.6	3,317	1,564	47	15.2	.29
Washington	172,416	4,126.9	31,370	2,896	9	16.8	.70
West Virginia	62,341	1,950.0	4,347	840	19	13.5	.43
Wisconsin	141,062	4,710.0	4,740	2,313	49	16.4	.49
Wyoming	251,756	470.8	19,506	2,125	11	8.4	4.51
Puerto Rico	8,860	3,400.0	6,582	1,207	18	136.3	.36
Virgin Islands	342	100.0	24	15	63	44.3	.15
United States[1]	9,168,660	229,623.5	891,331	333,141	37	36.3	1.45

[1]United States, Puerto Rico, and the Virgin Islands.

Source of water-use data: Mann and others, 1982 require the construction of distant reservoirs and long pipelines. It is usually of good quality, normally free of suspended sediment, and, except in limited areas where it has been polluted, free of bacteria and other disease-causing organisms and thus not requiring extensive treatment and filtration prior to use. These characteristics are not only an economic benefit, but also a benefit to health.

Although ground water is available nearly everywhere in the United States, the quantity available and the conditions controlling its occurrence and development differ from one part of the country to another. The purpose of this report is to describe briefly the ground-water system in different parts of the country, as an aid to those involved in the development, conservation, and protection of the Nation's ground-water resources. For the purpose of preparing these descriptions, the United States, Puerto Rico, and the Virgin Islands are divided into 15 regions in which ground-water conditions are relatively similar.

GEOLOGY AND GROUND WATER

Ground water occurs in openings in the rocks that form the Earth's crust. The volume of the openings and the other water-bearing characteristics of the rocks depend on the mineral composition and structure of the rocks. Therefore, to understand the occurrence of ground water it is first necessary to become familiar with the major groups of rocks in which ground water occurs.

Geologists divide all rocks exposed at the Earth's surface into three major groups: (1) igneous, (2) sedimentary, and (3) metamorphic. *Igneous rocks* are rocks that have formed from a molten or partially molten state. Some types of igneous rocks, including granite, solidify at great depth below the land surface and are referred to as *intrusive igneous rocks.* Other igneous rocks form from lava or volcanic ash ejected onto the surface and are referred to as *extrusive igneous rocks.*

Sedimentary rocks are formed by the deposition of sediment by water, ice, or air. Most sedimentary rocks are unconsolidated (soil-like) at the time of formation. If they are, in time, buried deeply enough and compressed, or if they undergo certain chemical changes, they may become consolidated.

Both igneous and sedimentary rocks may, over the course of geologic time, reach depths beneath the Earth's crust at which they are subjected to great heat and pressure. This may alter both their structural characteristics and their mineral composition to such an extent that they are changed into *metamorphic rocks.* Depending on their original mode of origin, they may be referred to, for example, as metavolcanic or metasedimentary rocks. Metamorphic rocks and intrusive igneous rocks are collectively termed *crystalline rocks* by some investigators.

The United States is underlain by many different types of rocks, including representatives of both the igneous and sedimentary groups and types of both groups that have been subjected to metamorphism. The nature of the water-bearing openings in these rocks depends to a large extent on the geologic age of the rocks as well as on the processes that formed the rocks. The youngest rocks are unconsolidated sedimentary deposits and extrusive igneous rocks. The openings in sedimentary deposits are pores between the mineral grains (fig. 2). The openings in extrusive igneous rocks are, among other types, lava tubes, pores in ash deposits, and cooling fractures (fig. 2). Both of these geologically young types of rocks tend to have a larger volume of openings than do older rocks of the same types which have been subjected to consolidation and to the partial or complete filling of openings by the deposition of minerals and sediment.

Intrusive igneous rocks and metamorphic rocks are among the oldest water-bearing rocks. At the time of their formation, they do not contain any appreciable openings. These rocks, as noted above, are formed at great depths below the surface. Thus, at the time of formation they are under the pressures exerted by the weight of the overlying rocks. Over the course of geologic time, most of these rocks have also been subjected to compressive forces acting more or less parallel to the land surface. As the rocks are gradually exposed by erosion of the overlying rocks, the vertical and lateral compressive forces on them are relieved and they break along sets of horizontal and vertical fractures which then serve as water-bearing openings (fig. 2). Similar fractures also form in sedimentary rocks that have been deeply buried, consolidated, and then exposed by erosion of the overlying rocks.

Because of the general relation of water-bearing openings to rock type and geologic age, both rock type and geologic age are important factors in ground-water hydrology. For convenience in studying the Earth's history, geologic time has been divided into several eras, periods, and epochs, as shown in table 2. The geologic time during which different groups of rocks that now serve as sources of ground water were formed are shown as vertical lines in the table. The geologic ages of the rocks underlying different parts of the country are shown on figure 3.

The Earth's surface is underlain at most places by unconsolidated rocks. These may be relatively young sedimentary deposits composed of rock fragments of all kinds, volcanic ash, *alluvium, glacial drift,* sand dunes, or material derived from the breakdown (weathering) of the underlying igneous, metamorphic, or consolidated sedimentary rocks. This surficial layer of unconsolidated material, regardless of its origin, is referred to by geologists as *regolith.* The regolith is underlain every place by consolidated rocks which, in different areas, are of igneous, metamorphic, or sedimentary origin. These consoli-

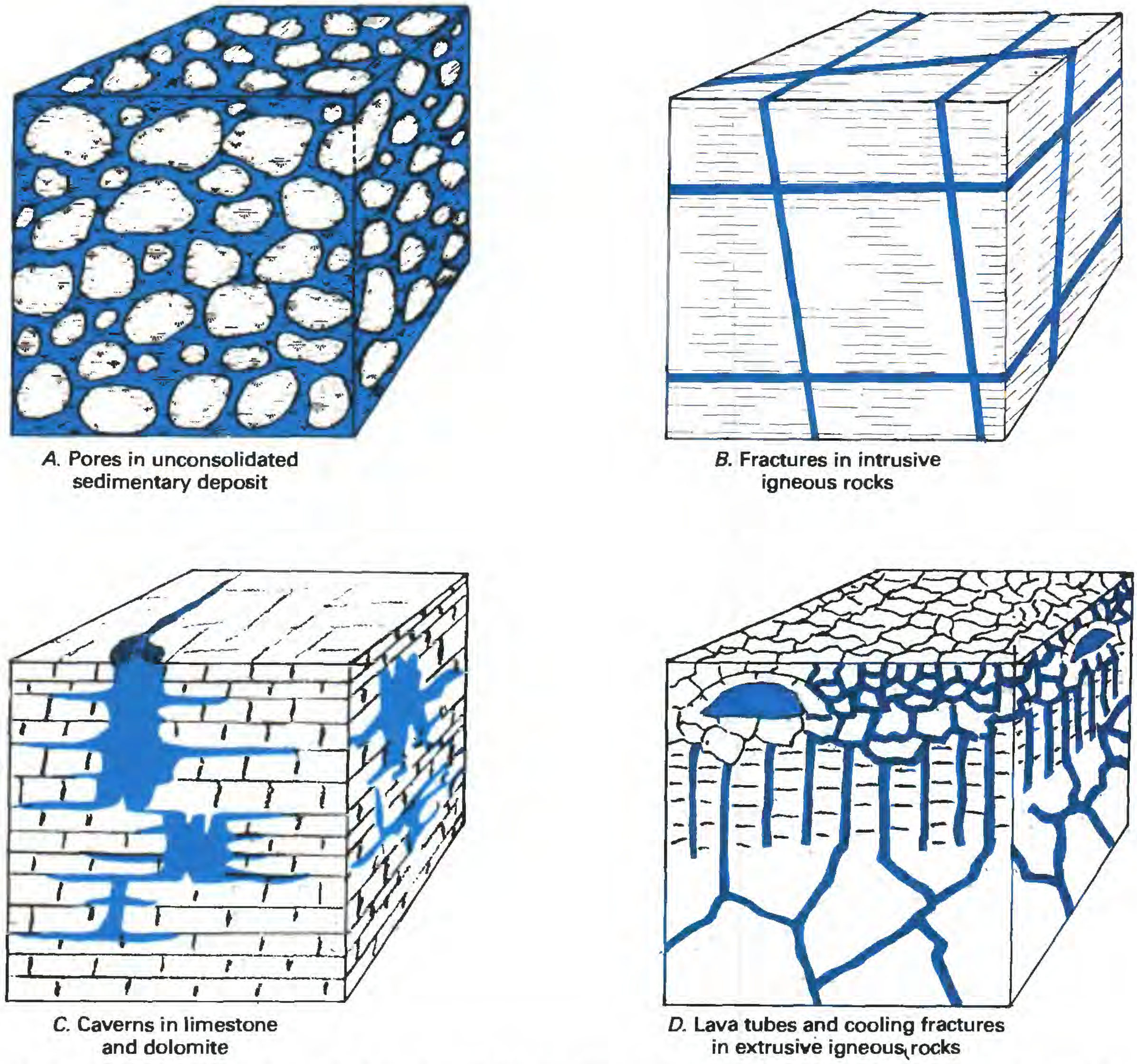


Figure 2. Types of openings in selected water-bearing rocks. Block *A* is a few millimeters wide, block *B* is a meter or two wide, and blocks *C* and *D* are a few tens of meters wide.

dated rocks are referred to collectively as *bedrock.*

The thickness of the surficial layer of unconsolidated deposits differs widely from place to place. Under parts of the Atlantic and Gulf Coastal Plain this layer consists of thousands of meters of gravel, sand, silt, clay, and limestone. In much of the south central part of the country, where it is composed of sandy and clayey material derived from weathering of consolidated sedimentary rocks of Paleozoic age (fig. 3), the surficial layer is generally only a few meters thick.

BASIC GROUND-WATER CONCEPTS AND TERMINOLOGY

Water below the Earth's surface is referred to as *underground water* (fig. 4). It occurs in two distinctly different zones. The uppermost zone extends from the land surface to depths ranging from less than a meter in parts of humid areas to a hundred meters or more in parts of some arid areas. Openings in this zone contain both water and air; as a consequence, the zone is referred to as the *unsaturated zone.* Below the unsaturated zone is a zone in which interconnected openings contain only water and which is referred to as the *saturated zone.* The *water table* is the level near the upper part of the saturated zone at which water occurs under a pressure equal to the atmospheric pressure. The position of the water table is indicated by the position of the water level in shallow wells. Water in the saturated zone above the water table occurs in a *capillary fringe* that is maintained by the strong surface tension of water. Water below the water table is referred to as *ground water.* It is this water that

Table 2. Relation of geologic age, major rock groups, and water-bearing openings

Era	Period	Epoch	Time before present (estimated in millions of years)	Sedimentary rocks: Unconsolidated (pores)	Sedimentary rocks: Semiconsolidated (pores and fractures)	Sedimentary rocks: Consolidated (fractures)	Igneous rocks: Extrusive (pores and fractures)	Igneous rocks: Intrusive (fractures)	Metamorphic rocks: Igneous and sedimentary (fractures)
Cenozoic	Quaternary	Holocene							
		Pleistocene	2						
	Tertiary	Pliocene	5						
		Miocene	24						
		Oligocene	38						
		Eocene	55						
		Paleocene	63						
Mesozoic	Cretaceous		138						
	Jurassic		205						
	Triassic		240						
Paleozoic	Permian		290						
	Pennsylvanian		330						
	Mississippian		360						
	Devonian		410						
	Silurian		435						
	Ordovician		500						
	Cambrian		570						
Precambrian									

discharges through springs, seeps, and free-flowing or pumping wells.

Part of the precipitation that reaches the land surface in areas in which an unsaturated zone exists percolates downward across the unsaturated zone to the saturated zone (fig. 5). These areas are known as *recharge areas* beause they are places where ground-water recharge occurs. After reaching the saturated zone, water moves downward and laterally under the hydraulic gradients prevailing in the ground-water system to *discharge areas.*

The capacity of rocks to transmit water is referred to as *hydraulic conductivity.* This term replaces the term "permeability," which was in common use for many years. Saturated rock units whose hydraulic conductivity is large enough to supply water in a usable quantity to a well or a spring are referred to as *aquifers.* Less permeable intervening rock layers are referred to as *confining beds.* Because the hydraulic conductivity of aquifers is commonly several hundred to several thousand times that of confining beds, aquifers function as pipelines that transmit ground water from recharge areas to discharge areas (fig. 5). In ground-water systems in which the aquifers and confining beds are essentially horizontal, confining beds impede the vertical movement of water. As a result, the most active lateral movement tends to occur in the shallowest aquifers.

The land surface in most areas is underlain by a relatively permeable layer, which in turn is underlain by less permeable materials. The surficial layer ranges in thickness, from one area to another, from a few meters to a few hundred meters. Water that infiltrates the ground in these areas collects in a saturated zone above the underlying confining bed and thereby forms an *unconfined aquifer*—that is, an aquifer that is not full of water and in which the saturated zone ranges in thickness from one time to another. If water percolates through the confining bed and completely fills an underlying permeable bed, it forms a *confined aquifer*—that is, an aquifer that is full of water and that is overlain by a confining bed (fig. 5).

To facilitate comparison of the water-transmitting capacity of different types of rocks, hydraulic conductivity is expressed in terms of the volume of water that would be transmitted in a unit of time through a unit cross-sectional area of rock under a unit hydraulic gradient. The metric units commonly used to express hydraulic conductivity are cubic meters for volume, a square meter for area, and meter per meter for hydraulic gradient. The unit of time is commonly a day. In the inch-pound system of measurements, the units are cubic feet (or gallons) per square foot under a hydraulic gradient of foot per foot. The water-transmitting capacity of an aquifer, in contrast to that of a unit volume of rock, is equal to the hydraulic conductivity times the aquifer thickness, when the thickness is expressed in either meters or feet. The resulting value is referred to as *transmissivity* (fig. 6).

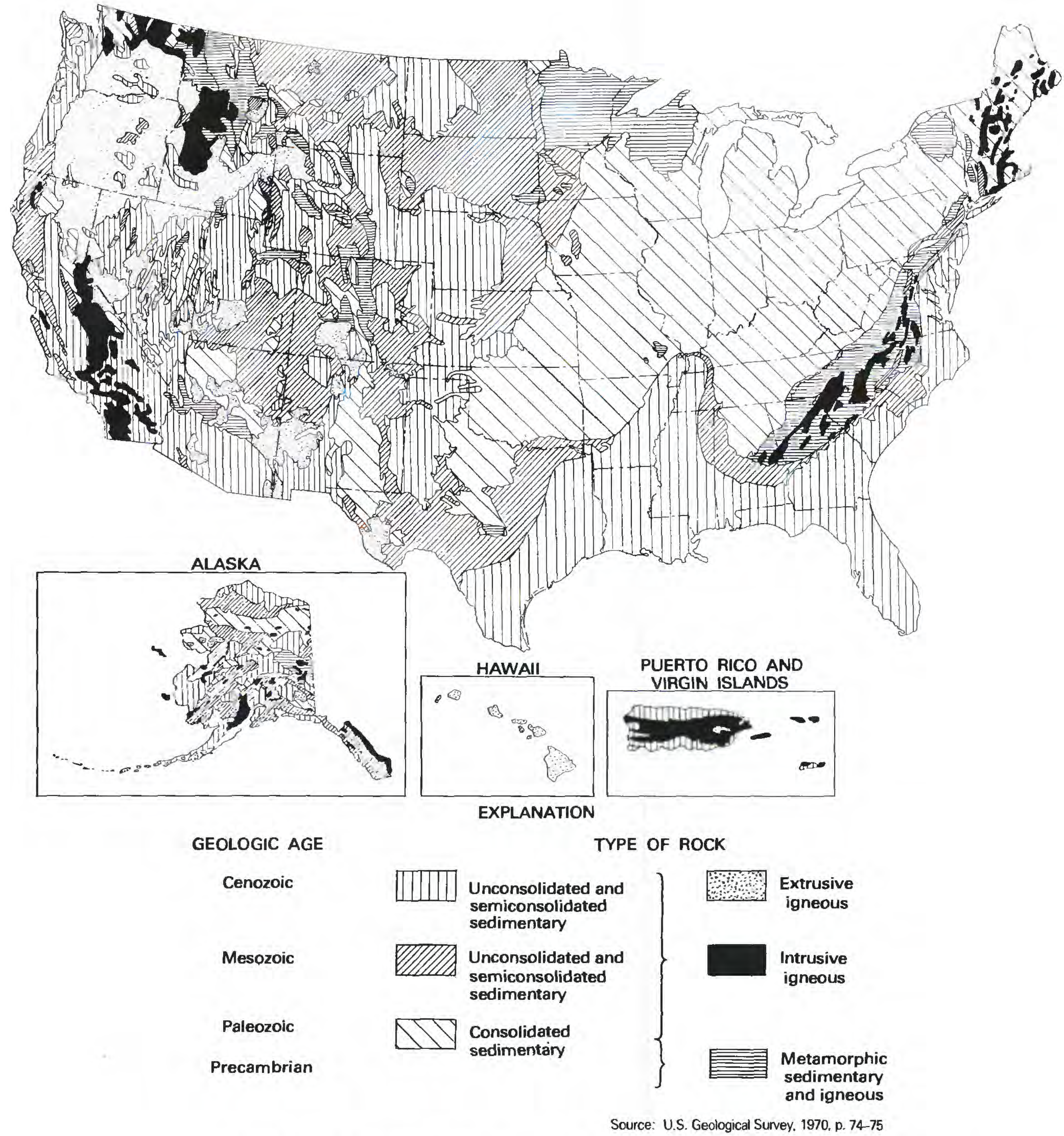


Figure 3. Geologic age of major rock groups in the United States.

The water in transit through ground-water systems may also be viewed as water in storage. Consequently, the storage properties of rocks are as important as their hydraulic conductivities. The volume of the openings in a rock is referred to as *porosity* and is generally expressed as a decimal fraction or as a percentage (fig. 7). When rock saturated with water is drained, water will remain in the smallest openings and as a film on the sides of the larger pores and other openings. Thus, porosity can usefully be viewed as consisting of two parts: the part that will drain, which is referred to as *specific yield,* and the part that will be retained, which is referred to as *specific retention* (fig. 8).

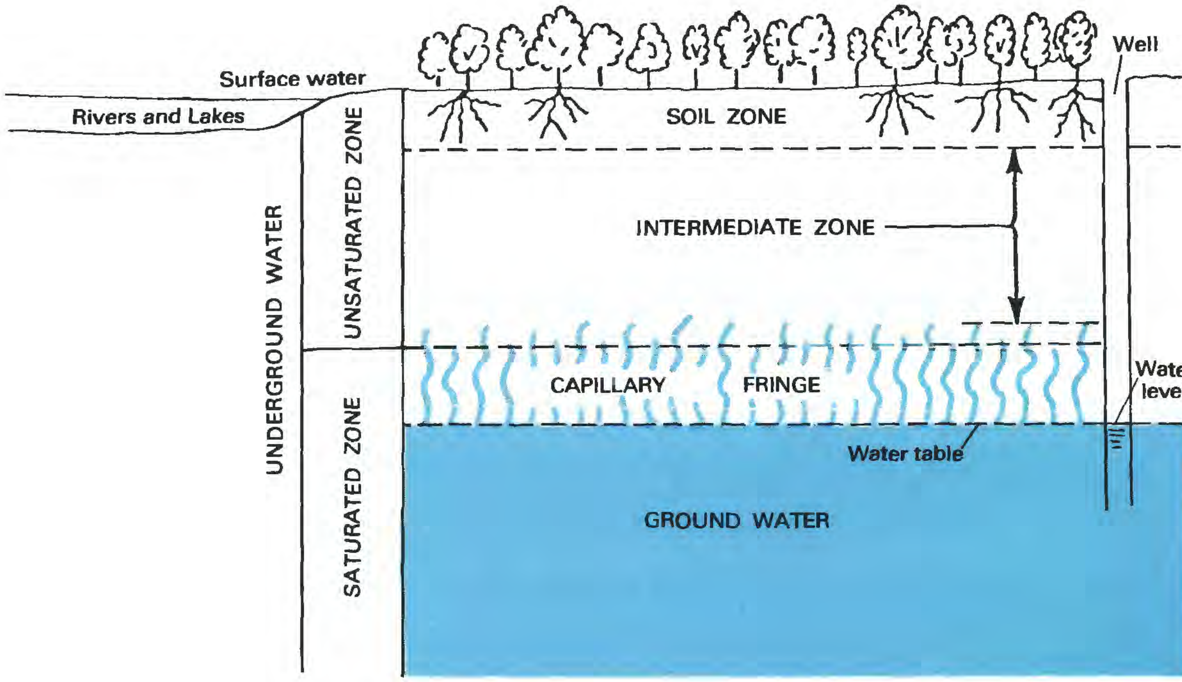


Figure 4. Occurrence of underground water. Underground water occurs in both an unsaturated zone and a saturated zone. The upper part of the saturated zone is occupied by water held in a capillary fringe by surface tension. The water table is the level in the saturated zone at which the water is under a pressure equal to atmospheric pressure. Its position is indicated by the water level in shallow wells.

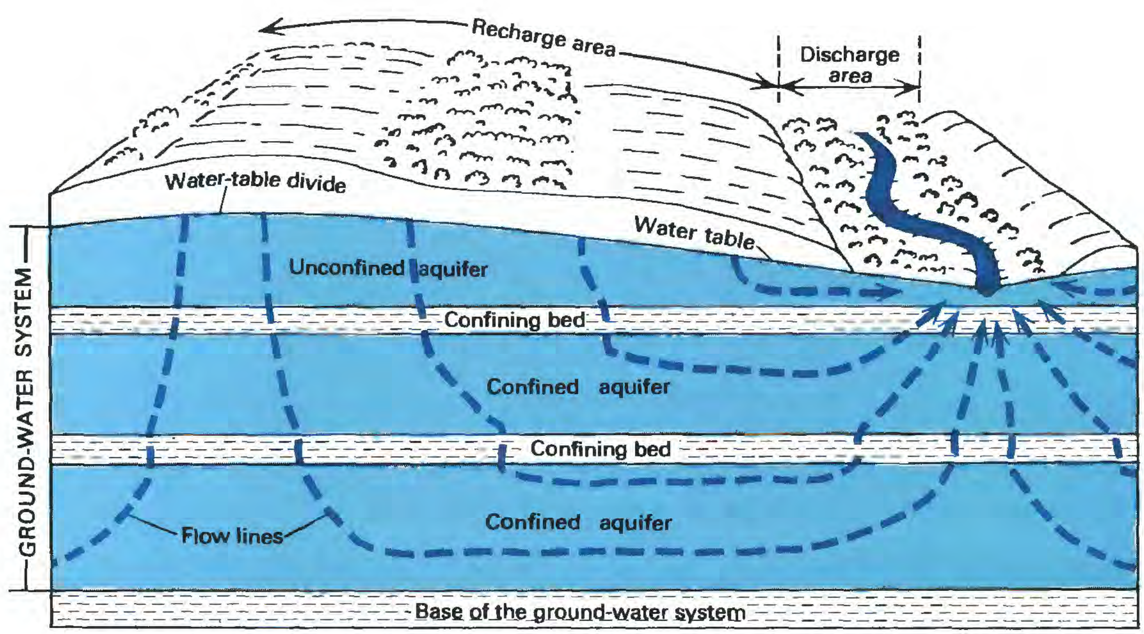


Figure 5. Movement of water through ground-water systems. Water that enters a ground-water system in recharge areas moves through the aquifers and confining beds comprising the system to discharge areas.

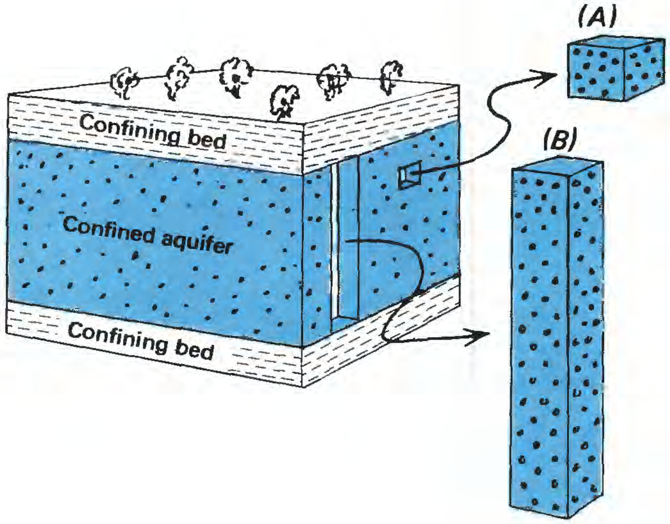


Figure 6. Difference between hydraulic conductivity and transmissivity. Hydraulic conductivity defines the water-transmitting capacity of a unit cube (*A*) of the aquifer. Transmissivity defines the water-transmitting capacity of a unit prism (*B*) of the aquifer.

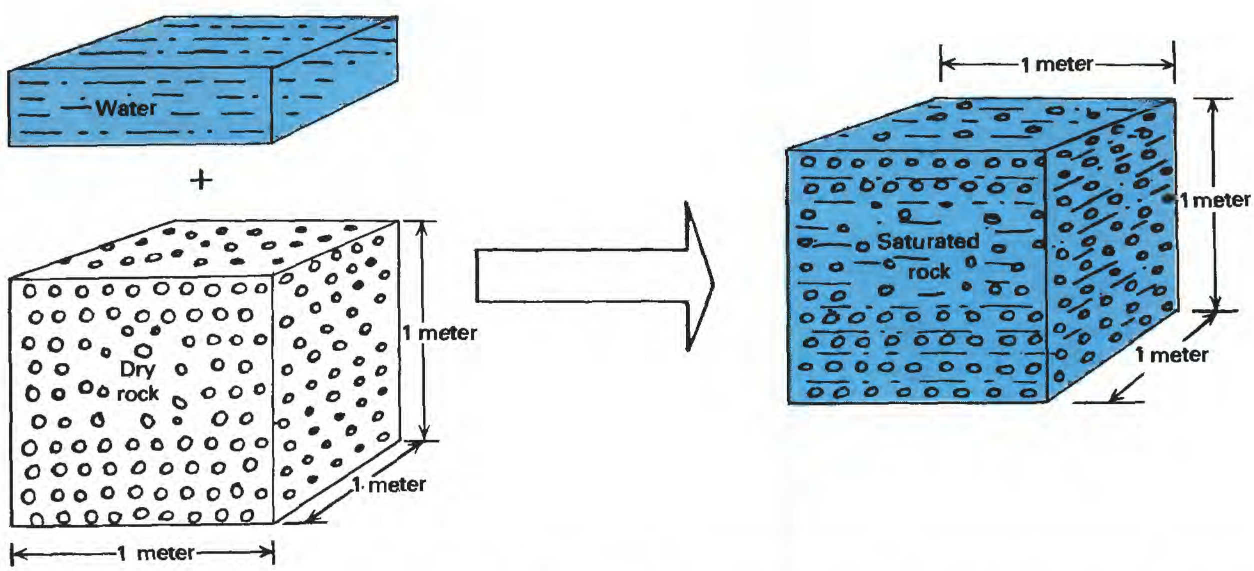


Figure 7. Porosity—the volume of a rock occupied by openings. Porosity determines the amount of water a dry sample of rock will absorb.

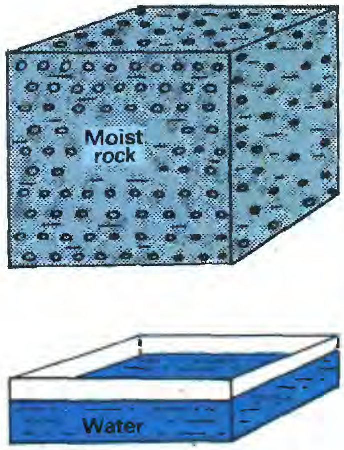


Figure 8. Specific yield and specific retention. Only a part of the water filling the pores of a rock will drain under the influence of gravity. This part is referred to as specific yield. Water retained in small openings and as a flm on the surface of the larger pores and openings is referred to as specific retention.

WATER-BEARING ROCKS

All of the types of rocks mentioned in the preceding discussion of geology and ground water are water bearing and serve as sources of ground water in one area or another. Each group is composed of several different kinds of rocks, each kind having different water-bearing characteristics. It is, therefore, useful to identify and discuss briefly the kinds of rocks that serve as important sources of water or as barriers to ground-water movement. Table 3 lists the rocks of most importance to ground-water hydrology, either as sources of water (aquifers) or as layers that hamper the movement of water (confining beds).

Rocks that are most important as sources of large amounts of ground water include (1) sand and gravel, (2) limestone and dolomite, (3) basalt, and (4) sandstone. The principal areas in which these rocks occur are shown on the map in figure 9. Other, relatively common rocks that serve as sources of small to moderate supplies are also listed in the table, but they are not shown on the map. Rocks that serve primarily as barriers to ground-water movement include clay and shale.

Sand and gravel are the sources of most of the water pumped from wells in the United States. As shown on figure 9, sand and gravel beds underlie much of the Atlantic and Gulf Coastal Plain, several large areas in the North-Central States, a large area east of the Rocky Mountains that extends from Texas to South Dakota, and numerous valleys in the west, including the Central Valley in California. At the scale of the map, it is not possible to show the numerous glaciated valleys in the central and northern parts of the country that are also underlain by highly productive deposits of sand and gravel. However, these valleys are shown in figure 13. The importance of sand and gravel as a source of ground water is a result of both their widespread occurrence and their capacity to yield water to wells at large rates.

Limestone and dolomites are the sources of some of the largest well and spring yields in the United States. Of the 65 or more first-magnitude springs in the United States—springs having a maximum discharge of more than 2.83 cubic meters per second (m^3sec^{-1}) (100 ft^3sec^{-1})—more than one-third are in limestone. Limestone and dolomite, collectively referred to as carbonate rocks, underlie large areas in the southeast and in the central part of the country, as seen in figure 9. Their yields are large because they are more soluble in water than are other common aquifer-forming rocks. Openings present in them at the time of deposition, and openings that form later, are enlarged by circulating water. One result of this is the formation of large and extensive cave systems (see figure 32).

Basalt and other volcanic rocks are among the most productive water-bearing materials. Basalt is a dark-colored volcanic rock that may spread in sheets or flows to form extensive plains, as has occurred in southern Idaho and eastern Washington and Oregon. The thickness of the flows ranges from a fraction of a meter to several tens of meters. Water-bearing openings in the basalt flows include *lava tubes, shrinkage cracks, joints,* and a fragmented and broken (*brecciated*) zone at the top of the flows. The interior of some flows is composed of basalt that cooled gradually, forming a dense rock in which most water-bearing openings are shrinkage cracks and joints. Hawaii is underlain by basalt laid down as a complex sequence of flows that formed dome-shaped masses around eruption centers.

Sandstone is the consolidated equivalent of sand and differs from it primarily by the presence of cementing material deposited between the grains or crystalline growth of the grains themselves. Any of several minerals, including calcium carbonate, silica, and iron oxide, may serve as "cement." Sandstone is most important as a source of ground water where the cementing minerals have been deposited only around the points of contact of the sand particles, resulting in the retention of appreciable intergranular porosity. Some geologists refer to such partially cemented rocks as semiconsolidated to differentiate them from other (consolidated) rocks in which all pores are filled with cementing minerals. Sandstone may be fractured along bedding planes and more or less per-

Table 3. Rocks of greatest importance in ground-water hydrology.

Sedimentary rocks			Igneous rocks	
Unconsolidated (pores)	Consolidated (pores, fractures, and solution openings)	Metamorphic rocks (fractures)	Intrusive (fractures)	Extrusive (pores, tubes, rubble zones, and fractures)
GRAVEL[1]	Conglomerate[2]	Gneiss	Granite and other coarse-grained igneous rocks	BASALT and other fine-grained igneous rocks
SAND	SANDSTONE	Quartzite-schist		
Silt	Siltstone	Schist		
Clay[3]	*Shale*	Slate-schist		
Till	Tillite (rare)			
Marl	LIMESTONE-DOLOMITE	Marble		
Coquina				

[1]Capitalized names indicate rocks that are major sources of large ground-water supplies.
[2]Lower-case names indicate rocks of relatively wide extent that are sources of small to moderate ground-water supplies.
[3]Italic names indicate rocks that function primarily as confining beds.

pendicular to the planes. Sandstone serves as an important source of ground water in a large area in the north-central part of the country, in an area in northeastern Texas, in an area in west Texas (interbedded with limestone), and in a relatively narrow zone west of the Appalachian Mountains from Alabama to Pennsylvania.

The fifth group of rocks shown on figure 9 includes several different igneous, metamorphic, and consolidated sedimentary rocks. Rocks in this group include granite, gneiss, schist, quartzite, slate, and interbedded shale and sandstone. It is possible, from a ground-water standpoint, to lump together such a large and diverse group of rocks because they contain water primarily in openings developed along fractures and other breaks. Because all these rocks are relatively insoluble, there is no appreciable enlargement of the fractures by solution, as has occurred in the carbonate rocks. The sandstones interbedded with shale, especially in the central part of the country, may retain some intergranular porosity that makes them somewhat more productive than the other rocks in this group, but it is not feasible in the scope of this discussion to treat them separately from the remainder of the group. Because water is present in this group of rocks primarily along fractures, they are the least productive of the rocks covered in this discussion.

Most of the rocks discussed in this section are irregularly overlain by, and interbedded with, clay and shale which serve as confining beds, or barriers to ground-water movement. Clay has a large porosity but, because its pores are microscopic, the movement of water through it is extremely slow. Shale, like other consolidated rocks, is fractured; however, the fractures tend to be more closely spaced and, therefore, the openings along them are smaller than those in carbonate rocks and sandstones.

CLASSIFICATION OF GROUND-WATER REGIONS

To describe concisely ground-water conditions in the United States, it is necessary to divide the country into regions in which these conditions are generally similar. Because the presence and availability of ground water depend primarily on geologic conditions, ground-water regions also are areas in which the composition, arrangement, and structure of rock units are similar (Heath, 1982).

Several divisions of the country into ground-water regions have been proposed, starting with Fuller's subdivision of the eastern part of the country in 1905. The two most successful and most useful subdivisions are those proposed by Meinzer in 1923 and by Thomas in 1952. Meinzer divided the country into 21 ground-water provinces, primarily on the basis of the rock units that serve as the principal sources of ground water. These provinces are shown in figure 10. Thomas reduced Meinzer's 21 provinces to 10 regions by combining provinces where differences in ground-water conditions are minor (fig. 11). This resulted in a very useful regional classification which has been used many times since 1952 in national summaries of ground-water conditions.

To divide the country into ground-water regions, it is necessary to develop a classification that identifies features of ground-water systems that affect the occurrence and availability of ground water. The five features pertinent to such a classification are (1) the components of the system and their arrangement, (2) the nature of the water-bearing openings of the dominent aquifer or aquifers with respect to whether they are of primary or secondary origin, (3) the mineral composition of the rock matrix of the dominant aquifers with respect to whether

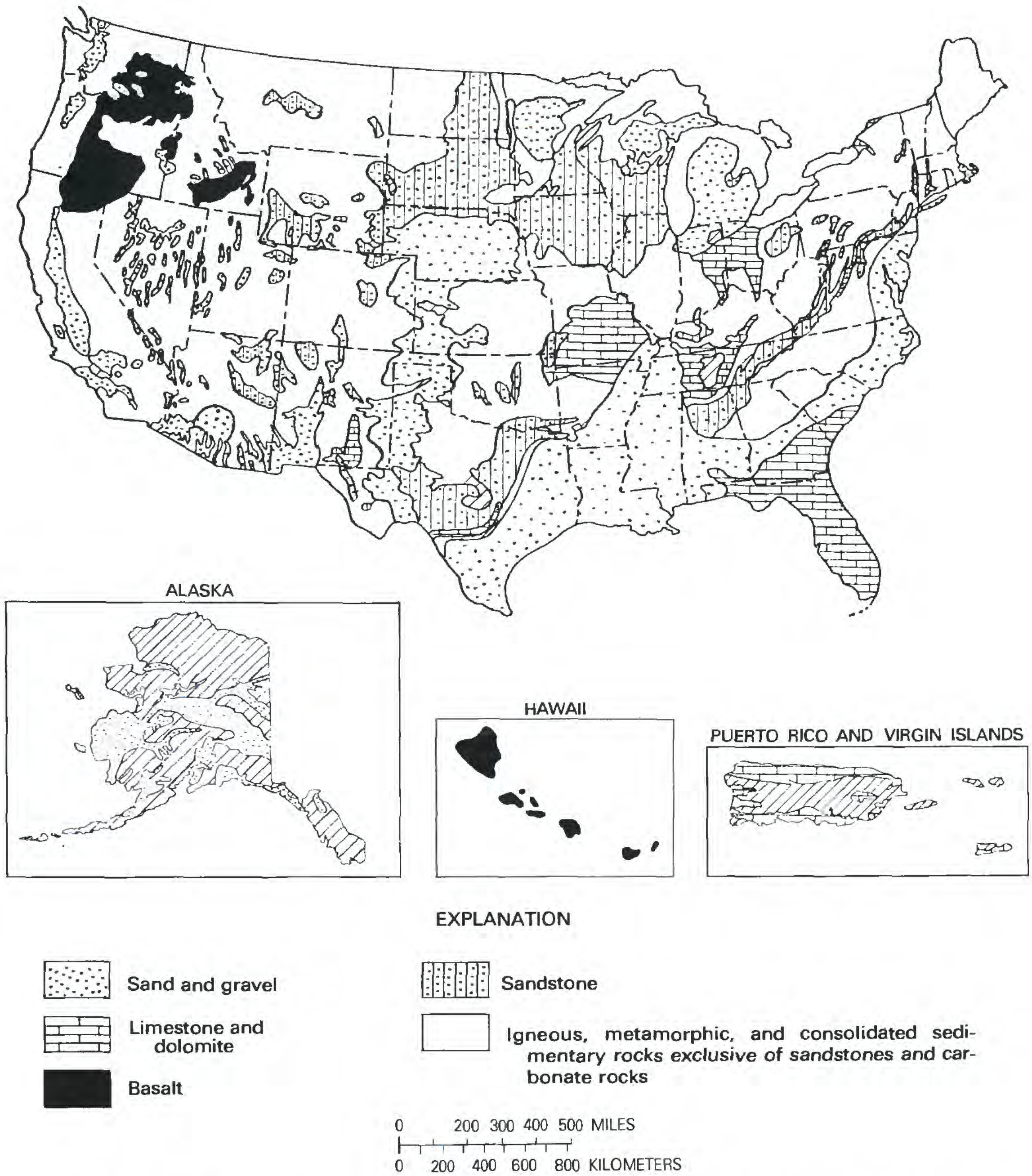


Figure 9. General occurrence of the principal types of water-bearing rocks in the United States.

it is soluble or insoluble, (4) the water storage and transmission characteristics of the dominant aquifer or aquifers, and (5) the nature and location of recharge and discharge areas.

The first two of these features are primary criteria used in all delineations of ground-water regions. The remaining three are secondary criteria that are useful in subdividing what might otherwise be large and unwieldy regions into areas that are more homogenous and, therefore, more convenient for descriptive purposes. Each of the five features is listed in table 4, together with explanatory information. The fact that most of the features are more or less interrelated is readily apparent from the comments in the column headed "Significance of Feature."

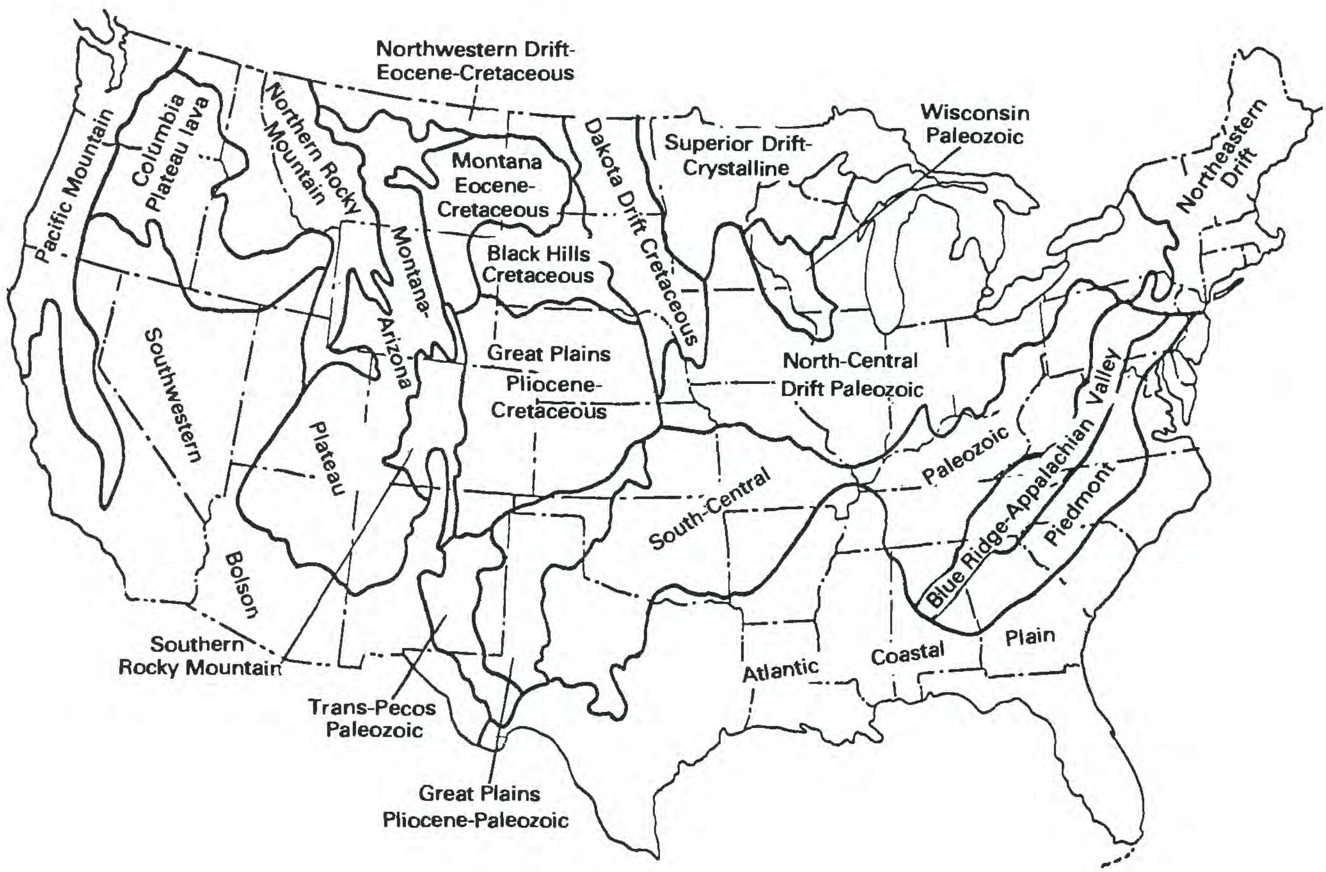


Figure 10. Ground-water provinces of Meinzer. (From Meinzer, 1923, pl. 31.)

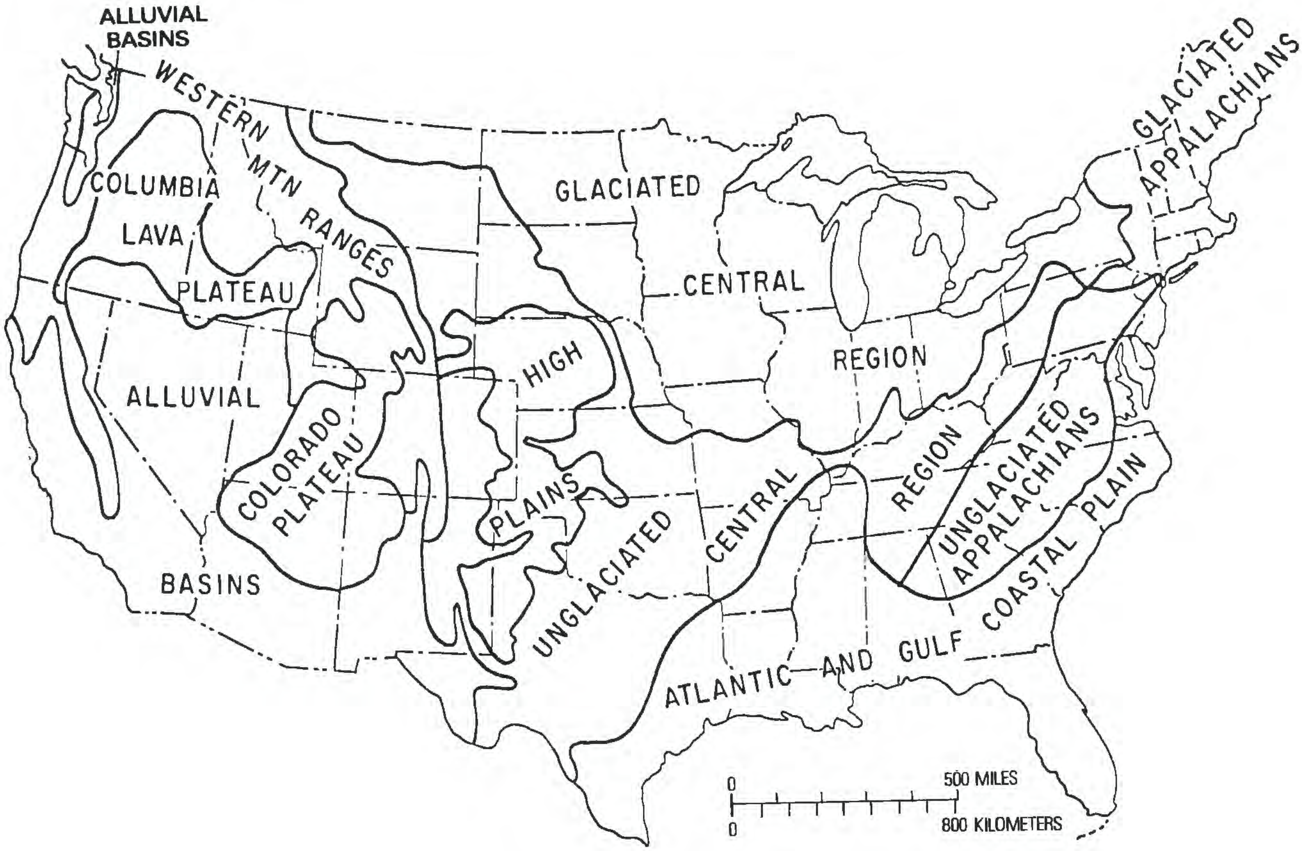


Figure 11. Ground-water regions of Thomas. (From Thomas, 1952, fig 1.)

Table 4. Features of ground-water systems useful in the delineation of ground-water regions

Feature	Aspect	Range in conditions	Significance of feature
Component of the system	Unconfined aquifer	Thin, discontinuous, hydrologically insignificant. Minor aquifer, serves primarily as a storage reservoir and recharge conduit for underlying aquifer. The dominant aquifer.	Affect response of the system to pumpage and other stresses. Affect recharge and discharge conditions. Determine susceptibility to pollution.
	Confining beds	Not present, or hydrologically insignificant. Thin, markedly discontinuous, or very leaky. Thick, extensive, and impermeable. Complexly interbedded with aquifers or productive zones.	
	Confined aquifers	Not present, or hydrologically insignificant. Thin or not highly productive. Multiple thin aquifers interbedded with nonproductive zones. The dominant aquifer—thick and productive.	
	Presence and arrangement of components	A single, unconfined aquifer. Two interconnected aquifers of essentially equal hydrologic importance. A three-unit system consisting of an unconfined aquifer, a confining bed, and confined aquifer. A complexly interbedded sequence of aquifers and confining beds.	
Water-bearing openings of dominant aquifer	Primary openings	Pores in unconsolidated deposits. Pores in semiconsolidated rocks. Pores, tubes, and cooling fractures in volcanic (extrusive-igneous) rocks.	Control water-storage and transmission characteristics. Affect dispersion and dilution of wastes.
	Secondary openings	Fractures and faults in crystalline and consolidated sedimentary rocks. Solution-enlarged openings in limestones and other soluble rocks.	
Composition of rock matrix of of dominant aquifer	Insoluble	Essentially insoluble. Both relatively insoluble and soluble constituents.	Affects water-storage and transmission characteristics. Has major influence on water quality.
	Soluble	Relatively soluble.	
Storage and transmission characteristics of dominant aquifer	Porosity	Large, as in well-sorted, unconsolidated deposits. Moderate, as in poorly-sorted unconsolidated deposits and semiconsolidated rocks. Small, as in fractured crystalline and consolidated sedimentary rocks.	Control response to pumpage and other stresses. Determine yield of wells. Affect long-term yield of system. Affect rate at which pollutants move.
	Transmissivity	Large, as in cavernous limestones, some lava flows, and clean gravels. Moderate, as in well-sorted, coarse-grained sands, and semiconsolidated limestones. Small, as in poorly-sorted, fine-grained deposits and most fractured rocks. Very small, as in confining beds.	

Table 4. Features of ground-water systems useful in the delineation of ground-water regions—Continued.

Feature	Aspect	Range in conditions	Significance of feature
Recharge and discharge conditions of dominant aquifer	Recharge	In upland areas between streams, particularly in humid regions. Through channels of losing streams. Largely or entirely by leakage across confining beds from adjacent aquifers.	Affect response to stress and long-term yields. Determine susceptibility to pollution. Affect water quality.
	Discharge	Through springs or by seepage to stream channels, estuaries, or the ocean. By evaporation on flood plains and in basin "sinks." By seepage across confining beds into adjacent aquifers.	

GROUND-WATER REGIONS OF THE UNITED STATES

On the basis of the criteria listed in the preceding section, the United States, Puerto Rico, and the Virgin Islands are divided into 15 ground-water regions. Table 5 contains a list of the regions and a checklist of the criteria that are believed to apply to each region. Because of the wide range in conditions within most of the regions, it is possible in a checklist such as that in table 5 to indicate only the most prevalent conditions. The boundaries of all regions, except region 12, are shown in figure 12. Region 12, which consists of those segments of the valleys of perennial streams that are underlain by sand and gravel thick enough to be hydrologically significant (thicknesses generally more than about 8 meters), is shown in figure 13.

The nature and extent of the dominant aquifers and their relations to other units of the ground-water system are the primary criteria used in delineating the regions. Consequently, the boundaries of the regions generally coincide with major geologic boundaries and at most places do not coincide with drainage divides. Although this lack of coincidence emphasizes that the physical characteristics of ground-water systems and stream systems are controlled by different factors, it does not mean that the two systems are not related. Ground-water systems and stream systems are intimately related, as shown in the following discussions of each of the ground-water regions.

Ranges of values for selected hydrologic characteristics of each region are listed in table 6. The range of values within regions indicates the wide range in conditions from one part of a region to another. The differences in values from one region to another indicate the wide range in ground-water conditions from one part of the country to another.

Table 5. Summary of the principal physical and hydrologic characteristics of the ground-water regions of the United States.

Region No.	Name	Components of the system														Characteristics of the dominant aquifers																				
																Water-bearing openings					Composition			Storage and transmission properties							Recharge and discharge conditions					
		Unconfined aquifer			Confining beds			Confined aquifers				Presence and arrangement				Primary			Secondary		Degree of solubility			Porosity			Transmissivity				Recharge			Discharge		
		Hydrologically insignificant	Minor aquifer or not very productive	Dominant aquifer	Hydrologically insignificant	Thin, discontinuous, or v. leaky	Interlayered with aquifers	Hydrologically insignificant	Not highly productive	Multiple productive aquifers	The dominant productive aquifer	Single unconfined aquifer	Two interconnected aquifers	Unconfined aquifer, confining bed, confined aquifer	complex interbedded sequence	Pores in unconsolidated dep.	Pores in semiconsolidated rocks	Tubes and cooling cracks in lava	Fractures and faults	Solution-enlarged openings	Insoluble	Mixed soluble and insoluble	Soluble	Large (>0.2)	Moderate (0.01–0.2)	Small (<0.01)	Large (>2,500 m^2day^{-1})	Moderate (250–2,500 m^2day^{-1})	Small (25–250 m^2day^{-1})	Very small (<25 m^2day^{-1})	Uplands between streams	Losing streams	Leakage through confining beds	Springs and surface seepage	Evaporation and basin sinks	Into other aquifers
1	Western Mountain Ranges		X		X				X				X			X			X		X				X				X		X	X		X		
2	Alluvial Basins			X			X			X					X	X					X			X			X					X			X	X
3	Columbia Lava Plateau		X				X			X					X	X		X	X		X					X	X					X		X		
4	Colorado Plateau and Wyoming Basin	X					X			X					X		X		X		X					X			X		X		X	X		
5	High Plains			X	X			X				X				X					X			X			X					X		X		
6	Nonglaciated Central Region		X				X			X					X		X		X	X		X				X		X			X		X	X		X
7	Glaciated Central Region		X				X			X					X	X	X		X	X		X			X			X					X			X
8	Piedmont and Blue Ridge		X		X				X				X			X			X		X					X				X	X			X		
9	Northeast and Superior Uplands		X			X			X				X			X			X		X					X			X		X			X		
10	Atlantic and Gulf Coastal Plain		X				X			X					X	X				X		X			X			X			X		X	X		X
11	Southeast Coastal Plain		X				X				X			X		X				X			X	X			X				X		X	X		
12	Alluvial Valleys			X		X		X				X				X					X			X			X				X			X		
13	Hawaii			X		X		X				X						X			X			X			X				X	X		X		
14	Alaska			X		X			X						X	X			X			X			X			X				X		X		
15	Puerto Rico and Virgin Islands			X		X				X					X	X				X			X		X			X			X		X	X		X

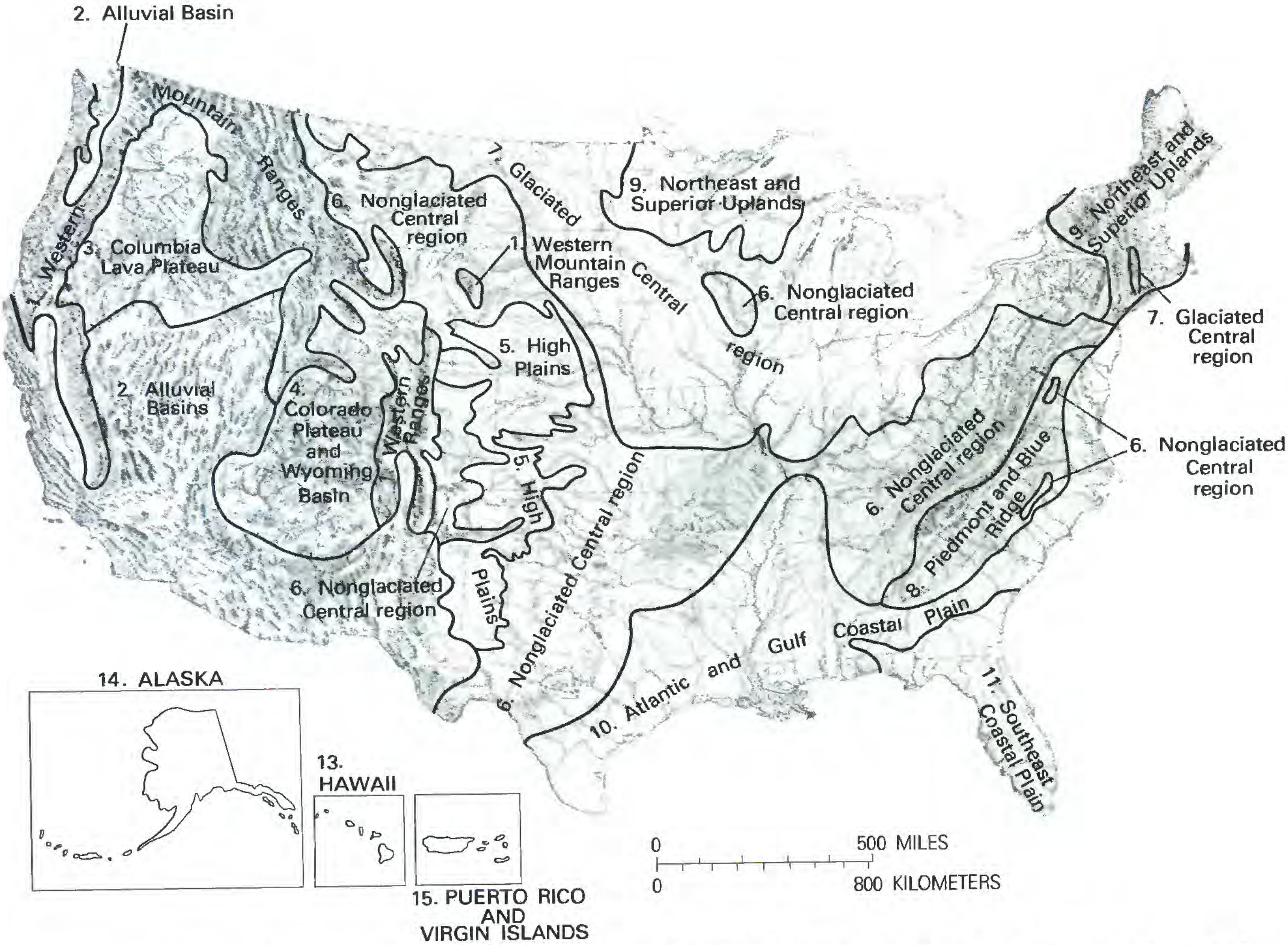


Figure 12. Ground-water regions used in this report. [The Alluvial Valleys region (region 12) is shown on figure 13.]

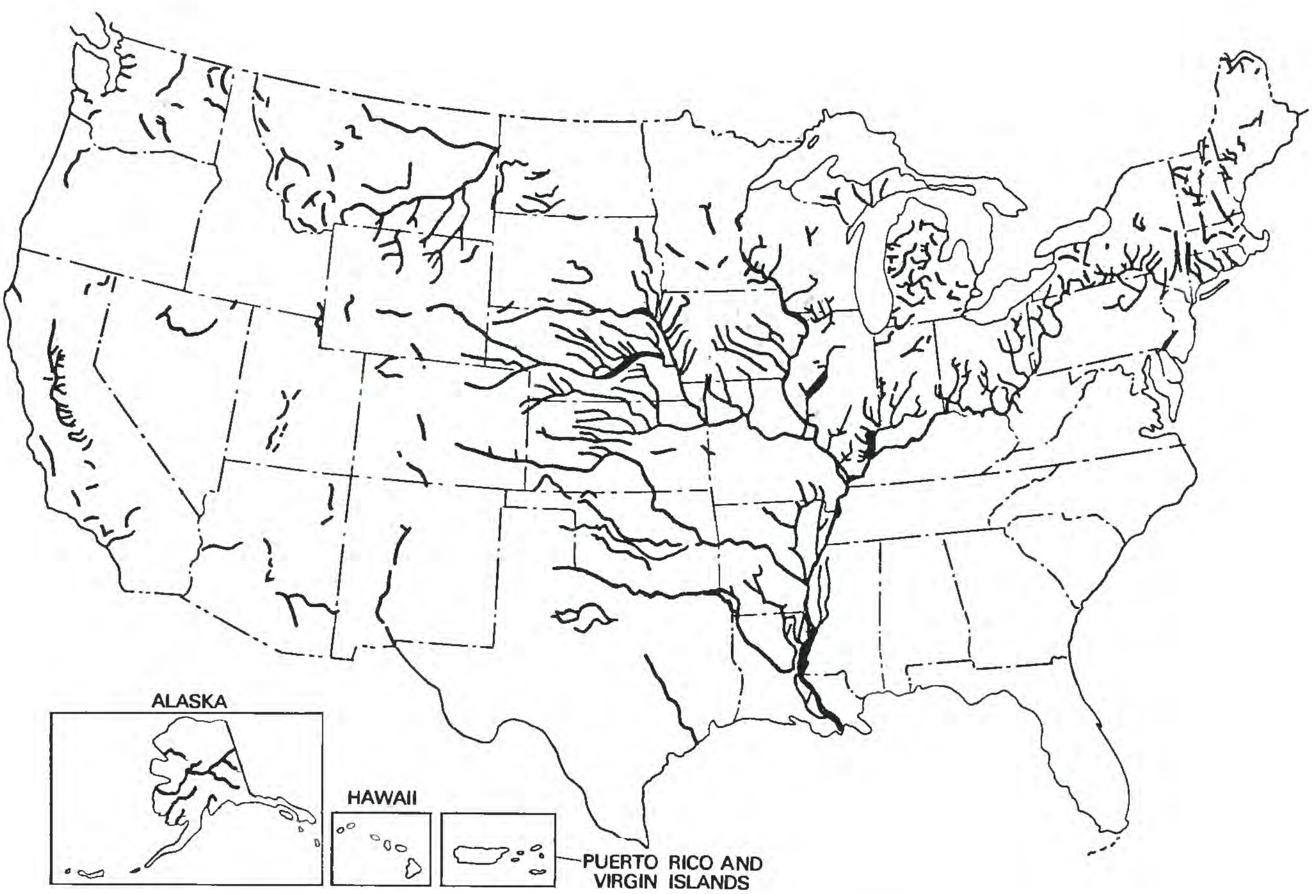


Figure 13. Alluvial Valleys ground-water region.

Table 6. Common ranges on the hydraulic characteristics of ground-water regions of the United States.
[All values rounded to one significant figure]

Region No.	Region	Geologic situation	Transmissivity $m^2 day^{-1}$	Transmissivity $ft^2 day^{-1}$	Hydraulic conductivity $m\ day^{-1}$	Hydraulic conductivity $ft\ day^{-1}$	Recharge rate $mm\ yr^{-1}$	Recharge rate $in.\ yr^{-1}$	Well yield $m^3 min^{-1}$	Well yield $gal\ min^{-1}$
1	Western Mountain Ranges	Mountains with thin soils over fractured rocks, alternating with narrow alluvial and, in part, glaciated valleys	-100	5-5,000,000	0.0003- 15	0.001- 50	3 - 50	0.1 - 2	0.04- 0.4	10- 100
2	Alluvial Basins	Thick[1] alluvial (locally glacial) deposits in basins and valleys bordered by mountains	20 - 20,000	2,000- 200,000	30 - 600	100 - 2,000	0.03- 30	0.001- 1	0.4 -20	100- 5,000
3	Columbia Lava Plateau	Thick sequence of lava flows interbedded with unconsolidated deposits and overlain by thin soils	2,000 -500,000	20,000-5,000,000	200 -3,000	500 -10,000	5 - 300	0.2 -10	0.4 -80	100-20,000
4	Colorado Plateau and Wyoming Basin	Thin[1] soils over fractured sedimentary rocks	0.5- 100	5- 1,000	0.003 - 2	0.01 - 5	0.3 - 50	0.01 - 2	0.04- 2	10- 1,000
5	High Plains	Thick alluvial deposits over fractured sedimentary rocks	1,000 - 10,000	10,000- 100,000	30 - 300	100 - 1,000	5 - 80	0.2 - 3	0.4 -10	100- 3,000
6	Nonglaciated Central region	Thin regolith over fractured sedimentary rocks	300 - 10,000	3,000- 100,000	3 - 300	10 - 1,000	5 - 500	0.2 -20	0.4 -20	100- 5,000
7	Glaciated Central region	Thick glacial deposits over fractured sedimentary rocks	100 - 2,000	1,000- 20,000	2 - 300	5 - 1,000	5 - 300	0.2 -10	0.2 - 2	50- 500
8	Piedmont and Blue Ridge	Thick regolith over fractured crystalline and metamorphosed sedimentary rocks	9 - 200	100- 2,000	0.001 - 1	0.003- 3	30 - 300	1 -10	0.2 - 2	50- 500
9	Northeast and Superior Uplands	Thick glacial deposits over fractured crystalline rocks	50 - 500	500- 5,000	2 - 30	5 - 100	30 - 300	1 -10	0.1 - 1	20- 200
10	Atlantic and Gulf Coastal Plain	Complexly interbedded sands, silts, and clays	500 - 10,000	5,000- 100,000	3 - 100	10 - 400	50 - 500	2 -20	0.4 -20	100- 5,000
11	Southeast Coastal Plain	Thick layers of sand and clay over semiconsolidated carbonate rocks	1,000 -100,000	10,000-1,000,000	30 -3,000	100 -10,000	30 - 500	1 -20	4 -80	1,000-20,000
12	Alluvial Valleys	Thick sand and gravel deposits beneath flood plains and terraces of streams	200 - 50,000	2,000- 500,000	30 -2,000	100 - 5,000	50 - 500	2 -20	0.4 -20	100- 5,000
13	Hawaiian Islands	Lava flows segmented by dikes, interbedded with ash deposits, and partly overlain by alluvium	10,000 -100,000	100,000-1,000,000	200 -3,000	500 -10,000	30 -1,000	1 -40	0.4 -20	100- 5,000
14	Alaska	Glacial and alluvial deposits in part perennially frozen and overlying crystalline, metamorphic, and sedimentary rocks	100 - 10,000	1,000- 100,000	30 - 600	100 - 2,000	3 - 300	0.1 -10	0.04- 4	10- 1,000
15	Puerto Rico and Virgin Islands	Alluvium and limestones overlying and bordering fractured igneous rocks	100 - 10,000	1,000- 100,000	3 - 300	10 - 1,000	3 - 300	0.1 -10	0.04-10	10- 3,000

[1]An average thickness of about 5 was used as the break point between thick and thin.

1. WESTERN MOUNTAIN RANGES

(Mountains with thin soils over fractured rocks, alternating with narrow alluvial and, in part, glaciated valleys)

The Western Mountain Ranges encompass three areas totaling 708,000 km^2. The largest area extends in an arc from the Sierra Nevada in California, north through the Coast Ranges and Cascade Mountains in Oregon and Washington, and east and south through the Rocky Mountains in Idaho and Montana into the Bighorn Mountains in Wyoming and the Wasatch and Uinta Mountains in Utah (fig. 14). The second area includes the southern Rocky Mountains, which extend from the Laramie Range in southeastern Wyoming through central Colorado into the Sangre de Cristo Range in northern New Mexico. The smallest area includes the part of the Black Hills in South Dakota in which Precambrian rocks are exposed. Summits in the Rocky Mountains and Sierra Nevada exceed 3,500 m. The general appearance of the Western Mountain Ranges, with the exception of the Black Hills, is tall, massive mountains alternating with relatively narrow, steep-sided valleys. The summits and sides of the mountains in much of the region have been carved into distinctive shapes by mountain glaciers. The ranges that comprise the southern Rocky Mountains are separated by major lowlands that include North Park, Middle Park, South Park, and the Wet Mountain Valley. These lowlands occupy downfolded or downfaulted structural troughs (fig. 15) as much as 70 km wide and 160 km long. The mountains in the Black Hills are lower in altitude than most of the mountains in other parts of the region.

As would be expected in such a large region, both the origin of the mountains and the rocks that form them are complex. Most of the mountain ranges are underlain by granitic and metamorphic rocks flanked by consolidated sedimentary rocks of Paleozoic to Cenozoic age. The other ranges, including the San Juan Mountains in southwestern Colorado and the Cascade Mountains in Washington and Oregon, are underlain by lavas and other igneous rocks.

The summits and slopes of most of the mountains consist of bedrock exposures or of bedrock covered by a layer of boulders and other rock fragments produced by frost action and other weathering processes acting on the bedrock. This layer is generally only a few meters thick on the upper slopes but forms a relatively thick apron along the base of the mountains. The narrow valleys are underlain by relatively thin, coarse, bouldery alluvium washed from the higher slopes. The large synclinal valleys and those that occupy downfaulted structural troughs are underlain by moderately thick deposits of coarse-grained alluvium transported by streams from the adjacent mountains (fig. 15).

The Western Mountain Ranges and the mountain ranges in adjacent regions are the principal sources of water supplies developed at lower altitudes in the western half of the conterminous United States. As McGuinness (1963) noted, the mountains of the West are moist "islands" in a sea of desert or semidesert that covers the western half of the Nation. The mountains force moisture-laden air masses moving eastward from the Pacific to rise to higher and cooler altitudes. As the air cools, moisture condenses into clouds and precipitates. The heaviest precipitation falls on the western slopes; thus, these slopes are the major source of runoff and are also the most densely vegetated (fig. 16). Much of the precipitation falls as snow during the winter, and its slow melting, starting at the lower altitudes in early spring, maintains streamflow at large rates until late June or early July. Small glaciers occur in the higher mountain ranges, especially in the northern Rocky Mountains, the Cascades, and the Sierra Nevada; locally, as in northern Washington, they also provide significant sources of summer runoff.

The Western Mountain Ranges are sparsely populated and have relatively small water needs. The region is an exporter of water to adjacent "have-not" areas. Figure 16 shows graphically the importance of the Western Mountain Ranges in the "water economy" of the West. Numerous surface reservoirs have been constructed in the region, both to regulate peak flows into the adjacent, dryer areas and to store water for diversion through pipelines and canals to urban areas and to irrigation projects. Many such impoundments have been developed on streams that drain the western flank of the Sierra Nevada in California and the Rocky Mountains in Colorado.

Melting snow and rainfall at the higher altitudes in the region provide abundant water for ground-water recharge. However, the thin soils and bedrock fractures in areas underlain by crystalline rocks fill quickly, and the remaining water runs off overland to streams. Because of their small storage capacity, the underground openings provide limited base runoff to the streams, which at the

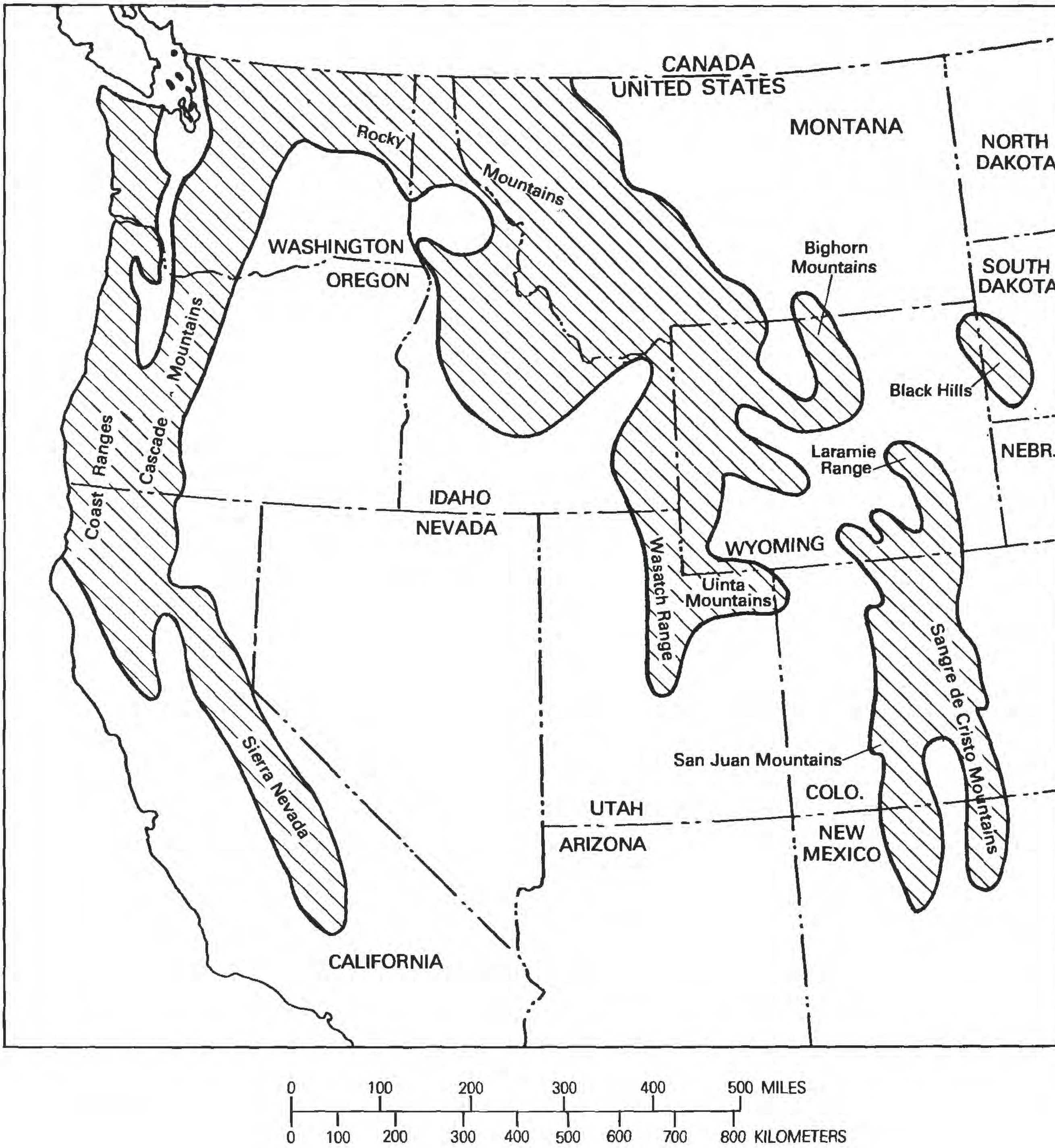


Figure 14. Western Mountain Ranges region.

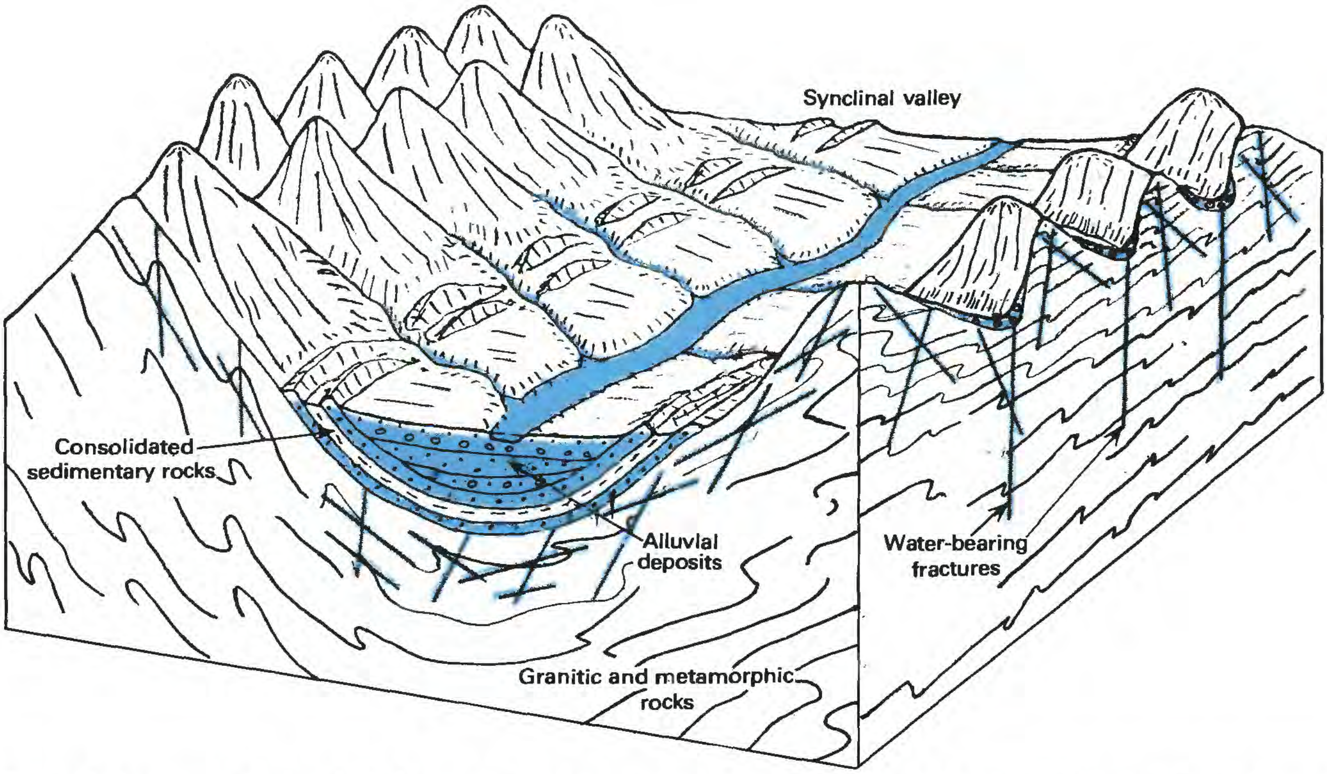


Figure 15. Topographic and geologic features in the southern Rocky Mountains part of the Western Mountain Ranges region.

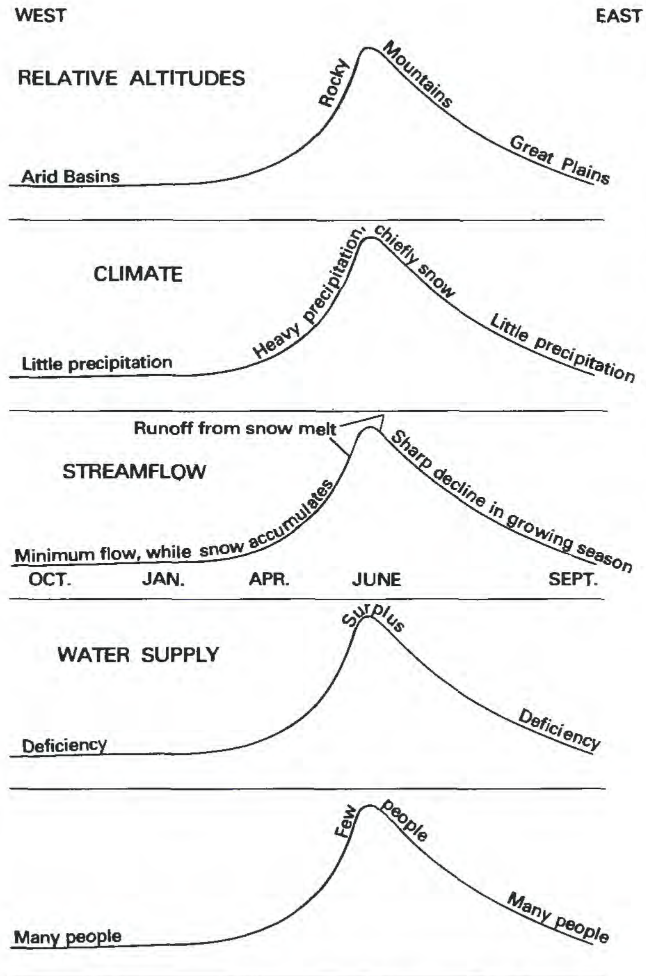


Figure 16. Relation of altitude, climate, streamflow, water supply, and population of the Western Mountain Ranges. (Adopted from Thomas, 1952.)

higher altitudes flow only during rains or snowmelt periods. Thus, at the higher altitudes in this region underlain by crystalline rocks, relatively little opportunity exists for development of ground-water supplies. The best opportunities exist in valleys that contain at least moderate thicknesses of saturated alluvium or in areas underlain by permeable sedimentary or volcanic rocks. Ground-water supplies in the valleys are obtained both from wells drawing from the alluvium and from wells drawing from the underlying rocks. The yields of wells in crystalline bedrock and wells drawing water from small, thin deposits of alluvium are generally adequate only for domestic and stock needs. Large yields can be obtained from the alluvial deposits that overlie the major lowlands and from wells completed in permeable sedimentary or volcanic rocks.

2. ALLUVIAL BASINS

(Thick alluvial deposits in basins and valleys bordered by mountains and locally of glacial origin)

The Alluvial Basins region occupies a discontinuous area of 1,025,000 km² extending from the Puget Sound-Williamette Valley area of Washington and Oregon to west Texas. The region consists of an irregular alternation of basins or valleys[1] and mountain ranges. From the standpoint of topography, it is useful to contrast this region with the Western Mountain Ranges. In the Western Mountain Ranges the high areas, the mountains, are the dominant feature. In the Alluvial Basins region the low areas, the basins and valleys, are the

[1]A basin as used in this discussion is a low area surrounded by a topographic divide and which, therefore, has no surface outlet for drainage. A valley is a low area having surface drainage to adjacent areas. Although both basins and valleys occur in ths region, the word "basin" is used to refer collectively to all the areas underlain by alluvial deposits when the distinction is not important.

dominant feature. The principal exception to this generalization is the Coast Ranges of southern California which, though included in this region, topographically more closely resemble the Western Mountain Ranges.

Most of the Nevada and all of the Utah parts of this region are an area of internal drainage referred to as the Great Basin. No surface or subsurface flow leaves this part of the region, and all water reaching it from adjacent areas and from precipitation is returned to the atmosphere by evaporation or by the transpiration of plants.

The basins and valleys are diverse in size, shape, and altitude. They range in altitude from about 85 m below sea level in Death Valley in California to 2,000 m above sea level in the San Luis Valley in Colorado. The basins range in size from a few hundred meters in width and a kilometer or two in length to, for the Central Valley of California, as much as 80 km in width and 650 km in length. The crests of the mountains are commonly 1,000 to 1,500 m above the adjacent valley floors.

The surrounding mountains, and the bedrock beneath the basins, consist of granite and metamorphic rocks of Precambrian to Tertiary age and consolidated sedimentary rocks of Paleozoic to Cenozoic age. The rocks are broken along fractures and faults that may serve as water-bearing openings. However, the openings in the granitic and metamorphic rocks in the mountainous areas have a relatively small capacity to store and to transmit ground water.

The dominant element in the hydrology of the region is the thick (several hundred to several thousand meters) layer of generally unconsolidated alluvial material that partially fills the basins (fig. 17, 18, and 19). Except for the part of the region in Washington and Oregon, the material was derived from erosion of the adjacent mountains and was transported down steep-gradient streams into the basins, where it was deposited as alluvial fans. Generally, the coarsest material in an alluvial fan occurs at its apex, adjacent to the mountains; the material gets progressively finer toward the centers of the basins. However, in most fans there are layers of sand and gravel that extend into the central parts of the basins (fig. 18). In time, the fans formed by adjacent streams coalesced to form a continuous and thick deposit of alluvium that slopes gently from the mountains toward the center of the basins. These alluvial-fan deposits are overlain by or grade into fine-grained flood plain, lake, or playa deposits in the central part of most basins. The fine-grained deposits are especially suited to large-scale cultivation.

The Puget Sound and Willamette Valley areas differ geologically from the remainder of the region. The Puget Sound area is underlain by thick and very permeable deposits of gravel and sand laid down by streams of glacial meltwater derived from ice tongues that invaded the area from the north during the Pleistocene. The gravel and sand are interbedded with clay in parts of the area. The Willamette Valley is mostly underlain by interbedded sand, silt, and clay deposited on floodplains by the Williamette River and other streams.

The Alluvial Basins region is the driest area in the United States, with large parts of it being classified as semiarid and arid. Annual precipitation in the valleys in Nevada and Arizona ranges from about 100 to 400 mm. However, in the mountainous areas throughout the

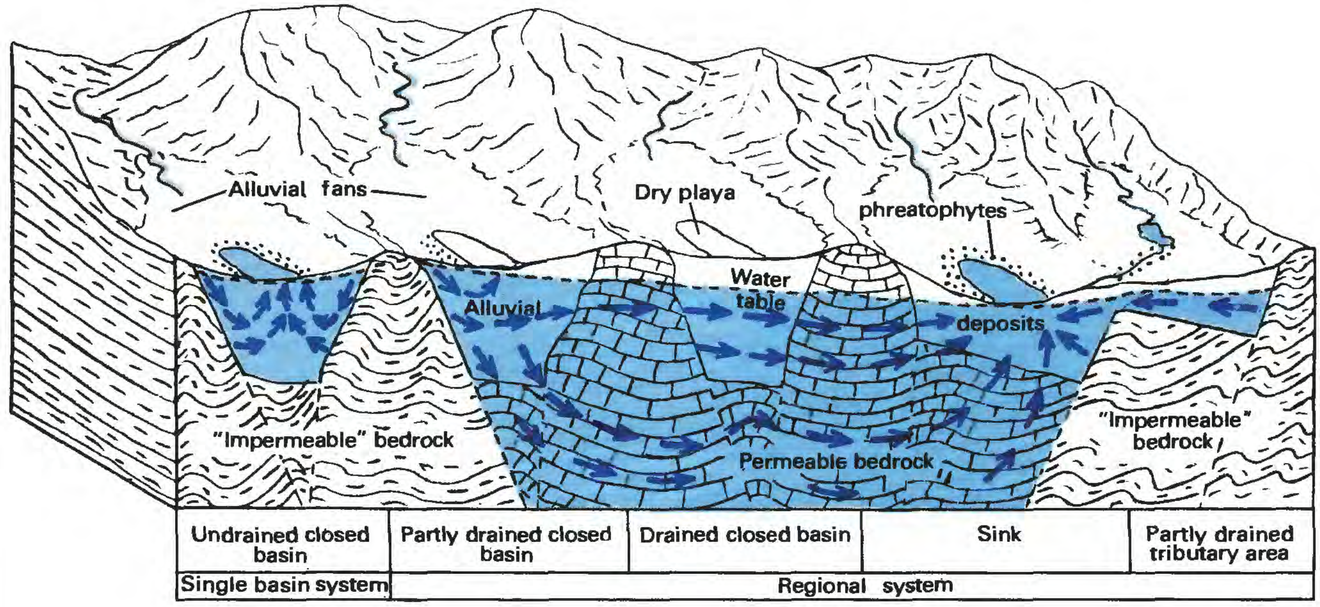


Figure 17. Common ground-water flow systems in the Alluvial Basins region. (From U.S. Geological Survey Professional Paper 813–G.)

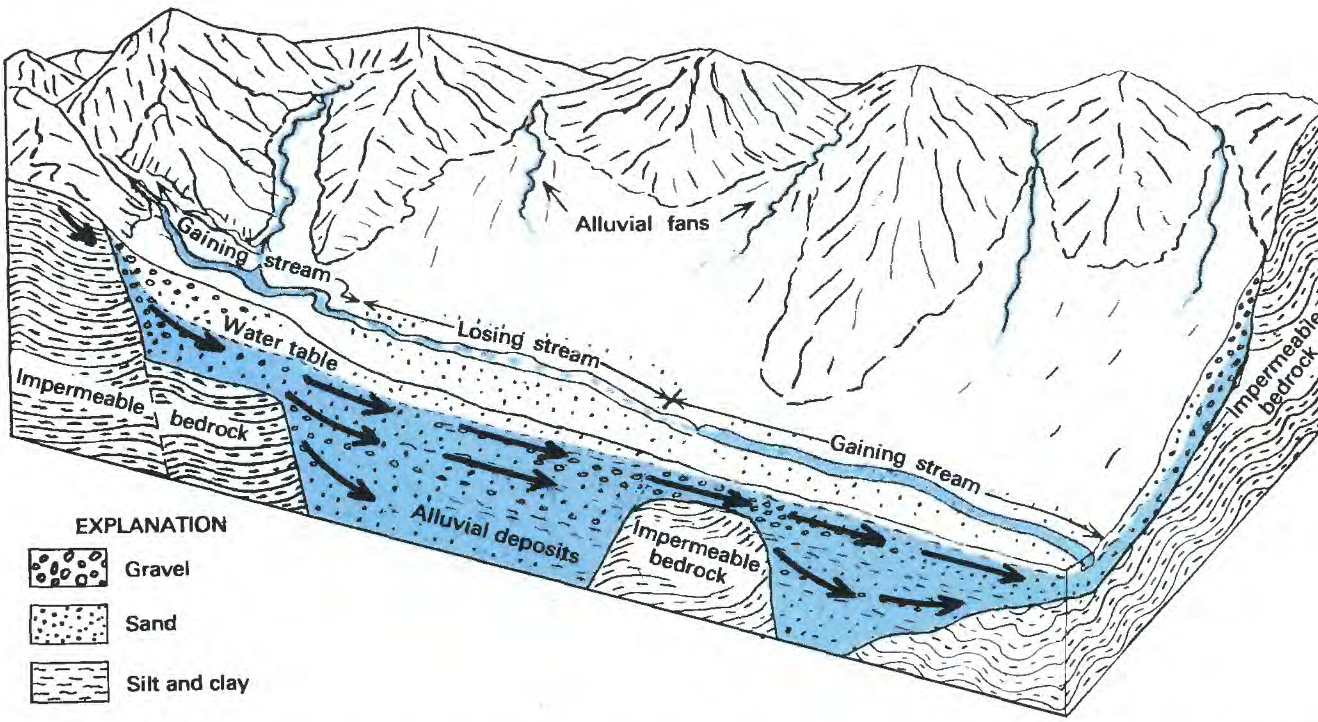


Figure 18. Common relationships between ground water and surface water in the Alluvial Basins region. (Modified from U.S. Geological Survey Professional Paper 813-C.)

region, in the northern part of the Central Valley of California, and in the Washington-Oregon area, annual precipitation ranges from about 400 mm to more than 800 mm. The region also receives runoff from streams that originate in the mountains of the Western Mountain Ranges region.

Because of the very thin cover of unconsolidated material on the mountains in the Alluvial Basins region, precipitation runs off rapidly down the valleys and out onto the fans, where it infiltrates into the alluvium. The water moves through the sand and gravel layers toward the centers of the basins. The centers of many basins consist of flat-floored, vegetation-free areas onto which ground water may discharge and on which overland runoff may collect during intense storms. The water that collects in these areas, which are called *playas,* evaporates relatively quickly, leaving both a thin deposit of clay and other sediment transported by overland runoff and a crust consisting of the soluble salts that were dissolved in the water (fig. 17).

Studies in the region have shown that the hydrology of the alluvial basins is more complex than that described in the preceding paragraph, which applies only to what has been described as "undrained closed basins." As shown in figure 17, water may move through permeable bedrock from one basin to another, arriving, ultimately, at a large playa referred to as a "sink." Water discharges from sinks not by "sinking" into the ground, as the name might imply, but by evaporating, as in other playas. In those parts of the Alluvial Basin region drained by perennial streams, including the Puget Sound–Willamette Valley area, the Central Valley of California, and some of the valleys in Arizona and New Mexico, ground water discharges to the streams from the alluvial deposits. However, before entering the streams, water may move down some valleys through the alluvial deposits for tens of kilometers. A reversal of this situation occurs along the lower Colorado River and at the upstream end of the valleys of some of the other perennial streams; in these areas, water moves from the streams into the alluvium to supply the needs of the adjacent vegetated zones.

Ground water is the major source of water in the Alluvial Basins region. Many of the valleys in this region have been developed for agriculture. Because of the dry climate, agriculture requires intensive irrigation. In the part of this region drained by the Colorado River, ground water used for irrigation in 1975 amounted to about 6 billion cubic meters (4,864,000 acre-feet). Most of the ground water is obtained from wells drawing from the sand and gravel deposits in the valley alluvium. These deposits are interbedded with finer grained layers of silt and clay that are also saturated with water. When hydraulic heads in the sand and gravel layers are lowered by withdrawals, the water in the silt and clay begins to move slowly into the sand and gravel. The movement, which in some areas takes decades to become significant, is accompanied by compaction of the silt and clay and subsidence of the land surface (fig. 20). Subsidence is most severe in parts of the Central Valley, where it exceeds 9 m in one area, and in southern Arizona, where

Figure 19. Areas underlain by sand and gravel in the Alluvial Basins region.

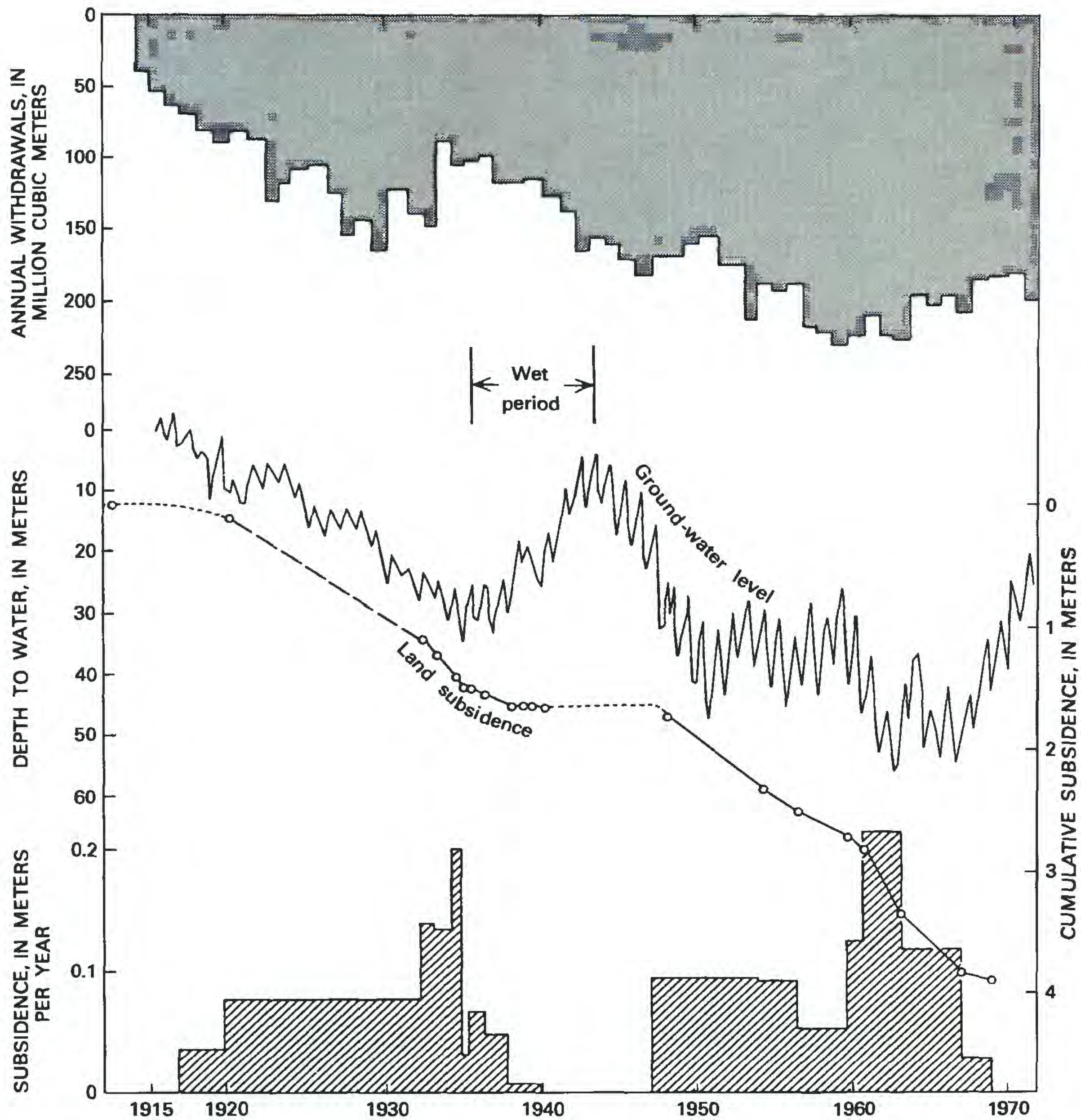


Figure 20. Pumpage in Santa Clara Valley, California, and correlative water-level changes and land subsidence. Ground-water level is in well 7S/1E-7R1. Land subsidence is at benchmark P7.

subsidence of more than 4 m has been observed.

Subsidence of the land surface caused by drainage of fine-grained beds represents a reduction in ground water that cannot be replaced, even if withdrawals are stopped and hydraulic heads return to their initial static levels. Such subsidence, therefore, represents mining of ground water to the extent that ground-water storage is being permanently depleted. Reduction in ground-water withdrawals, which has been made possible in several areas of subsidence in California through the importation of water, has resulted in a reduction in the rate of subsidence. Similar reductions in withdrawals have not yet occurred in Arizona, where ground-water levels continue to decline at a rate of 1 to 3 m per year in developed areas.

In both the Alluvial Basins and the Colorado Plateau regions, large volumes of water are transpired by *phreatophytes* (water-loving plants) of small economic value that live along streams and in other wet areas. In an effort to increase the amount of water available for irrigation and other uses, numerous studies have been made to determine the volumes of water used by phreatophytes and to devise means to control them. A few small control efforts have been made, but none have proven economically effective.

3. COLUMBIA LAVA PLATEAU

(Thick sequence of lava flows irregularly interbedded with thin unconsolidated deposits and overlain by thin soils)

The Columbia Lava Plateau occupies an area of 366,000 km^2 in northeastern California, eastern Washington and Oregon, southern Idaho, and northern Nevada. As its name implies, it is basically a plateau standing at an altitude generally between 500 and 1,800 m above sea level that is underlain by a great thickness of lava flows irregularly interbedded with silt, sand, and other unconsolidated deposits. The plateau is bordered on the west by the Cascade Range, on the north by the Okanogan Highlands, and on the east by the Rocky Mountains (fig. 21). On the south it grades into the Alluvial Basins region, as the area occupied by lava flows decreases and the typical "basin and range" topography of the Alluvial Basins region gradually prevails. Most of the plateau in Idaho is exceptionally flat over large areas, the principal relief being low cinder (volcanic) cones and lava domes. This area and much of the area in California, southeastern Oregon, and Nevada is underlain by much of the youngest lava, some of which is less than 1,000 years old. In Washington the flows are older, some dating back to the Miocene Epoch. Altitudes in a few of the mountainous areas in the plateau region exceed 3,000 m.

The great sequence of lava flows, which ranges in thickness from less than 50 m adjacent to the bordering mountain ranges to more than 1,000 m in south-central Washington and southern Idaho, is the principal water-bearing unit in the region (fig. 22). The water-bearing lava is underlain by granite, metamorphic rocks, older lava flows, and sedimentary rocks, none of which are very permeable. Individual lava flows in the water-bearing zone range in thickness from several meters to more than 50 m and average about 15 m. Most of the lava is basalt which reached the surface both through extensive fissures and through local eruption centers. Because basaltic lava is very fluid when molten, it flows considerable distances down surface depressions and over gently sloping surfaces and forms, when it solidifies, a relatively flat surface. Some flows are sheetlike and can be followed visually for several kilometers along the walls of steep canyons. Other flows, where the lava issuing from eruption centers followed surface depressions, are lobate, or tonguelike.

The volcanic rocks yield water mainly from permeable zones that occur at or near the contacts between some flow layers. The origin of these flow-contact or interflow zones is complex but involves, among other causes, the relatively rapid cooling of the top of flows, which results in formation of a crust. As the molten lava beneath continues to flow, the crust may be broken into a rubble of angular fragments which in places contain numerous holes where gas bubbles formed and which give the rock the appearance of a frozen froth. The slower cooling of the central and lower parts of the thicker flows results in a dense, flint-like rock which in the lower part contains relatively widely spaced, irregular fractures and which grade upward into a zone containing relatively closely spaced vertical fractures that break the rock into a series of hexagonal columns (fig. 2*D*) (Newcomb, 1961).

Periods of time ranging from less than 100 years to thousands of years elapsed between extrusion of successive lava flows. As a result, parts of some flows are separated by soil zones and, at places, by sand, silt, and clay deposited by streams or in lakes that existed on the land surface before being buried by subsequent lava extrusions. These sedimentary layers, where they occur between lava flows, are commonly referred to as "interflow sediments." Gravel, sand, silt, and clay, partly formed by the present streams and partly of glacial origin, cover the volcanic rocks and the older exposed bedrock in parts of the area.

From the standpoint of the hydraulic characteristics of the volcanic rocks, it is useful to divide the Columbia Lava Plateau region into two parts: (1) the area in southeastern Washington, northeastern Oregon, and the Lewiston area of Idaho, part of which is underlain by volcanic rocks of the Columbia River Group; and (2) the remainder of the area shown on figure 21, which also includes the Snake River Plain. The basalt underlying the Snake River Plain is referred to as the Snake River Basalt; that underlying southeastern Oregon and the remainder of this area has been divided into several units, to which names of local origin are applied (Hampton, 1964).

The Columbia River Group is of Miocene to Pliocene(?) age and consists of relatively thick flows that have been deformed into a series of broad folds and offset locally along normal faults. Movement of ground water occurs primarily through the interflow zones near the top of flows and, to a much smaller extent, through fault zones and through joints developed in the dense central and lower parts of the flows. The axes of sharp folds and

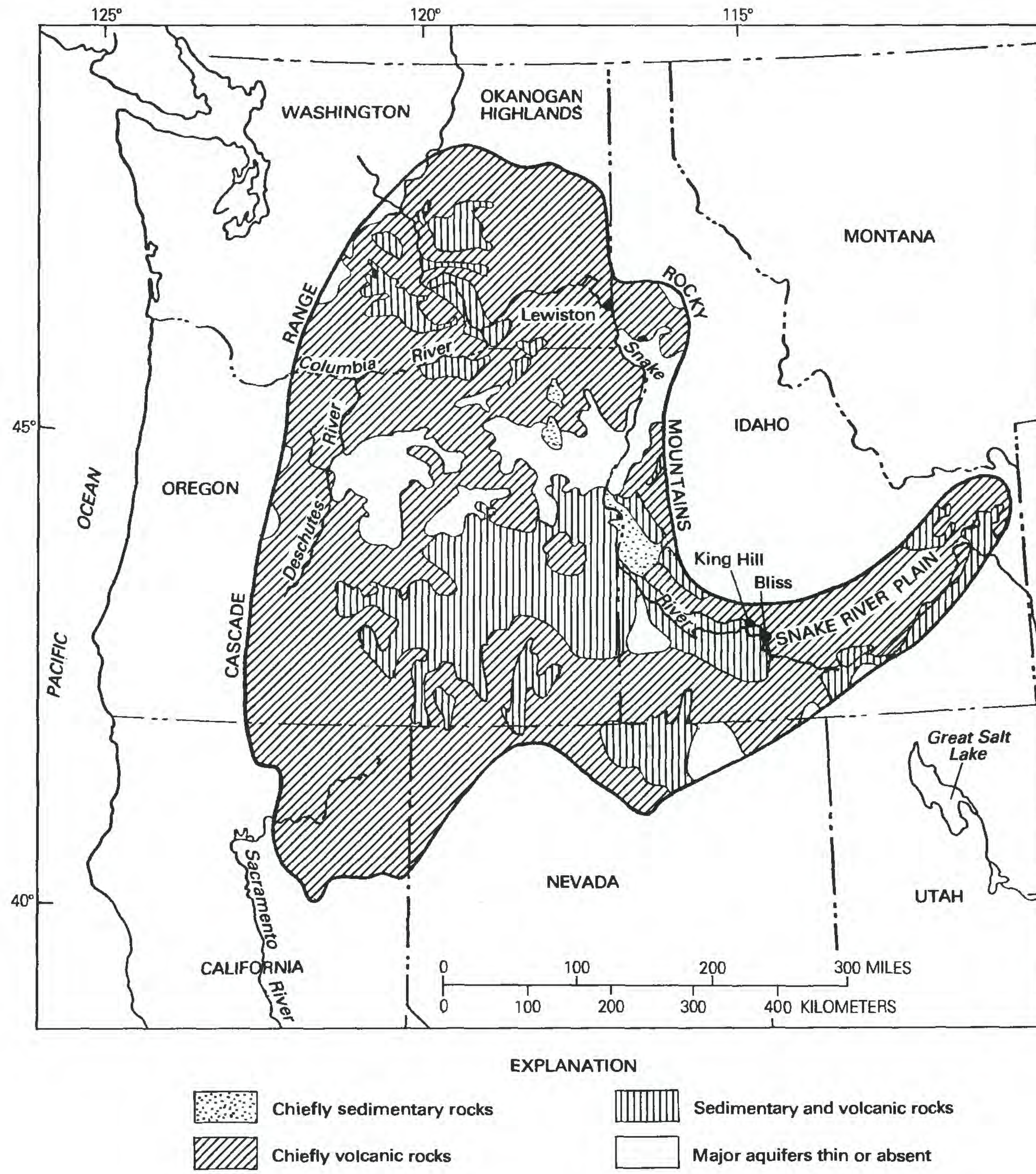


Figure 21. Generalized distribution and types of major aquifers of the Columbia Lava Plateau region. (Modified from U.S. Geological Survey Professional Paper 813-S.)

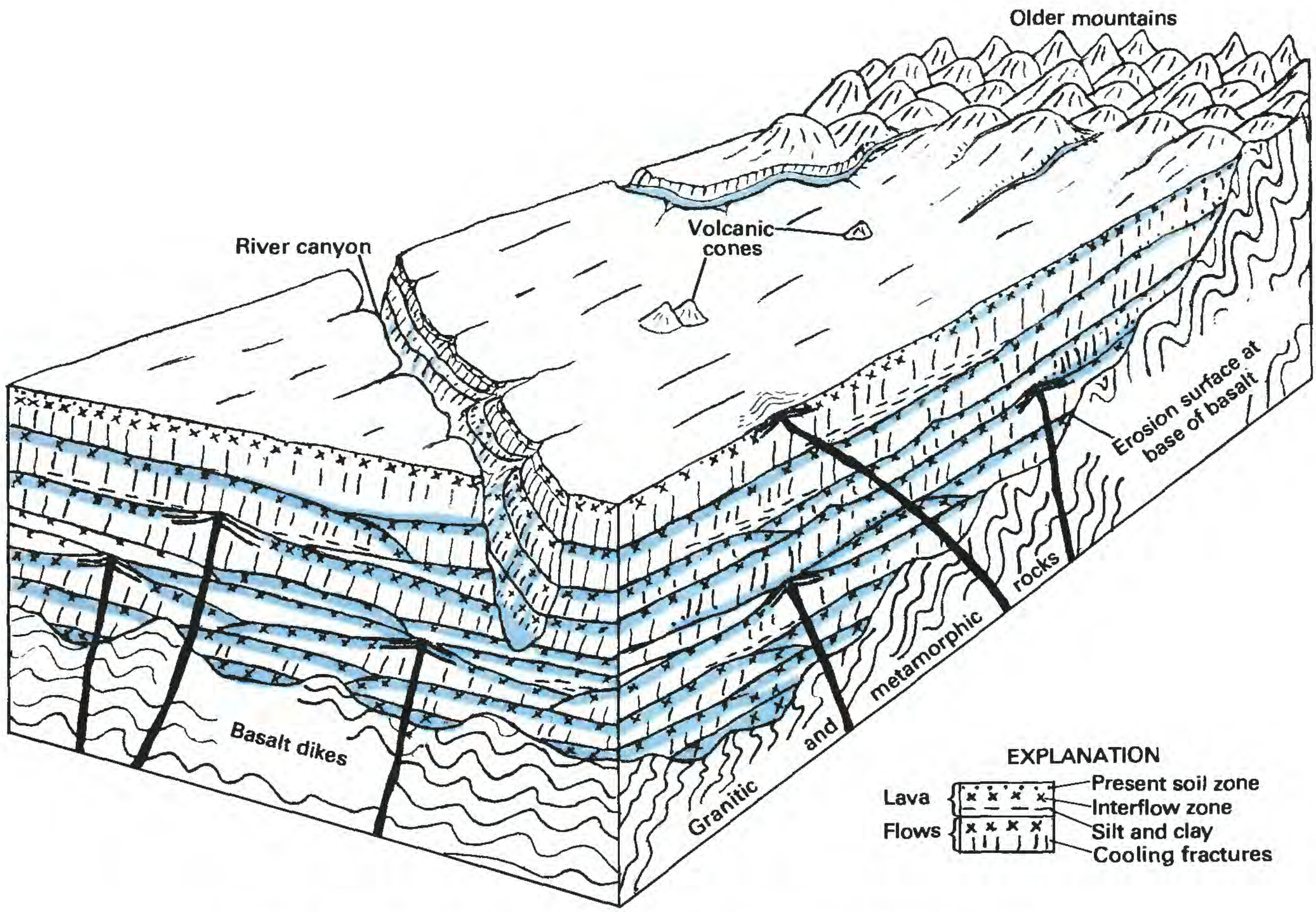


Figure 22. Topographic and geologic features of the Columbia Lava Plateau region.

the offset of the interflow zones along faults form subsurface dams that affect the movement of ground water. Water reaching the interflow zones tends to move down the dip of the flows from fold axes and to collect undip behind faults that are transverse to the direction of movement (Newcomb, 1961). As a result, the basalt in parts of the area is divided into a series of barrier-controlled reservoirs which are only poorly connected hydraulically to adjacent reservoirs.

The water-bearing basalt underlying California, Nevada, southeastern Oregon, and southern Idaho is of Pliocene to Holocene age and consists of small, relatively thin flows that have been affected to a much smaller extent by folding and faulting than has the Columbia River Group. The thin flows contain extensive, highly permeable interflow zones that are relatively effectively interconnected through a dense network of cooling fractures. Structural barriers to ground-water movement, such as those of the Columbia River Group, are of minor importance. This is demonstrated by conditions in the 44,000-square-kilometer area of the Snake River Plain east of Bliss, Idaho, which Nace (1958, p. 136) thought might be the largest unified ground-water reservoir on the North American continent. (It is probable that this distinction is held by the Floridan aquifer, which underlies an area of 212,000 km^2 in Alabama, Florida, Georgia, and South Carolina. See region 11.)

The interflow zones form a complex sequence of relatively horizontal aquifers that are separated vertically by the dense central and lower parts of the lava flows and by interlayered clay and silt. Hydrologists estimate that the interflow zones, which range in thickness from about 1 m to about 8 m, account for about 10 percent of the basalt. MacNish and Barker (1976) have estimated, on the basis of studies in the Walla Walla River basin in Washington and Oregon, that the hydraulic conductivity along the flow-contact zones may be a billion times larger than the hydraulic conductivity across the dense zones. The lateral extent of individual aquifers depends on the area covered by the different lava flows, on the presence of dikes and other igneous intrusions, and on faults and folds that terminate the porous zones, especially in the Columbia River Group.

The large differences in hydraulic conductivity between the aquifers and the intervening "confining zones" result in significant differences in *hydraulic heads* between different aquifers. These differences reflect the head losses that occur as water moves vertically through the system. As a result, heads decrease with increasing depth in recharge areas and increase with increasing depth near the streams that serve as major lines of ground-water discharge. The difference in heads between different aquifers can result in the movement of large volumes of water between aquifers through the open-hold (uncased) sections of wells (fig. 23). The irregular enlargement of the well bore in the interflow zones shown in figure 23 occurs during well construction as broken fragments of rock move into the well and are removed by the drill.

Much of the Columbia Lava Plateau region is in the "rain shadow" east of the Cascades and, as a result, receives only 200 to 1,200 mm of precipitation annually. The areas that receive the least precipitation include the plateau area immediately east of the Cascades and the Snake River Plain. The areas that receive the largest amounts of precipitation include the east flank of the

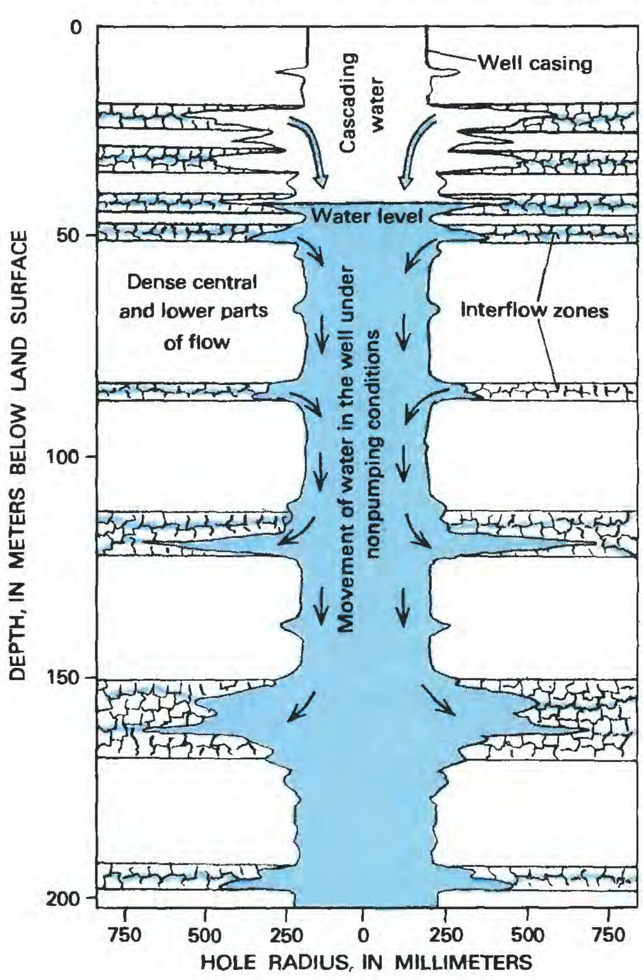


Figure 23. Well in a recharge area in the Columbia River Group. (Modified from Luzier and Burt, 1974.)

Cascades and the areas adjacent to the Okanogan Highlands and the Rocky Mountains. Recharge to the ground-water system depends on several factors, including the amount and seasonal distribution of precipitation and the permeability of the surficial materials. Most precipitation occurs in the winter and thus coincides with the cooler, nongrowing season when conditions are most favorable for recharge. Mundorff (Columbia-North Pacific Technical Staff, 1970) estimates that recharge may amount to 600 mm in areas underlain by highly permeable young lavas that receive abundant precipitation. Considerable recharge also occurs by infiltration of water from streams that flow onto the plateau from the adjoining mountains. These sources of natural recharge are supplemented in agricultural areas by the infiltration of irrigation water.

Discharge from the ground-water system occurs as seepage to streams, as spring flow, and by evapotranspiration in areas where the water table is at or near the land surface. The famous Thousand Springs and other springs along the Snake River canyon in southern Idaho are, in fact, among the most spectacular displays of ground-water discharge in the world.

The Columbia Lava Plateau region is mantled by mostly thin soils developed on alluvial and wind-laid deposits that are well suited for agriculture. Because of the arid and semiarid climate in most of the region, many crops require intensive irrigation. In 1970, for example, more than 15,000 km^2 (3.75 million acres) were being irrigated on the Snake River Plain. Water for irrigation is obtained both by diversions from streams and by wells that tap the lava interflow zones. Much of the water applied for irrigation percolates downward into the lava and then moves through the ground-water system to the Columbia and Snake Rivers and to other streams that have deeply entrenched channels. The effect of this "return flow" is graphically indicated by a long-term increase in the flow of the Thousand Springs and other large springs along the Snake River gorge between Milner and King Hill—from about 110 $m^3 sec^{-1}$ in 1902, prior to significant irrigation, to more than 225 $m^3 sec^{-1}$ by 1942, after decades of irrigation on adjacent and upstream parts of the plateau. Prior to the start of irrigation, the water represented by this increased flow reached the Snake River below King Hill through tributary streams and natural ground-water discharge.

The large withdrawal of water in the Columbia Lava Plateau for irrigation, industrial, and other uses has resulted in declines in ground-water levels of as much as 30 to 60 m in several areas. In most of these areas, the declines have been slowed or stopped through regulatory restrictions or other changes that have reduced withdrawals. Declines are still occurring, at rates as much as a few meters per year, in a few areas.

4. COLORADO PLATEAU AND WYOMING BASIN

(Thin soils over consolidated sedimentary rocks)

The Colorado Plateau and Wyoming Basin region occupies an area of 414,000 km² in Arizona, Colorado, New Mexico, Utah, and Wyoming. It is a region of canyons and cliffs; of thin, patchy, rocky soils; and of sparse vegetation adapted to the arid and semiarid climate. The large-scale structure of the region is that of a broad plateau standing at an altitude of 2,500 to 3,500 m and underlain by essentially horizontal to gently dipping layers of consolidated sedimentary rocks. The plateau structure has been modified by an irregular alternation of basins and domes, in some of which major faults have caused significant offset of the rock layers (fig. 24).

The region is bordered on the east, north, and west by mountain ranges that tend to obscure its plateau structure. The northern part of the region—the part occupied by the Wyoming Basin—borders the Nonglaciated Central region at the break in the Rocky Mountains between the Laramie Range and the Bighorn Mountains (fig. 14). The region contains small, isolated mountain ranges, the most prominent being the Henry Mountains and the La Sal Mountains in southeastern Utah. It also contains, rather widely scattered over the region, extinct volcanoes and lava fields (fig. 24), the most prominent example being the San Francisco Mountains in north-central Arizona.

The rocks that underlie the region consist principally of sandstone, shale, and limestone of Paleozoic to Cenozoic age. In parts of the region these rock units include significant amounts of gypsum (calcium sulfate). In the Paradox Basin in western Colorado the rock units include thick deposits of sodium- and potassium-bearing minerals, principally halite (sodium chloride). The sandstones and shales are most prevalent and most extensive in occurrence. The sandstones are the principal sources of ground water in the region and contain water in fractures developed both along bedding planes and across the beds and in interconnected pores. The most productive sandstones are those in which calcium carbonate or other cementing material has been deposited only around the point of contact of the sand grains. Thus, many of the sandstones are only partially cemented and retain significant *primary porosity.*

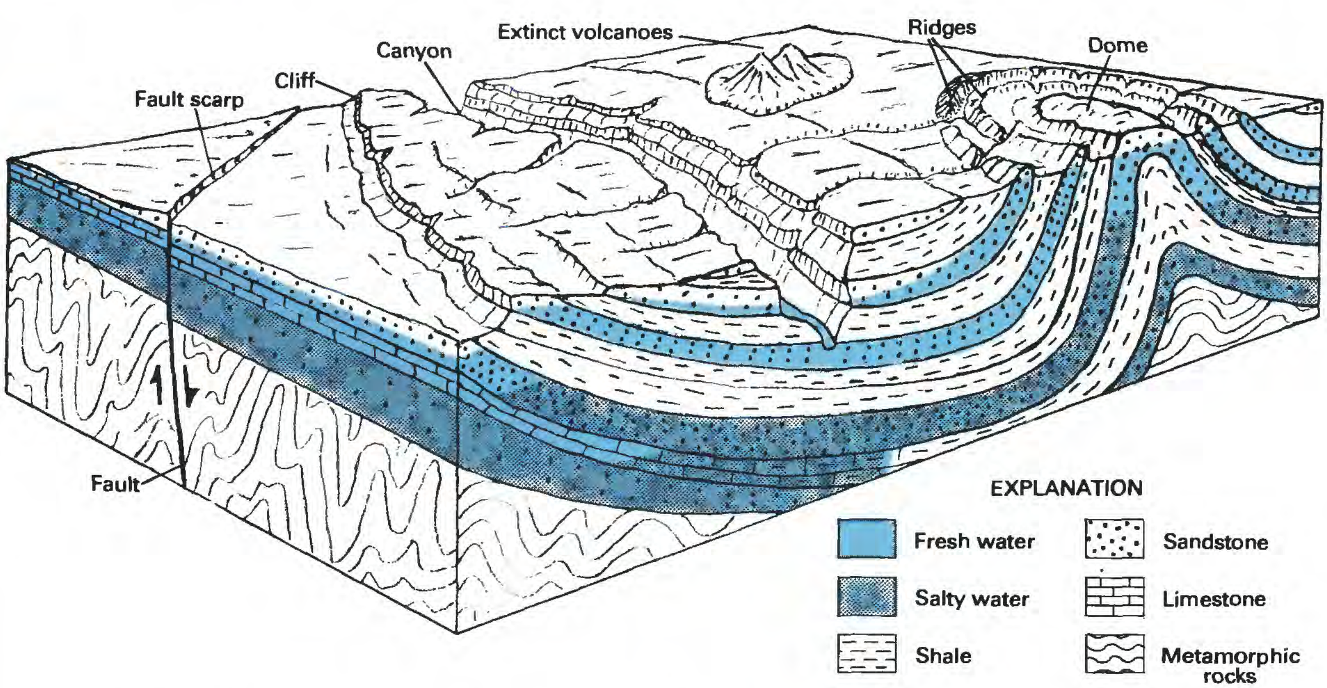


Figure 24. Topographic and geologic features of the Colorado Plateau and Wyoming Basin region.

Unconsolidated deposits are of relatively minor importance in this region. Thin deposits of alluvium capable of yielding small to moderate supplies of ground water occur along parts of the valleys of major streams, especially adjacent to the mountain ranges in the northern and eastern parts of the region. These deposits are partly of glacial origin. In most of the remainder of the region there are large expanses of exposed bedrock, and the soils, where present, are thin and rocky.

Erosion has produced extensive lines of prominent cliffs in the region. The tops of these cliffs are generally underlain and protected by resistant sandstones. Erosion of the domes has produced a series of concentric, steeply dipping ridges, also developed on the more resistant sandstones (fig. 24).

Recharge of the sandstone aquifers occurs where they are exposed above the cliffs and in the ridges. Average precipitation ranges from about 150 mm in the lower areas to about 1,000 mm in the higher mountains. The heaviest rainfall occurs in the summer in isolated, intense thunderstorms during which some recharge occurs where intermittent streams flow across sandstone outcrops. However, most recharge occurs in the winter during snowmelt periods. Water moves down the dip of the beds away from the recharge areas to discharge along the channels of major streams through seeps and springs and along the walls of canyons cut by the streams (fig. 24).

The condition described in the preceding paragraph, whereby intermittent streams serve as sources of ground-water recharge and perennial streams serve as lines of ground-water discharge, is relatively common in this region and in the Alluvial Basins region to the south and west. Streams into which ground water discharges are referred to as *gaining streams*. Conversely, streams that recharge ground-water systems are referred to as *losing streams*. The gaining streams and the losing streams may be different streams. However, in many areas the same stream may be a gaining stream in its headwaters, especially where these drain the wetter mountainous areas, become a losing stream as it flows onto the adjoining lower areas, and, ultimately, become a gaining stream again in its lowermost reaches where it serves as a regional drain (fig. 25).

The quantity of water available for recharge is

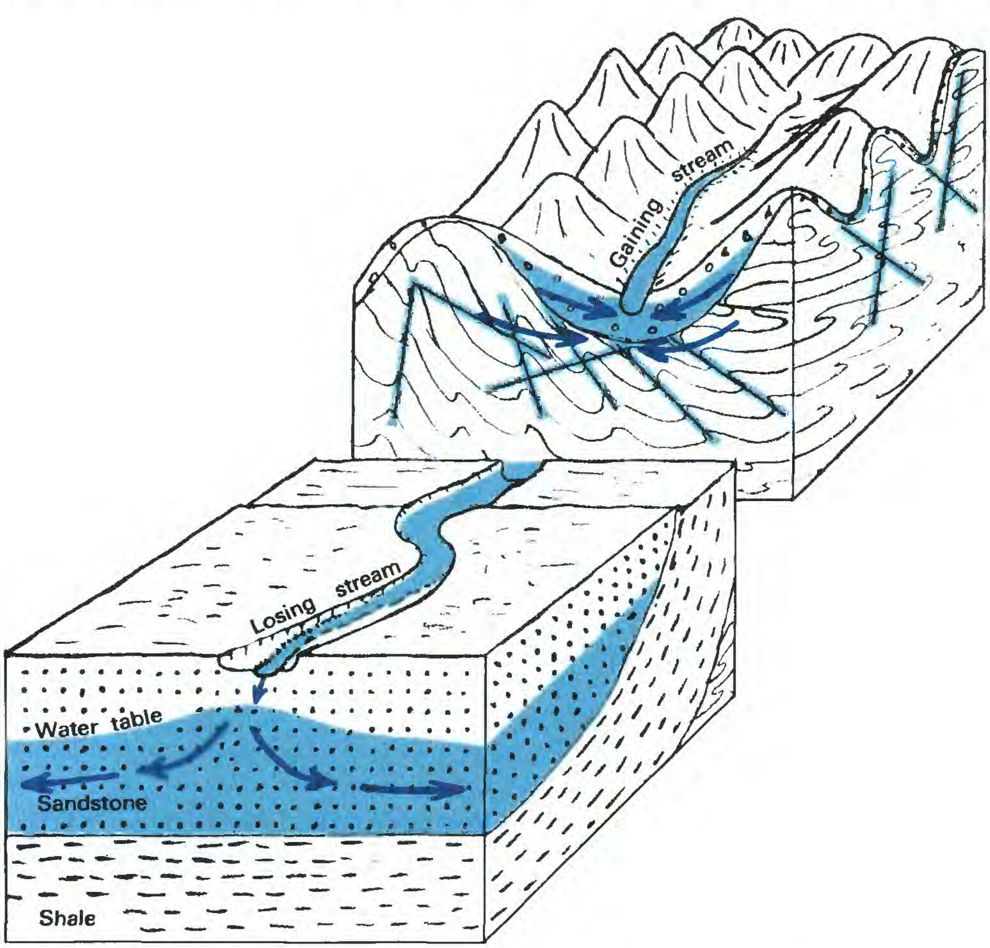


Figure 25. Relation between the ground-water system and gaining and losing streams.

small, but so are the porosity and the transmissivity of most of the sandstone aquifers. Because of the general absence of a thick cover of unconsolidated rock in the recharge areas, there is relatively little opportunity for such materials to serve as a storage reservoir for the underlying bedrock. The water in the sandstone aquifers is unconfined in the recharge areas and is confined downdip. Because most of the sandstones are consolidated, the *storage coefficient* in the confined parts of the aquifers is very small. This small storage coefficient together with the small transmissivities, results in even small rates of withdrawal causing extensive *cones of depression* around pumping wells.

Springs exist at places near the base of the sandstone aquifers where they crop out along the sides of canyons. Discharge from the springs results in dewatering the upper parts of the aquifers for some distance back from the canyon walls.

The Colorado Plateau and Wyoming Basin is a dry, sparsely populated region in which most water supplies are obtained from the perennial streams that flow across it from the bordering mountains. Less than 5 percent of the water needs are supplied by ground water, and the development of even small ground-water supplies requires the application of considerable knowledge of the occurrence of both rock units and their structure, and of the chemical quality of the water. Also, because of the large surface relief and the dip of the aquifers, wells even for domestic or small livestock supplies must penetrate to depths of a few hundred meters in much of the area. Thus, the development of ground-water supplies is far more expensive than in most other parts of the country. These negative aspects notwithstanding, ground water in the region can support a substantial increase over the present withdrawals.

As in most other areas of the country underlain by consolidated sedimentary rocks, *mineralized (saline) water*—that is, water containing more than 1,000 mg/L of dissolved solids—is widespread in occurrence (see fig. 35). Most of the shales and siltstones contain mineralized water throughout the region and below altitudes of about 2,000 m. *Freshwater*—water containing less than 1,000 mg/L of dissolved solids—occurs only in the most permeable sandstones and limestones (fig. 24). Much of the mineralized water is due to the solution of gypsum and halite by water circulating through beds that contain these minerals. Although the aquifers that contain mineralized water are commonly overlain by aquifers containing freshwater, this situation is reversed in a few places where aquifers containing mineralized water are underlain by more permeable aquifers containing freshwater.

5. HIGH PLAINS

(Thick alluvial deposits over fractured sedimentary rocks)

The High Plains region occupies an area of 450,000 km² extending from South Dakota to Texas. The plains are a remnant of a great alluvial plain built in Miocene time by streams that flowed east from the Rocky Mountains. The plain originally extended from the foot of the mountains to a terminous some hundreds of kilometers east of its present edge. Erosion by streams has removed a large part of the once extensive plain, including all of the part adjacent to the mountains, except in a small area in southeastern Wyoming.

The original depositional surface of the alluvial plain is still almost unmodified in large areas, especially in Texas and New Mexico, and forms a flat, imperceptibly eastward-sloping tableland that ranges in altitude from about 2,000 m near the Rocky Mountains to about 500 m along its eastern edge. The surface of the southern High Plains contains numerous shallow circular depressions, called playas, that intermittently contain water following heavy rains. Some geologists believe these depressions are due to solution of soluble materials by percolating water and accompanying compaction of the alluvium. Other significant topographic features include sand dunes, which are especially prevalent in central and northern Nebraska, and wide, downcut valleys of streams that flow eastward across the area from the Rocky Mountains (fig. 26).

The High Plains region is underlain by one of the most productive and most intensively developed aquifers in the United States. The alluvial materials derived from

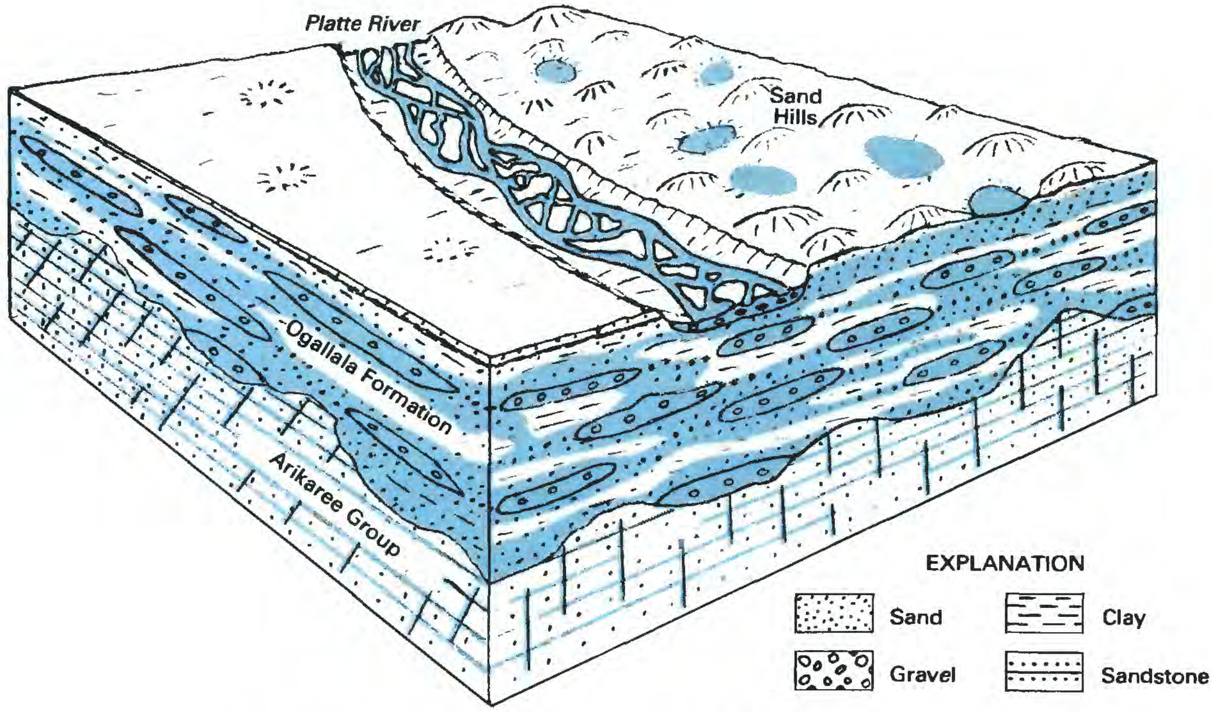


Figure 26. Topographic and geologic features of the High Plains region.

the Rocky Mountains, which are referred to as the Ogallala Formation, are the dominant geologic unit of the High Plains aquifer. The Ogallala ranges in thickness from a few meters to more than 200 m and consists of poorly sorted and generally unconsolidated clay, silt, sand, and gravel.

Younger alluvial materials of Quaternary age overlie the Ogallala Formation of late Tertiary age in most parts of the High Plains. Where these deposits are saturated, they form a part of the High Plains aquifer; in parts of south-central Nebraska and central Kansas, where the Ogallala is absent, they comprise the entire aquifer. The Quaternary deposits are composed largely of material derived from the Ogallala and consist of alluvial deposits of gravel, sand, silt, and clay and extensive areas of sand dunes. The most extensive area of dune sand occurs in the Sand Hills area north of the Platte River in Nebraska.

Other, older geologic units that are hydrologically connected to the Ogallala and thus form a part of the High Plains aquifer include the Arikaree Group of Miocene age and a small part of the underlying Brule Formation. The Arikaree Group underlies the Ogallala in parts of western Nebraska, southwestern South Dakota, southeastern Wyoming, and northeastern Colorado. It is predominantly a massive, very fine to fine-grained sandstone that locally contains beds of volcanic ash, silty sand, and sandy clay. The maximum thickness of the Arikaree is about 300 m, in western Nebraska. The Brule Formation of Oligocene age underlies the Arikaree. In most of the area in which it occurs, the Brule forms the base of the High Plains aquifer. However, in the southeastern corner of Wyoming and the adjacent parts of Colorado and Nebraska, the Brule contains fractured sandstones hydraulically interconnected to the overlying Arikaree Group; in this area the Brule is considered to be a part of the High Plains aquifer.

In the remainder of the region, the High Plains aquifer is underlain by several formations, ranging in age from Cretaceous to Permian and composed principally of shale, limestone, and sandstone. The oldest of these, of Permian age, underlies parts of northeastern Texas, western Oklahoma, and central Kansas and contains layers of relatively soluble minerals including gypsum, anhydrite, and halite (common salt) which are dissolved by circulating ground water. Thus, water from the rocks of Permian age is relatively highly mineralized and not usable for irrigation and other purposes that require freshwater. The older formations in the remainder of the area contain fractured sandstones and limestones interconnected in parts of the area with the High Plains aquifer. Although these formations yield freshwater, they are not widely used as water sources.

Prior to the erosion that removed most of the western part of the Ogallala, the High Plains aquifer was recharged by the streams that flowed onto the plain from the mountains to the west as well as by local precipitation. The only source of recharge now is local precipitation, which ranges from about 400 mm along the western boundary of the region to about 600 mm along the eastern boundary. Precipitation and ground-water recharge on the High Plains vary in an east-west direction, but recharge to the High Plains aquifer also varies in a north-south direction. The average annual rate of recharge has been determined to range from about 5 mm in Texas and New Mexico to about 100 mm in the Sand Hills in Nebraska. This large difference is explained by differences in evaporation and transpiration and by differences in the permeability of the surficial materials.

In some parts of the High Plains, especially in the southern part, the near-surface layers of the Ogallala have been cemented with lime (calcium carbonate) to form a material of relatively low permeability called caliche. Precipitation on areas underlain by caliche soaks slowly into the ground. Much of this precipitation collects in playas that are underlain by silt and clay, which hamper infiltration, with the result that most of the water is lost to evaporation. During years of average or below-average precipitation, all or nearly all of the precipitation is returned to the atmosphere by evapotranspiration. Thus, it is only during years of excessive precipitation that significant recharge occurs and this, as noted above, averages only about 5 mm per year in the southern part of the High Plains.

In the Sand Hills area, the lower evaporation and transpiration and the permeable sandy soil results in about 20 percent of the precipitation (or about 100 mm annually) reaching the water table as recharge.

The water table of the High Plains aquifer has a general slope toward the east of about 2 to 3 m per km (10 to 15 ft per mile) (fig. 27). Gutentag and Weeks (1980) estimate, on the basis of the average *hydraulic gradient* and aquifer characteristics, that water moves through the aquifer at a rate of about 0.3 m (1 ft) per day.

Natural discharge from the aquifer occurs to streams, to springs and seeps along the eastern boundary of the plains, and by evaporation and transpiration in areas where the water table is within a few meters of the land surface. However, at present the largest discharge is probably through wells. The widespread occurrence of permeable layers of sand and gravel, which permit the construction of large-yield wells almost any place in the region, has led to the development of an extensive agricultural economy largely dependent on irrigation. Gutentag and Weeks (1980) estimate that in 1977 about 3.7×10^{10} m^3 (30,000,000 acre-ft) of water was pumped from more than 168,000 wells to irrigate about 65,600 km^2 (16,210,000 acres). Most of this water is derived from ground-water storage, resulting in a long-term continuing decline in ground-water levels in parts of the region of as much as 1 m per year. The lowering of the water table has resulted in a 10 to 50 percent reduction in the saturated thickness of the High Plains aquifer in an area of 130,000 km^2 (12,000 mi^2). The largest reductions have occurred in the Texas panhandle and in parts of Kansas and New Mexico (fig.28).

The depletion of ground-water storage in the High Plains, as reflected in the decline in the water table and the reduction in the saturated thickness, is a matter of increasing concern in the region. However, from the standpoint of the region as a whole, the depletion does not yet represent a large part of the storage that is available for use. Weeks and Gutentag (1981) estimate, on the basis of a specific yield of 15 percent of the total volume of saturated material, that the available (usable) storage in 1980 was about $4\times10^{12}m^3$ (3.3 billion acre-ft). Luckey, Gutentag, and Weeks (1981) estimate that this is only about 5 percent less than the storage that was available at the start of withdrawals. However, in areas where intense irrigation has long been practiced, depletion of storage is severe.

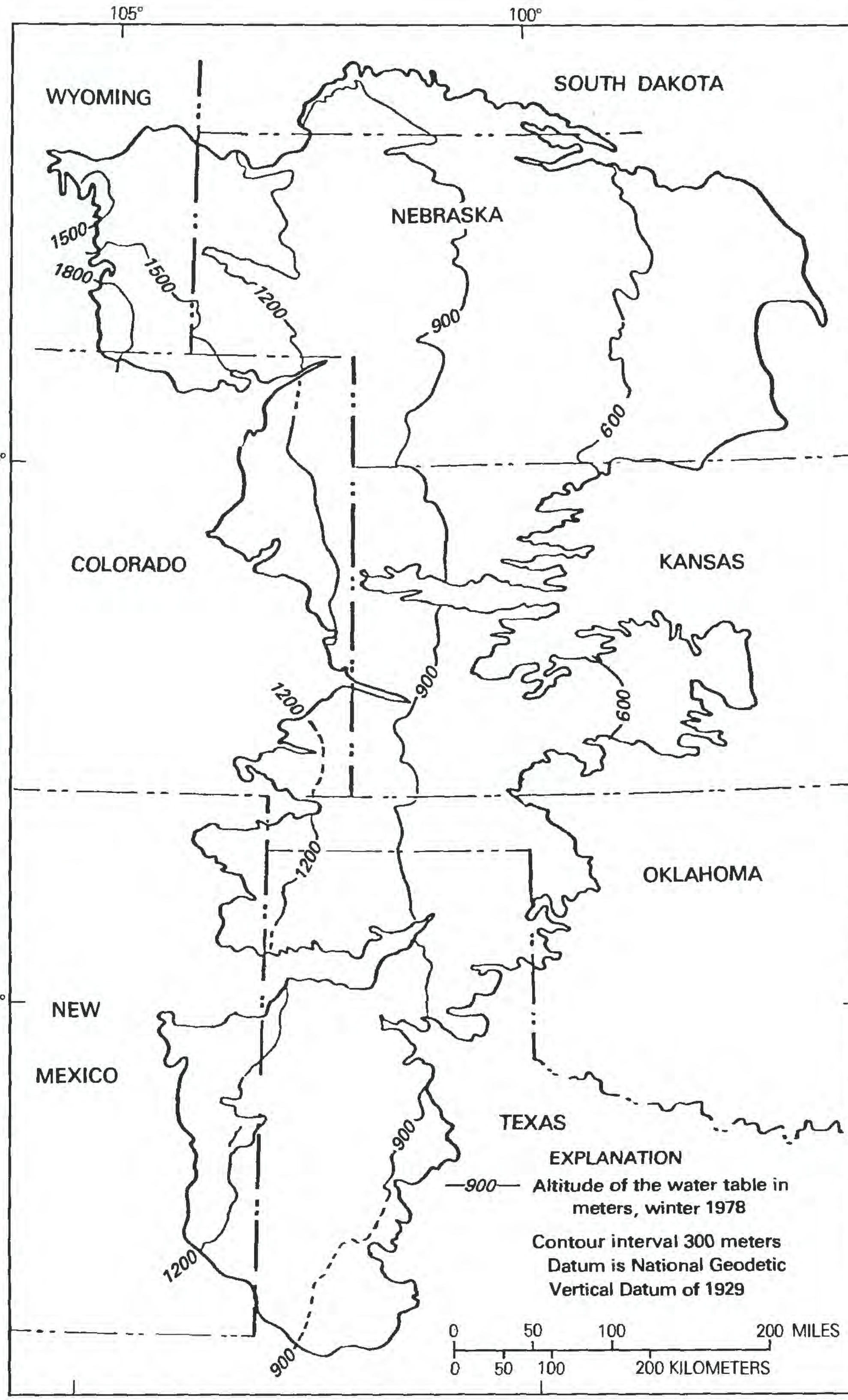


Figure 27 Altitude of the water table of the High Plains aquifer.

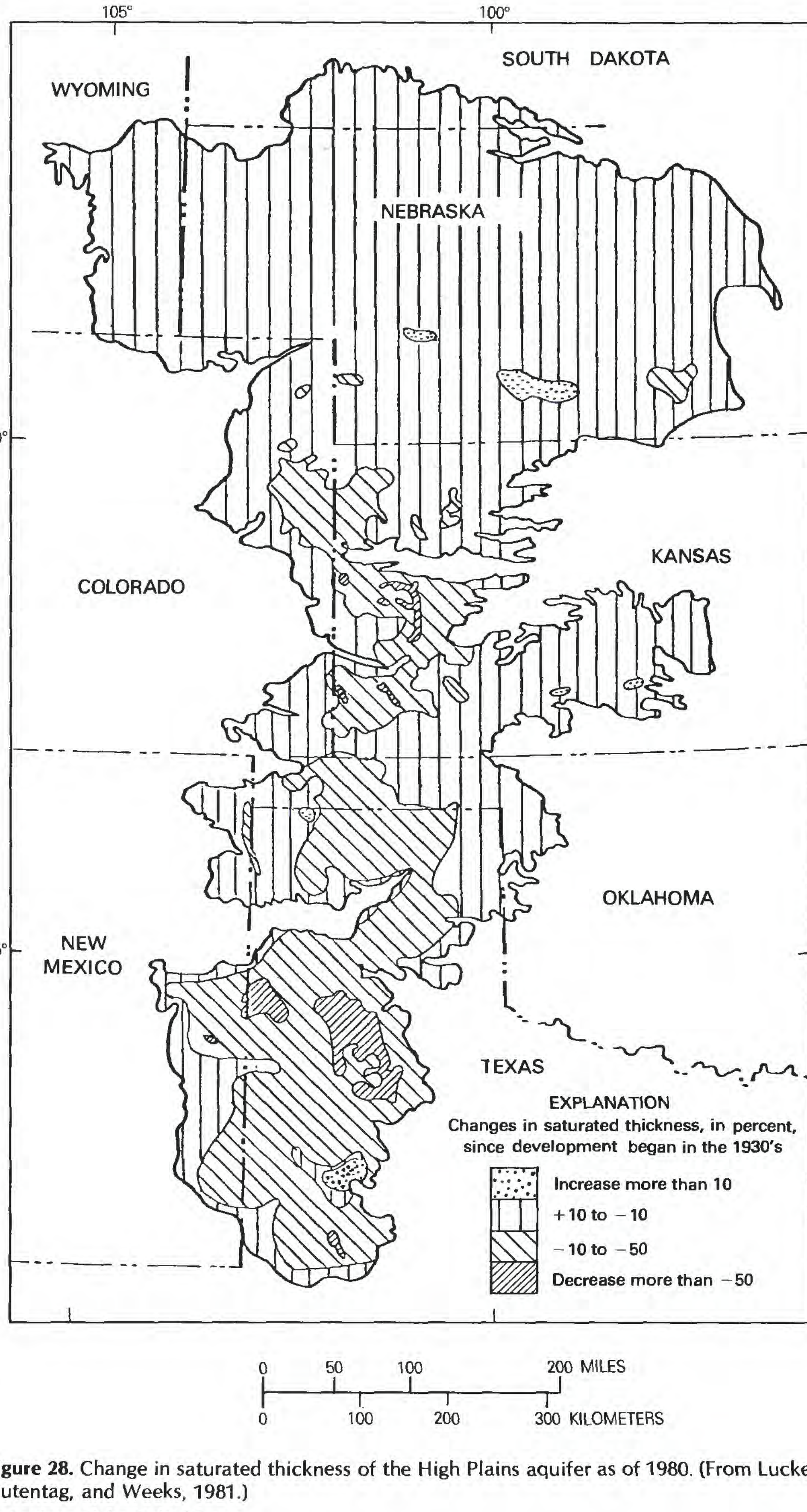


Figure 28. Change in saturated thickness of the High Plains aquifer as of 1980. (From Luckey, Gutentag, and Weeks, 1981.)

6. NONGLACIATED CENTRAL REGION

(Thin regolith over fractured sedimentary rocks)

The nonglaciated Central region is an area of about 1,737,000 km² extending from the Appalachian Mountains on the east to the Rocky Mountains on the west. The part of the region in eastern Colorado and northeastern New Mexico is separated from the remainder of the region by the High Plains region. The Nonglaciated Central region also includes the Triassic Basins in Virginia and North Carolina and the "driftless" area in Wisconsin, Minnesota, Iowa, and Illinois where glacial deposits, if present, are thin and of no hydrologic importance (fig. 29). The region is a topographically complex area that ranges from the Valley and Ridge section of the Appalachian Mountains on the east westward across the Great Plains to the foot of the Rocky Mountains. It includes, among other hilly and mountainous areas, the Ozark Plateaus in Missouri and Arkansas. Altitudes range from 150 m above sea level in central Tennessee and Kentucky to 1,500 m along the western boundary of the region.

The region is also geologically complex. Most of it is underlain by consolidated sedimentary rocks that range in age from Paleozoic to Tertiary and consist largely of sandstone, shale, carbonate rocks (limestone and dolomite), and conglomerate. A small area in Texas and western Oklahoma is underlain by gypsum. Throughout most of the region the rock layers are horizontal or gently dipping (fig. 30). Principal exceptions are the Valley and Ridge section, the Wichita and Arbuckle Mountains in Oklahoma, and the Ouachita Mountains in Oklahoma

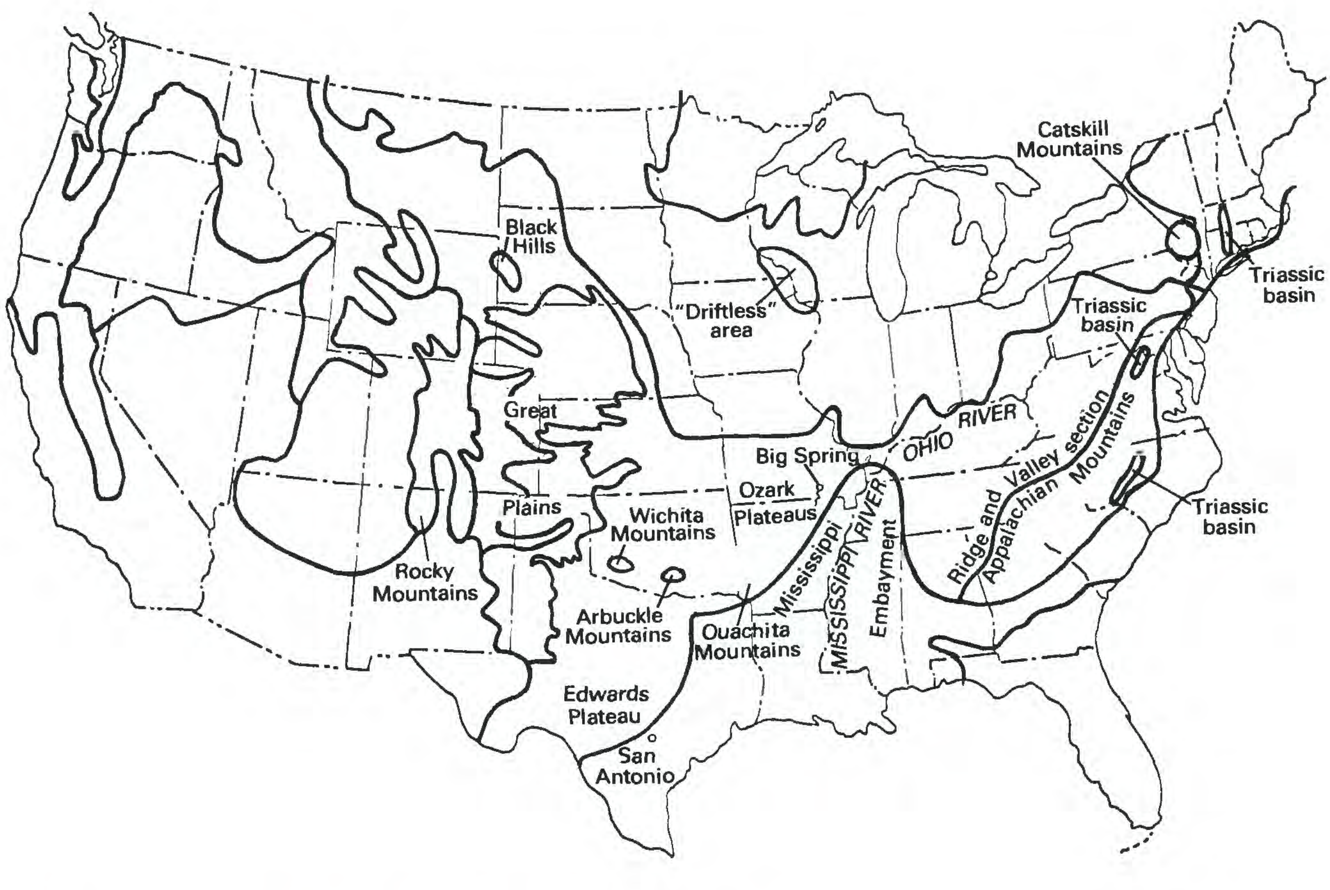


Figure 29. Location of geographic features mentioned in the discussions of regions covering the central and eastern parts of the United States.

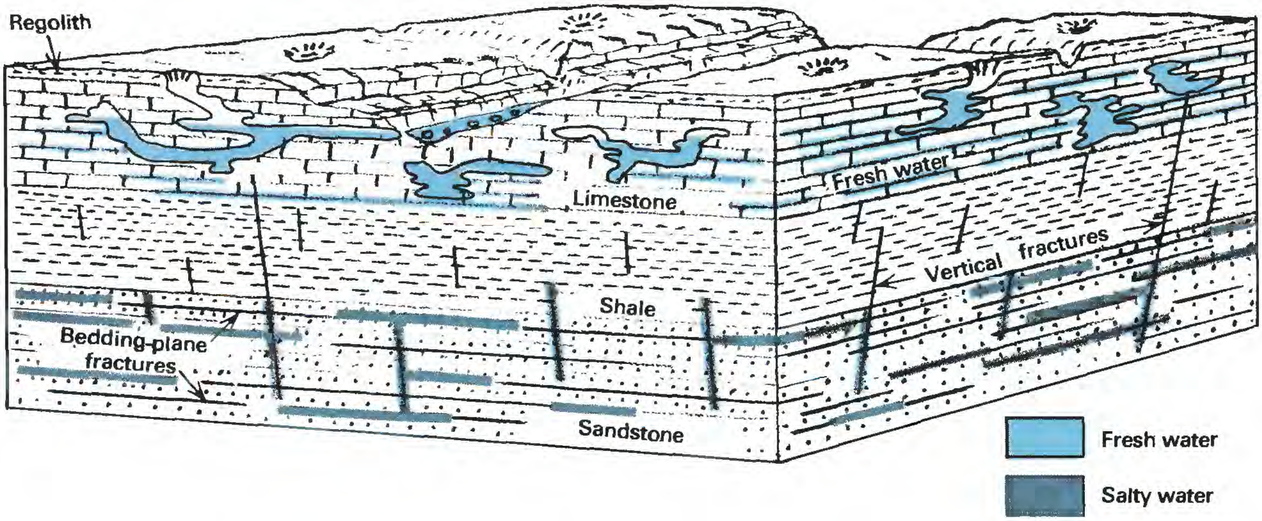


Figure 30. Topographic and geologic features of the Nonglaciated Central region.

and Arkansas, in all of which the rocks have been folded and extensively faulted. Around the Black Hills and along the eastern side of the Rocky Mountains the rock layers have been bent up sharply toward the mountains and truncated by erosion (fig. 31). The Triassic Basins in Virginia and North Carolina are underlain by moderate to gently dipping beds of shale and sandstone that have been extensively faulted and invaded by narrow bodies of igneous rock. These basins were formed in Triassic time when major faults in the crystalline rocks of the Piedmont resulted in the formation of structural depressions up to several thousand meters deep and more than 25 km wide and 140 km long.

The land surface in most of the region is underlain by regolith formed by chemical and mechanical breakdown of the bedrock. In the western part of the Great Plains the residual soils are overlain by or intermixed with eolian (wind-laid) deposits. The thickness and composition of the regolith depend on the composition and structure of the parent rock and on the climate, land cover, and topography. In areas underlain by relatively pure limestone, the regolith consists mostly of clay and is

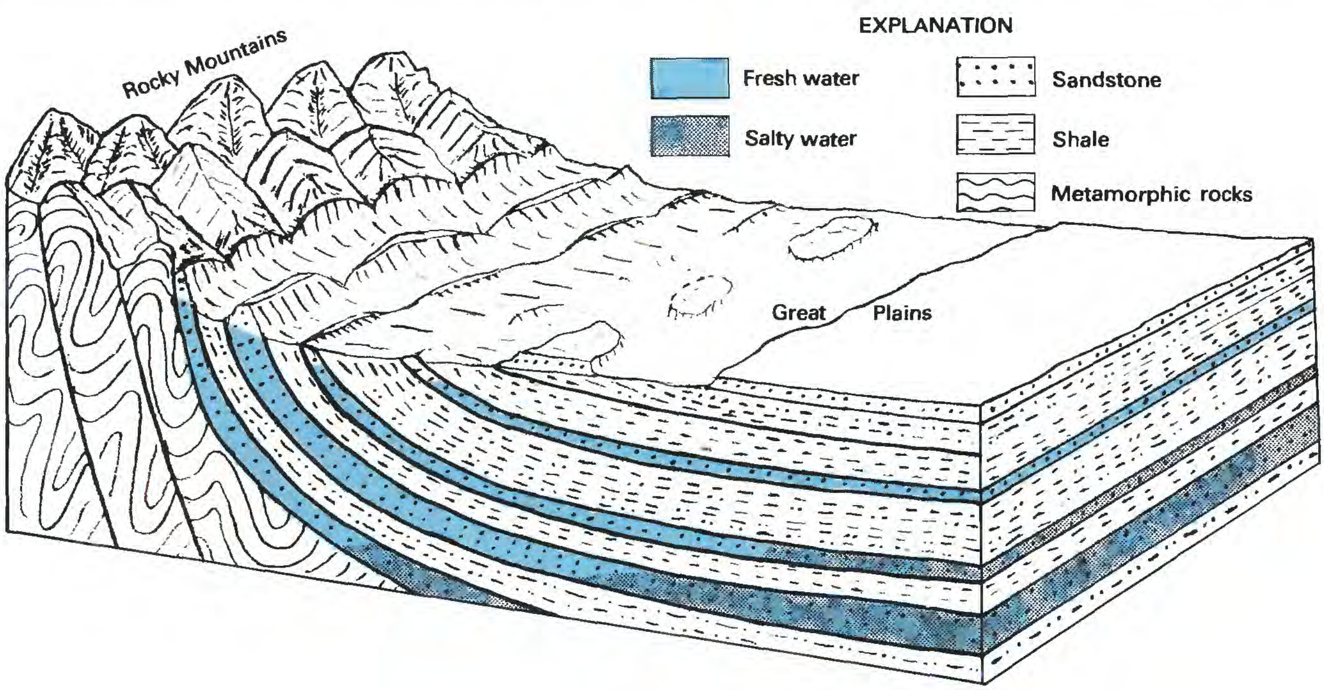


Figure 31. Topographic and geologic features along the western boundary of the Nonglaciated Central region.

generally only a few meters thick. Where the limestones contain chert and in areas underlain by shale and sandstone, the regolith is thicker, up to 30 m or more in some areas. The chert and sand form moderately permeable soils, whereas the soils developed on shale are finer grained and less permeable.

The principal water-bearing openings in the bedrock are fractures along which the rocks have been broken by stresses imposed on the Earth's crust at different times since the rocks were consolidated. The fractures generally occur in three sets. The first set, and the one that is probably of greatest importance from the standpoint of ground water and well yields, consists of fractures developed along the contact between different rock layers, in other words, along bedding planes. Where the sedimentary layers making up the bedrock are essentially horizontal, the bedding-plane fractures are more or less parallel to the land surface (fig. 30). The two remaining sets of fractures are essentially vertical and thus cross the bedding planes at a steep angle (fig. 30). The primary difference between the sets of vertical fractures is in the orientation of the fractures in each set. For example, in parts of the region one set of vertical fractures is oriented in a northwest-southeast direction and the other set in a northeast-southwest direction. The vertical fractures facilitate movement of water across the rock layers and thus serve as the principal hydraulic connection between the bedding-plane fractures.

In the parts of the region in which the bedrock has been folded or bent, the occurrence and orientation of fractures are more complex. In these areas the dip of the rock layers and the associated bedding-plane fractures range from horizontal to vertical. Fractures parallel to the land surface, where present, are probably less numerous and of more limited extent than in areas of flat-lying rocks.

The openings developed along most fractures are less than a millimeter wide. The principal exception occurs in limestones and dolomites, which are more soluble in water than most other rocks. Water moving through these rocks gradually enlarges the fractures to form, in time, extensive cavernous openings or cave systems. Cave systems developed in limestones, dolomites, and other carbonate rocks in the United States are shown in figure 32. Many large springs emerge from these openings; one in this region is Big Spring, in Missouri, which has an average discharge of 36.8 m^3sec^{-1}.

Recharge of the ground-water system in this region occurs primarily in the outcrop areas of the bedrock aquifers in the uplands between streams. Precipitation in the region ranges from about 400 mm per year in the western part to more than 1,200 mm in the eastern part. This wide difference in precipitation is reflected in recharge rates, which range from about 5 mm per year in west Texas and New Mexico to as much as 500 mm per year in Pennsylvania and eastern Tennessee. Discharge from the ground-water system is by springs and seepage into streams and by evaporation and transpiration in areas where the water table is within a few meters of land surface.

The yield of wells depends on (1) the number and size of fractures that are penetrated and the extent to which they have been enlarged by solution, (2) the rate of recharge, and (3) the storage capacity of the bedrock and regolith. Yields of wells in most of the region are small, in the range of 0.01 to 1 m^3min^{-1} (about 2.5 to about 250 gallons per minute), making the Nonglaciated Central region one of the least favorable ground-water regions in the country. Even in parts of the areas underlain by cavernous limestone, yields are moderately low because of both the absence of a thick regolith and the large water-transmitting capacity of the cavernous openings which quickly discharge the water that reaches them during periods of recharge.

The exceptions to the small well yields are the cavernous limestones of the Edwards Plateau, the Ozark Plateaus, and the Ridge and Valley section (fig. 29). The Edwards Plateau in Texas is bounded on the south by the Balcones Fault Zone, in which limestone and dolomite up to 150 m in thickness has been extensively faulted. The faulting has facilitated the development of solution openings which makes this zone one of the most productive aquifers in the country. Wells of the City of San Antonio are located in this zone; individually, they have yields of more than 60 m^3min^{-1}.

Another feature that makes much of this region unfavorable for ground-water development is the occurrence of salty water at relatively shallow depths (see fig. 35). In most of the Nonglaciated Central region, except the Ozark Plateaus, the Ouachita and Arbuckle Mountains, and the Ridge and Valley section, the water in the bedrock contains more than 1,000 mg/L of dissolved solids at depths less than 150 m (figs. 30, 31). Most of the salty water is believed to be *connate*—that is, it was trapped in the rocks when they emerged from the sea in which they were deposited. Other possible sources include: (1) seawater that entered the rocks during a later time when the land again was beneath the sea and (2) salty water derived from solution of salt beds that underlie parts of the region.

The presence of connate water at relatively shallow depths is doubtless due to several factors, including, in the western part of the area, a semiarid climate and, consequently, a small rate of recharge. Other factors probably include an extremely slow rate of ground-water circulation at depths greater than a few hundred meters.

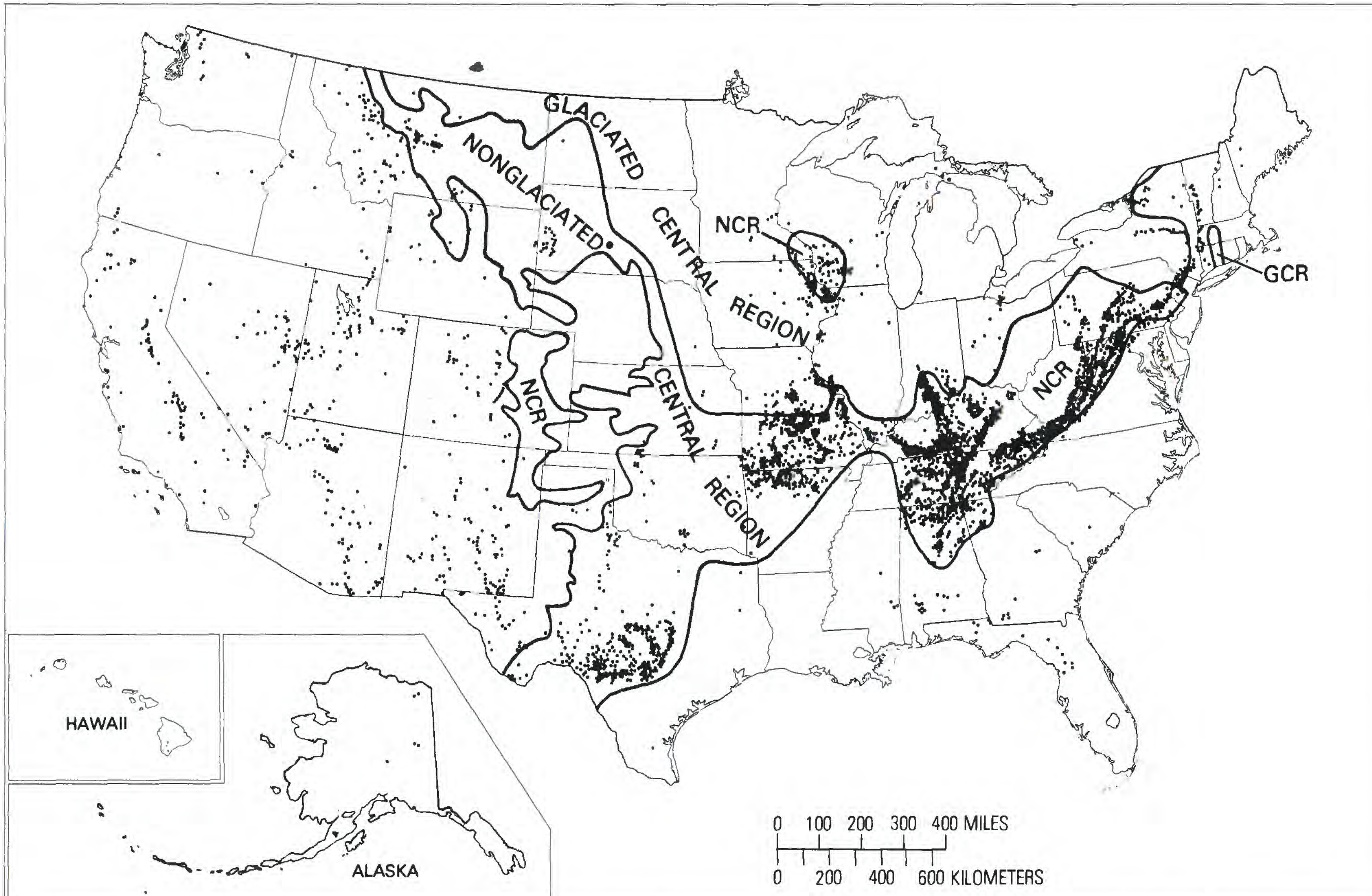


Figure 32. Location of cave systems in carbonate rocks in the United States. (Adopted from U.S. Geological Survey, 1970, p. 77.)

7. GLACIATED CENTRAL REGION

(Glacial deposits over fractured sedimentary rocks)

The Glaciated Central region occupies an area of 1,297,000 km^2 extending from the Triassic Basin in Connecticut and Massachusetts and the Catskill Mountains in New York on the east to the northern part of the Great Plains in Montana on the west (fig. 29). The part of the region in New York and Pennsylvania is characterized by rolling hills and low, rounded mountains that reach altitudes of 1,500 m. Westward across Ohio to the western boundary of the region along the Missouri River, the region is flat to gently rolling. Among the more prominent topographic features in this part of the region are low, relatively continuous ridges (moraines) which were formed at the margins of ice sheets that moved southward across the area one or more times during the Pleistocene (fig. 33).

The Glaciated Central region is underlain by relatively flat-lying consolidated sedimentary rocks that range in age from Paleozoic to Tertiary. They consist primarily of sandstone, shale, limestone, and dolomite. The bedrock is overlain by glacial deposits which, in most of the area, consist chiefly of *till*, an unsorted mixture of rock particles deposited directly by the ice sheets. The till is interbedded with and overlain by sand and gravel deposited by meltwater streams, by silt and clay deposited in glacial lakes, and, in large parts of the North-Central States, by *loess*, a well-sorted silt believed to have been deposited primarily by the wind (fig. 33).

On the Catskill Mountains and other uplands in the eastern part of the region, the glacial deposits are typically only a few to several meters thick, but localized deposits as much as 30 m thick are common on southerly slopes. In much of the central and western parts of the region, the glacial deposits exceed 100 m in thickness. The principal exception is the "driftless" area in Wisconsin, Minnesota, Iowa, and Illinois, where the ice, if it invaded the area, was too thin to erode preexisting soils or to deposit a significant thickness of till. Thus, the bedrock in this area is overlain by thin soils derived primarily from weathering of the rock. This area, both geologically and hydrologically, resembles the Nonglaciated Central region and is, therefore, included as part of that region.

The glacial deposits are thickest in valleys in the bedrock surface; thicknesses of 100 to 300 m occur in the

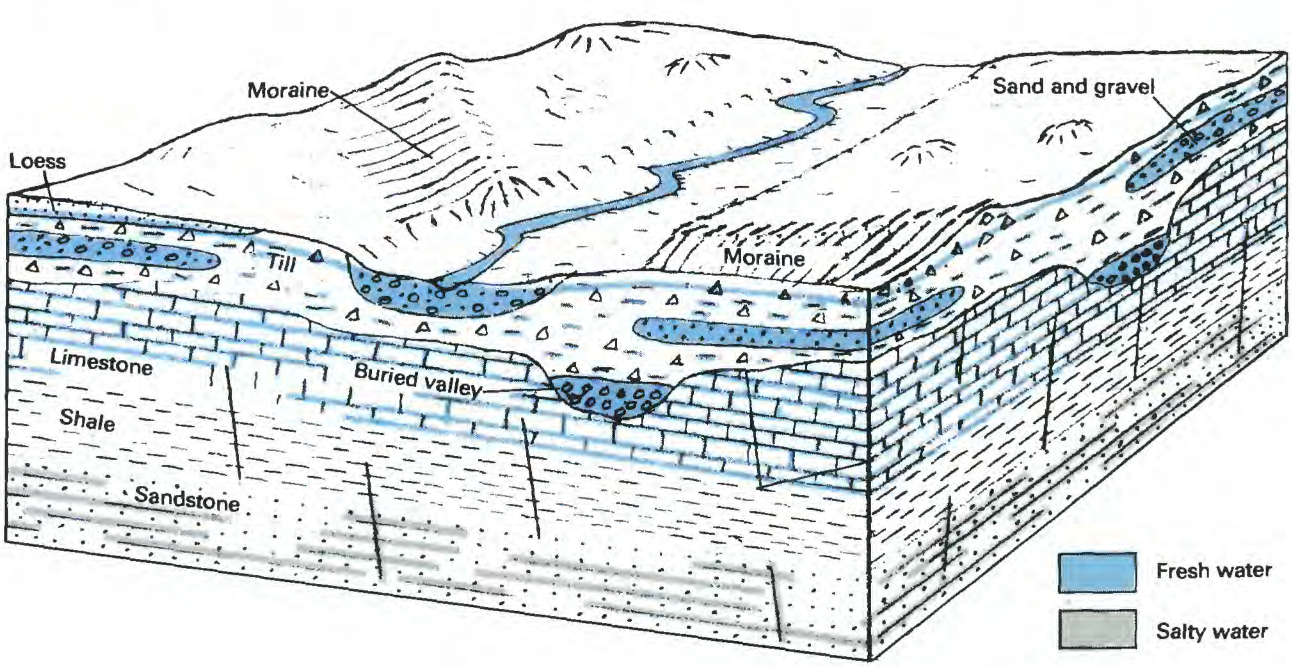


Figure 33. Topographic and geologic features of the Glaciated Central region.

valleys of the Finger Lakes in New York. In most of the region westward from Ohio to the Dakotas, the thickness of the glacial deposits exceeds the relief on the preglacial surface, with the result that the locations of valleys and stream channels in the preglacial surface are no longer discernible from the land surface. The glacial deposits in valleys include, in addition to till and lacustrine silts and clays, substantial thicknesses of highly permeable sand and gravel (fig. 33). (See region 12, "Alluvial Valleys.")

Ground water occurs both in the glacial deposits and in the bedrock. Water occurs in the glacial deposits in pores between the rock particles and in the bedrock primarily along fractures. The dominant water-bearing fractures in the bedrock are along bedding planes. Water also occurs in the bedrock in steeply dipping fractures that cut across the beds and, in some sandstones and conglomerates, in primary pores that were not destroyed in the process of cementation and consolidation.

Large parts of the region are underlain by limestones and dolomites in which the fractures have been enlarged by solution. Caves are relatively common in the limestones where the ice sheets were relatively thin, as near the southern boundary of the region and in the "driftless" area (see fig. 32). A few caves occur in other parts of the region, notably in the Mohawk River valley in central New York, where they were apparently protected from glacial erosion by the configuration of the bedrock surface over which the ice moved. However, on the whole, caves and other large solution openings, from which large springs emerge and which yield large quantities of water to wells in parts of the Nonglaciated Central region, are much less numerous and hydrologically much less important in the Glaciated Central region (see fig. 32).

The glacial deposits are recharged by precipitation on the interstream areas and serve both as a source of water to shallow wells and as a reservoir for recharge to the underlying bedrock. Precipitation ranges from about 400 mm per year in the western part of the region to about 1,000 mm in the eastern part. Recharge also depends on the permeability of the glacial deposits exposed at the land surface and on the slope of the surface. On sloping hillsides underlain by clay-rich till, the annual rate of recharge, even in the humid eastern part of the region, probably does not exceed 50 mm. In contrast, relatively flat areas underlain by sand and gravel may receive as much as 300 mm of recharge annually in the eastern part of the region. Recharge of the ground-water system in the Glaciated Central region occurs primarily in the fall, after plant growth has stopped and cool temperatures have reduced evaporation, and again during the spring thaw before plant growth begins. Of these recharge periods, the spring thaw is usually dominant except, as illustrated in figure 34, when fall rains are unusually heavy. Minor amounts of recharge also may occur during midwinter thaws and during unusually wet summers.

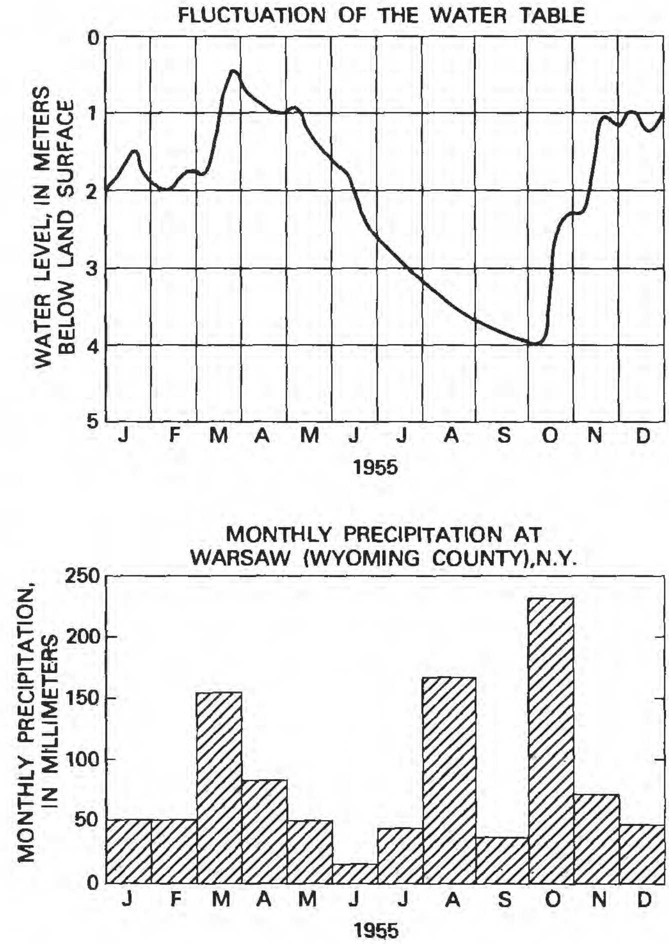


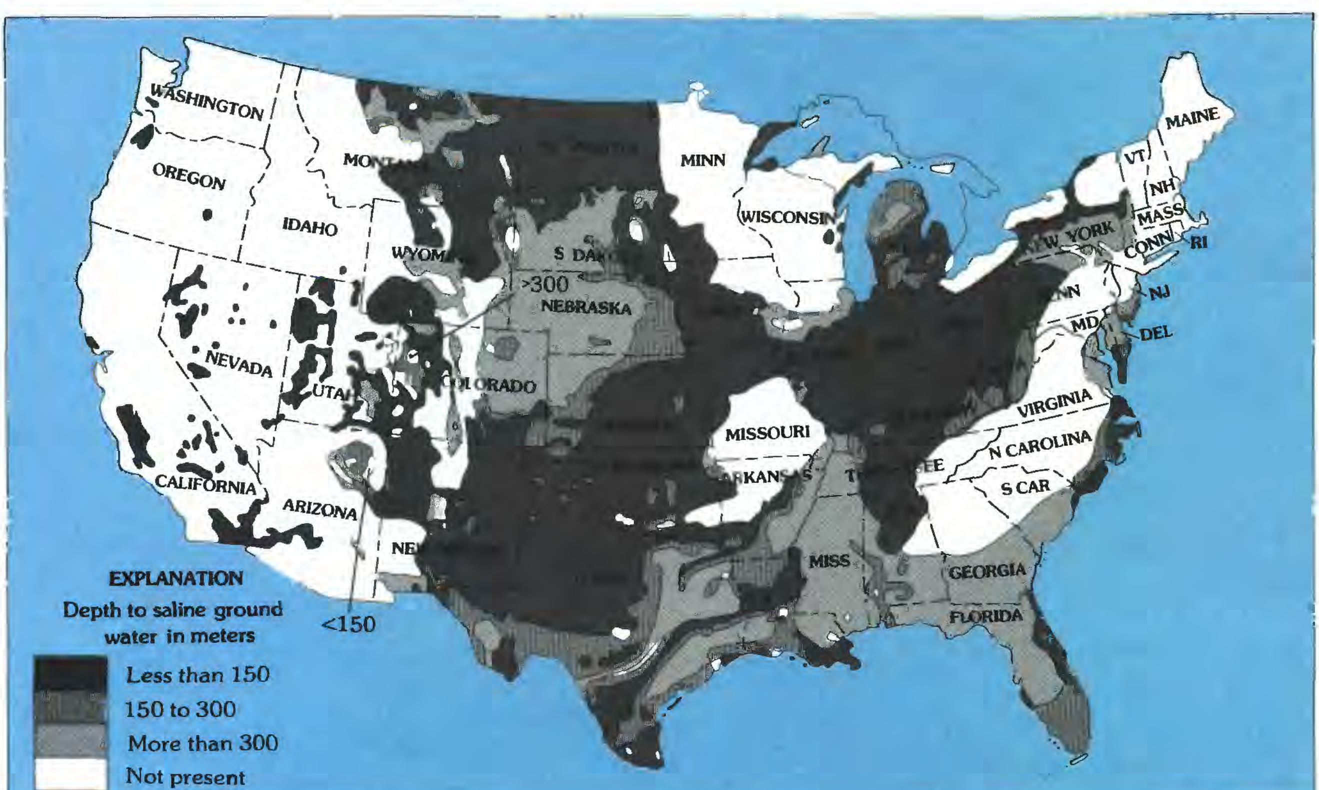
Figure 34. Fluctuation of the water table in glacial deposits in western New York and monthly precipitation at a nearby weather station, 1955.

Ground water in small to moderate amounts can be obtained anyplace in the region, both from the glacial deposits and from the bedrock. Large to very large amounts are obtained from the sand and gravel deposits and from some of the limestones, dolomites, and sandstones in the North-Central States. The shales are the least productive bedrock formations in the region.

Because of the widespread occurrence of limestone and dolomite, water from both the glacial deposits and the bedrock contains as much as several hundred milligrams per liter of dissolved minerals and is moderately hard. Concentrations of iron in excess of 0.3 mg/L is a problem in water from some of the sandstone aquifers in Wisconsin and Illinois and locally in glacial deposits throughout the region. Sulfate in excess of 250 mg/L is a problem in water both from the glacial deposits and from the bedrock in parts of New York, Ohio, Indiana, and Michigan.

As is the case in the Nonglaciated Central region, mineralized water occurs at relatively shallow depth in the bedrock in large parts of this region (fig. 35). Because the principal constituent in the mineralized water is sodium chloride (common salt), the water is commonly referred to as saline or salty. The thickness of the freshwater zone in the bedrock depends on the vertical hydraulic conductivity of both the bedrock and the glacial deposits and on the effectiveness of the hydraulic connection between them. Both the freshwater and the underlying saline water move toward the valleys of perennial streams to discharge. As a result, the depth to saline water is less under valleys than under uplands, both because of lower altitudes and because of the upward movement of the saline water to discharge. In those parts of the region underlain by saline water, the concentration of dissolved solids increases with depth. At depths of 500 to 1,000 m in much of the region, the mineral content of the water approaches that of seawater (about 35,000 mg/L). At greater depths, the mineral content may reach concentrations several times that of seawater.

Because the Glaciated Central region resembles in certain aspects both the Nonglaciated Central region (region 6) to the south and the Northwest and Superior Uplands region (region 9) to the north, it may be useful to comment on the principal differences among these three regions. First, and as is already apparent, the bedrock in the Glaciated Central and the Nonglaciated Central regions is similar in composition and structure. The difference in these two regions is in the composition and other characteristics of the overlying unconsolidated material. In the Nonglaciated Central region this material consists of a relatively thin layer that is derived from weathering of the underlying bedrock and that in any particular area is of relatively uniform composition. In the Glaciated Central region, on the other hand, the unconsolidated material consists of a layer, ranging in thickness from a few meters to several hundred meters, of diverse composition deposited either directly from glacial ice (till) or by meltwater streams (glaciofluvial deposits). From a hydrologic standpoint, the unconsolidated material in the Nonglaciated Central region is of minor importance both as a source of water and as a reservoir for storage of water for the bedrock. In contrast, the glacial deposits in the Glaciated Central region serve both as a source of ground water and as an important storage



Todd, Groundwater Hydrology, 2nd Ed., 1980

APPROXIMATE
0 200 400 600 MILES
0 200 400 600 KILOMETERS

Figure 35. Depth to saline ground water in the conterminous United States. (From Feth and others, 1965.)

reservoir for the bedrock.

The Glaciated Central region and the Northeast and Superior Uplands region are similar in that the unconsolidated material in both consists of glacial deposits. However, the bedrock in the two regions is different. The bedrock in the Glaciated Central region, as we have already seen, consists of consolidated sedimentary rocks that contain both steeply dipping fractures and fractures along bedding planes. In the Northeast and Superior Uplands, on the other hand, the bedrock is composed of intrusive igneous and metamorphic rocks (nonbedded) in which most water-bearing openings are steeply-dipping fractures. As a result of the differences in fractures, the bedrock in the Glaciated Central region is, in general, a more productive and more important source of ground water than the bedrock in the Northeast and Superior Uplands region.

8. PIEDMONT BLUE RIDGE REGION

(Thick regolith over fractured crystalline and metamorphosed sedimentary rocks)

The Piedmont and Blue Ridge region is an area of about 247,000 km^2 extending from Alabama on the south to Pennsylvania on the north. The Piedmont part of the region consists of low, rounded hills and long, rolling, northeast-southwest tranding ridges whose summits range from about a hundred meters above sea level along its eastern boundary with the Coastal Plain to 500 to 600 m along its boundary with the Blue Ridge area to the west. The Blue Ridge is mountainous and includes the highest peaks east of the Mississippi. The mountains, some of which reach altitudes of more than 2,000 m, have smooth-rounded outlines and are bordered by well-graded streams flowing in relatively narrow valleys.

The Piedmont and Blue Ridge region is underlain by bedrock of Precambrian and Paleozoic age consisting of igneous and metamorphosed igneous and sedimentary rocks. These include granite, gneiss, schist, quartzite, slate, marble, and phyllite. The land surface in the Piedmont and Blue Ridge is underlain by clay-rich, unconsolidated material derived from in situ weathering of the underlying bedrock. This material, which averages about 10 to 20 m in thickness and may be as much as 100 m thick on some ridges, is referred to as saprolite. In many valleys, especially those of larger streams, flood plains are underlain by thin, moderately well-sorted alluvium deposited by the streams. When the distinction between saprolite and alluvium is not important, the term regolith is used to refer to the layer of unconsolidated deposits.

The regolith contains water in pore spaces between rock particles. The bedrock, on the other hand, does not have any significant intergranular porosity. It contains water, instead, in sheetlike openings formed along fractures (that is, breaks in the otherwise "solid" rock) (fig. 36). The hydraulic conductivities of the regolith and the bedrock are similar and range from about 0.001 to 1 m day^{-1}. The major difference in their water-bearing characteristics is their porosities, that of regolith being about 20 to 30 percent and that of the bedrock about 0.01 to 2 percent (fig. 37). Small supplies of water adequate for domestic needs can be obtained from the regolith through large-diameter bored or dug wells. However, most wells, especially those where moderate supplies of water are needed, are relatively small in diameter and are cased through the regolith and finished with open holes in the bedrock. Although, as noted, the hydraulic conductivity of the bedrock is similar to that of the regolith, bedrock wells generally have much larger yields than regolith wells because, being deeper, they have a much larger available drawdown.

All ground-water systems function both as reservoirs that store water and as pipelines (or conduits) that transmit water from recharge areas to discharge areas. The yield of bedrock wells in the Piedmont and Blue Ridge region depends on the number and size of fractures penetrated by the open hole and on the replenishment of the fractures by seepage into them from the overlying regolith. Thus, the ground-water system in this region can be viewed, from the standpoint of ground-water development, as a terrane in which the reservoir and pipeline functions are effectively separated. Because of its larger porosity, the regolith functions as a reservoir which slowly feeds water downward into the fractures in

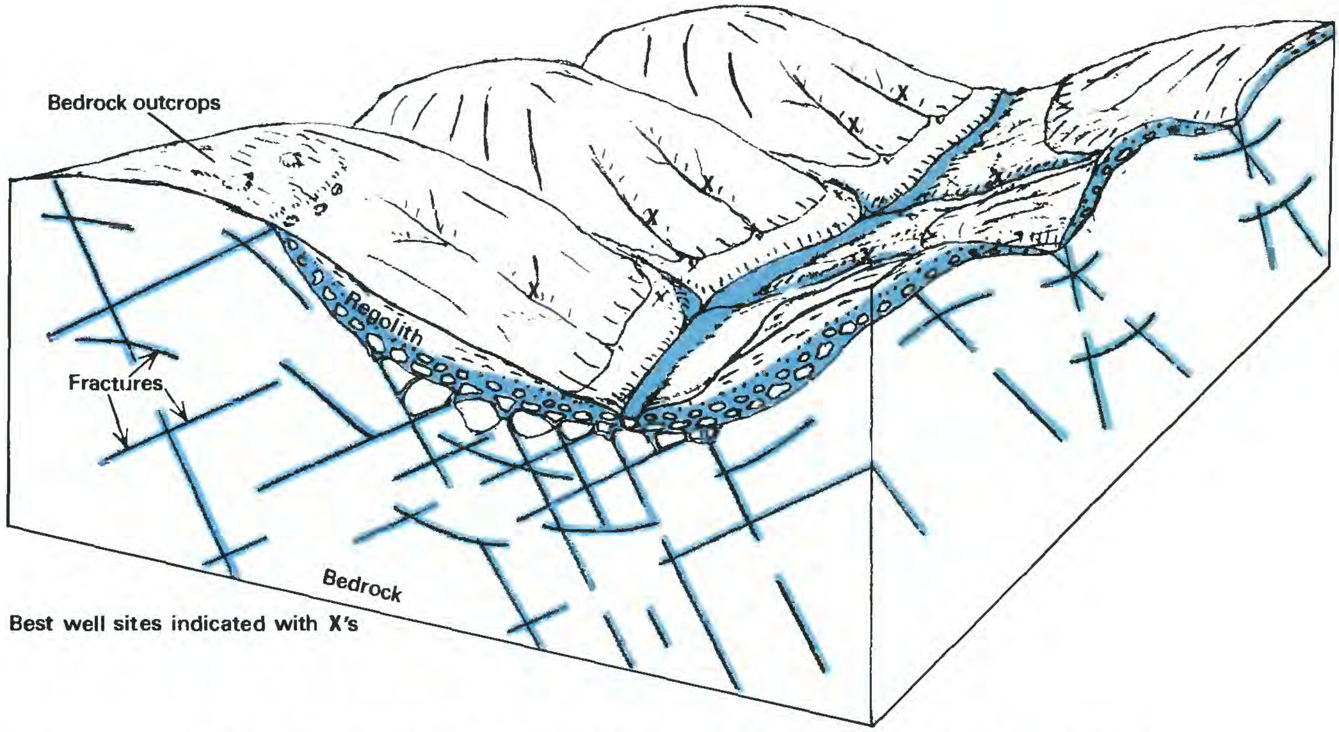


Figure 36. Topographic and geologic features of the Piedmont and Blue Ridge region.

the bedrock. The fractures serve as an intricate interconnected network of pipelines that transmit water either to springs or streams or to wells (fig. 38).

Recharge of the ground-water system occurs on the areas above the flood plains of streams, and natural discharge occurs as seepage springs that are common near the bases of slopes and as seepage into streams. With respect to recharge conditions, it is important to note that forested areas, which include most of the Blue Ridge and much of the Piedmont, have thick and very permeable soils overlain by a thick layer of forest litter. In these areas, even on steep slopes, most of the precipitation seeps into the soil zone, and most of this moves laterally through the soil in a thin, temporary, saturated zone to surface depressions or streams to discharge. The remainder seeps into the regolith below the soil zone, and much of this ultimately seeps into the underlying bedrock.

Because the yield of bedrock wells depends on the number of fractures penetrated by the wells, the key element in selecting well sites is recognizing the relation between the present surface topography and the location of fractures in the bedrock. Most of the valleys, draws, and other surface depressions indicate the presence of more intensely fractured zones in the bedrock which are more susceptible to weathering and erosion than are the intervening areas. Because fractures in the bedrock are the principal avenues along which ground water moves, the best well sites appear to be in draws on the sides of the valleys of perennial streams where the bordering ridges are underlain by substantial thicknesses of regolith (fig. 36). Wells located at such sites seem to be most effective in penetrating open water-bearing fractures and in intercepting ground water draining from the regolith. Chan-

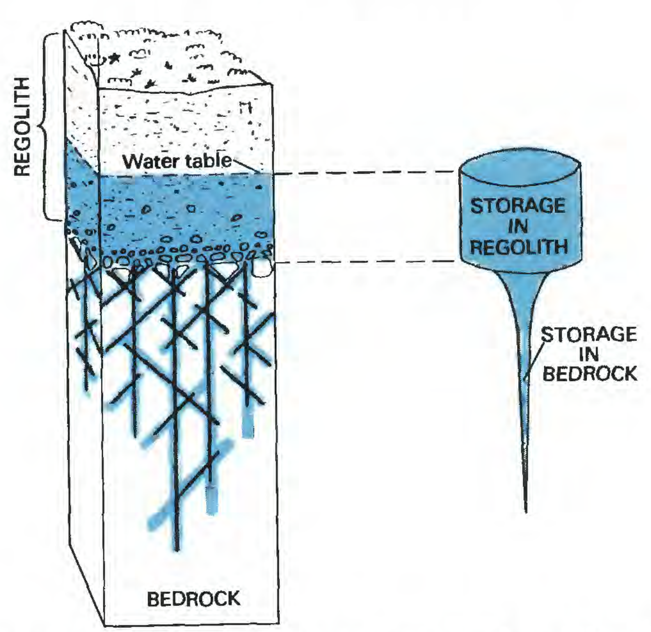


Figure 37. Differences in storage capacity of regolith and bedrock.

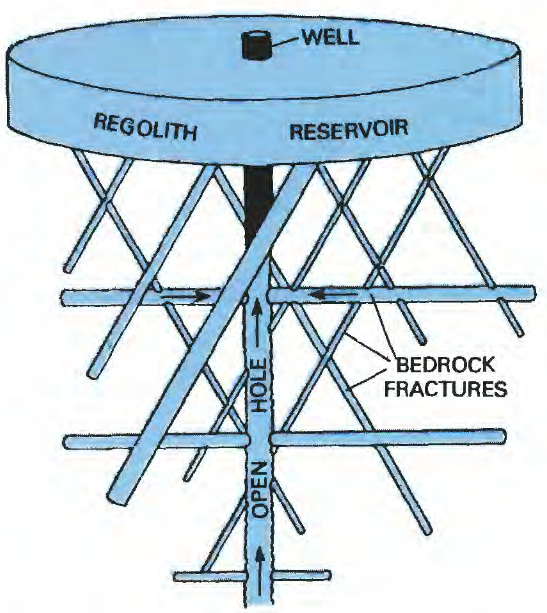


Figure 38. Separation of the storage and pipeline functions in the Piedmont and Blue Ridge region.

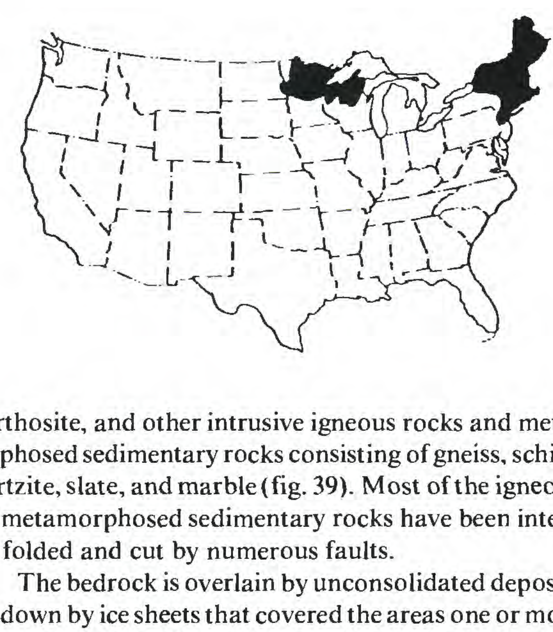
ces of success seem to be somewhat less for wells on the flood plains of perennial streams, possibly because the alluvium obscures the topographic expression of bedrock fractures. The poorest sites for wells are on the tops of ridges and mountains where the regolith cover is thin or absent and the bedrock is sparsely fractured.

As a general rule, fractures near the bedrock surface are most numerous and have the largest openings, so that the yield of most wells is not increased by drilling to depths greater than about 100 m. Exceptions to this occur in Georgia and some other areas where water-bearing, low-angle faults or fractured zones are present at depths as great as 200 to 300 m.

The Piedmont and Blue Ridge region has long been known as an area generally unfavorable for ground-water development. This reputation seems to have resulted both from the small reported yields of the numerous domestic wells in use in the region that were, generally, sited as a matter of convenience and from a failure to apply existing technology to the careful selection of well sites where moderate yields are needed. As water needs in the region increase and as reservoir sites on streams become increasingly more difficult to obtain, it will be necessary to make more intensive use of ground water.

9. NORTHEAST AND SUPERIOR UPLANDS

(Glacial deposits over fractured crystalline rocks)



The Northeast and Superior Uplands region is made up of two separate areas totaling about 415,000 km². The Northeast Upland encompasses the Adirondack Mountains, the Lake Champlain valley, and nearly all of New England. The parts of New England not included are the Cape Cod area and nearby islands, which are included in the Atlantic and Gulf Coastal Plain region, and the Triassic lowland along the Connecticut River in Connecticut and Massachusetts, which is included in the Glaciated Central region. The Superior Upland encompasses most of the northern parts of Minnesota and Wisconsin adjacent to the western end of Lake Superior. The Northeast and Superior Uplands are characterized by rolling hills and low mountains. Land-surface altitudes in the Northeast Upland range from sea level to more than 1,500 m on some of the peaks in the Adirondacks and White Mountains. In contrast to the mountainous areas in the Northeast, the Superior Upland is in an area of rolling hills whose summits reach altitudes of only 300 to 600 m.

Bedrock in the region ranges in age from Precambrian to Paleozoic and consists mostly of granite, syenite, anorthosite, and other intrusive igneous rocks and metamorphosed sedimentary rocks consisting of gneiss, schist, quartzite, slate, and marble (fig. 39). Most of the igneous and metamorphosed sedimentary rocks have been intensely folded and cut by numerous faults.

The bedrock is overlain by unconsolidated deposits laid down by ice sheets that covered the areas one or more times during the Pleistocene (fig. 40) and by gravel, sand, silt, and clay laid down by meltwater streams and in lakes that formed during the melting of the ice (fig. 39). The thickness of the glacial deposits ranges from a few meters on the higher mountains, which also have large expanses of barren rock, to more than 100 m in some valleys. The most extensive glacial deposit is till, which was laid down

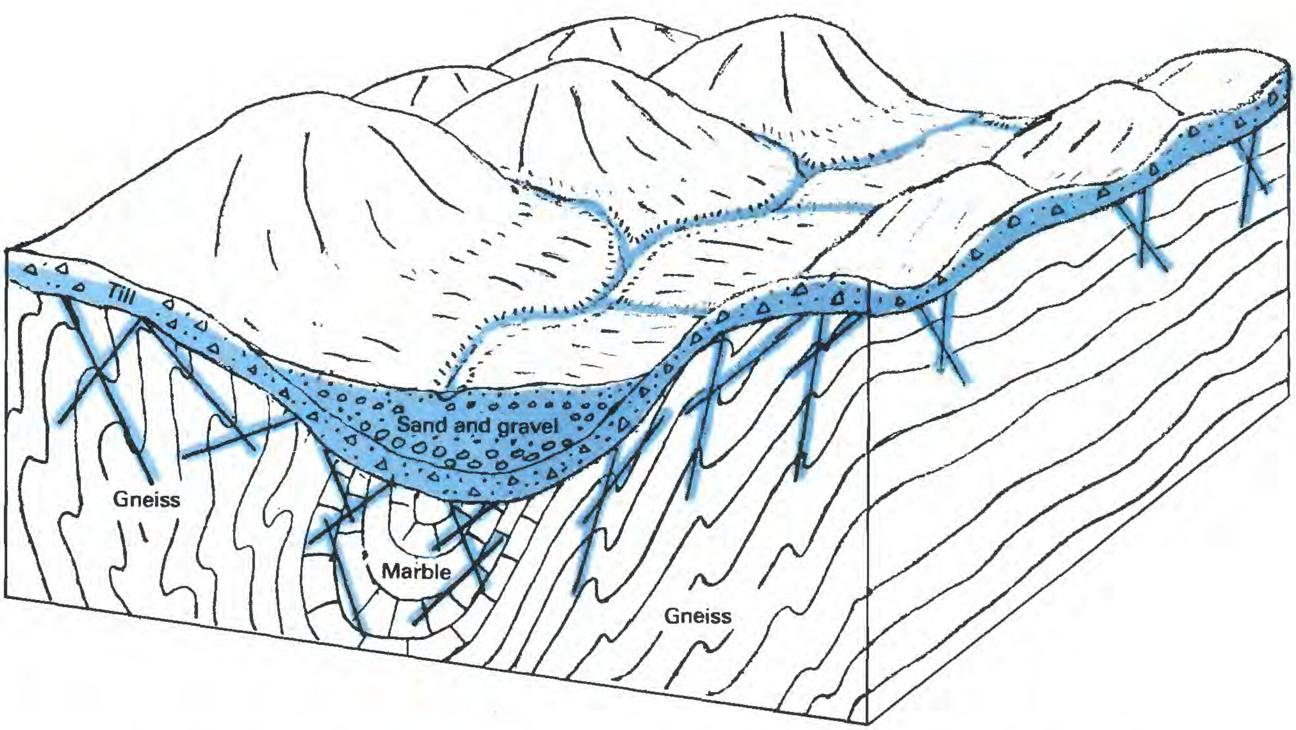


Figure 39. Topographic and geologic features of the Northeast and Superior Uplands region.

as a nearly continuous blanket by the ice, both in valleys and on the uplands. In most of the valleys and other low areas, the till is covered by glacial outwash consisting of interlayered sand and gravel, ranging in thickness from a few meters to more than 20 m, that was deposited by streams supplied by glacial meltwater (fig. 39). In several areas, including parts of the Champlain valley and the lowlands adjacent to Lake Superior, the unconsolidated deposits consist of clay and silt deposited in lakes that formed during the melting of the ice sheets.

Ground-water supplies are obtained in the region from both the glacial deposits and the underlying bedrock. The largest yields come from the sand and gravel deposits, which in parts of the valleys of large streams are as much as 60 m thick. These and other valleys in the United States underlain by thick and productive deposits of sand and gravel are covered in the discussion of the Alluvial Valleys region (region 12). Other sand and gravel deposits, not thick or productive enough to be included in the Alluvial Valleys region, occur locally in most valley and lowland areas in the Northeast and Superior Uplands region and serve as important sources of water.

Water occurs in the bedrock in fractures similar in origin, occurrence, and hydraulic characteristics to those in the Piedmont and Blue Ridge region. In fact, the primary difference in ground-water conditions between the Piedmont and Blue Ridge region and the Northeast and Superior Uplands region is related to the materials that overlie the bedrock. In the Piedmont and Blue Ridge, these consist of unconsolidated material derived from weathering of the underlying bedrock. In the Northeast and Superior Uplands the overlying materials consist of glacial deposits which, having been transported either by ice or by streams, do not have a composition and structure controlled by that of the underlying bedrock. These differences in origin of the regolith between the Northeast and Superior Uplands and the Piedmont and Blue Ridge are an important consideration in the development of water supplies, as is discussed in the following paragraphs.

Recharge from precipitation generally begins in the fall after plant growth stops. It continues intermittently over the winter during thaws and culminates during the period between the spring thaw and the start of the growing season. Precipitation on the Northeast Upland, about 1,200 mm per year, is twice that on the Superior Upland, with the result that recharge, both to the glacial deposits and to the underlying bedrock, is largest in the Northeast. The glacial deposits in the region serve as a storage reservoir for the fractures in the underlying bedrock, in the same way the saprolite functions in the Piedmont and Blue Ridge region. The major difference is that the glacial deposits on hills and other upland areas are much thinner than the saprolite in similar areas in the Piedmont and

Blue Ridge and, therefore, have a much smaller ground-water storage capacity.

Water supplies in the Northeast and Superior Uplands region are obtained from open-hole drilled wells in bedrock, from drilled and screened or open-end wells in sand and gravel, and from large-diameter bored or dug wells in till. The development of water supplies from bedrock, especially in the Superior Upland, is more uncertain than from the fractured rocks in the Piedmont and Blue Ridge region because the ice sheets that advanced across the region removed the upper, more fractured part of the rock and also tended to obscure many of the fracture-caused depressions in the rock surface with the layer of glacial till. Thus, use of surface depressions in this region to select sites of bedrock wells is not as satisfactory as in the Piedmont and Blue Ridge.

Most of the rocks that underlie the Northeast and Superior Uplands are relatively insoluble, and, consequently, the ground water in both the glacial deposits and the bedrock generally contains less than 500 mg/L of dissolved solids. Two of the most significant water-quality problems confronting the region, especially the Northeast Upland section, are acid precipitation and pollution caused by salts used to de-ice highways. Much of the precipitation now falling on the Northeast (in 1982) has a *pH* in the range of 4 to 6 units. Because of the low buffering capacity of the soils derived from the rocks underlying the area, there is relatively little opportunity for the pH to be increased. One of the results of this is the gradual elimination of living organisms from many lakes and streams. The effect on ground-water quality, which will develop much more slowly, has not yet been determined. The second problem—that of de-icing salts—affects ground-water quality adjacent to streets and roads maintained for winter travel.

Figure 40. Glacial features of the United States. (Adapted from U.S. Geological Survey, 1970, p. 76.)

10. ATLANTIC AND GULF COASTAL PLAIN

(Complexly interbedded sand, silt, and clay)

The Atlantic and Gulf Coastal Plain region is an area of about 844,000 km^2 extending from Cape Cod, Mass., on the north to the Rio Grande in Texas on the south. This region does not include Florida and parts of the adjacent States; although those areas are a part of the Atlantic and Gulf Coastal Plain physiographic province, they together form a separate ground-water region. (See region 11, "Southeast Coastal Plain.")

The Atlantic and Gulf Coastal Plain region ranges in width from a few kilometers near its northern end to nearly a thousand kilometers in the vicinity of the Mississippi River. The great width near the Mississippi reflects the effect of a major downwarped zone in the Earth's crust that extends from the Gulf of Mexico to about the confluence of the Mississippi and Ohio Rivers (fig. 29). This area is referred to as the Mississippi embayment.

The topography of the region ranges from extensive, flat, coastal swamps and marshes 1 to 2 m above sea level to rolling uplands, 100 to 250 m above sea level, along the inner margin of the region.

The region is underlain by unconsolidated sediments that consist principally of sand, silt, and clay transported by streams from the adjoining uplands. These sediments, which range in age from Jurassic to the present, range in thickness from less than a meter near the inner edge of the region to more than 12,000 m in southern Louisiana. The greatest thicknesses are along the seaward edge of the region and along the axis of the Mississippi embayment. The sediments were deposited on floodplains and as deltas where streams reached the coast and, during different invasions of the region by the sea, were reworked by waves and ocean currents. Thus, the sediments are complexly interbedded to the extent that most of the named geologic units into which they have been divided contain layers of the different types of sediment that underlie the region. These named geologic units (or formations) dip toward the coast or toward the axis of the Mississippi embayment, with the result that those that crop out at the surface form a series of bands roughly parallel to the coast or to the axis of the embayment (fig. 41). The oldest formations crop out along the inner margin of the region, and the youngest crop out in the coastal area.

Within any formation the coarsest grained materials (sand, at places interbedded with thin gravel layers) tend to be most abundant near source areas. Clay and silt layers become thicker and more numerous downdip (fig. 41).

Although sand, silt, and clay, as noted above, are the principal types of material underlying the Atlantic and Gulf Coastal Plain, there are also a small amount of gravel interbedded with the sand, a few beds composed of mollusk shells, and a small amount of limestone present in the region. The most important limestone is the semiconsolidated Castle Hayne Limestone of Eocene age which underlies an area of about 26,000 km^2 in eastern North Carolina, is more than 200 m thick in much of the area, and is the most productive aquifer in North Carolina. A soft, clayey limestone (the chalk of the Selma Group) of Late Cretaceous age underlies parts of eastern Mississippi and western Alabama, but instead of being an aquifer it is an important confining bed.

From the standpoint of well yields and ground-water use, the Atlantic and Gulf Coastal Plain is one of the most important regions in the country. Recharge to the ground-water system occurs in the interstream areas, both where sand layers crop out and by percolation downward across the interbedded clay and silt layers. Discharge from the system occurs by seepage to streams, estuaries, and the ocean. Movement of water from recharge areas to discharge areas is controlled, as in all ground-water systems, by hydraulic gradients, but in this region the pattern of movement is complicated by downdip thickening of clay which hampers upward discharge. As a result, movement down the dip of the permeable layers becomes increasingly slow with increasing distance from the outcrop areas. This causes many flow lines to converge on the discharge areas located on major streams near the downdip part of outcrop areas. These areas of concentrated ground-water discharge are referred to as "artesian-water gaps" by LeGrand and Pettyjohn (1981). Figure 42 illustrates the effect of an artesian-water gap on heads and flow lines in an ideal situation.

Wells that yield moderate to large quantities of water can be constructed almost anywhere in the region. Because most of the aquifers consist of unconsolidated sand, wells require screens; where the sand is fine-grained and well sorted, the common practice is to surround the screens with a coarse sand or gravel envelope.

Withdrawals near the outcrop areas of aquifers are rather quickly balanced by increases in recharge and (or) reductions in natural discharge. Withdrawals at signifi-

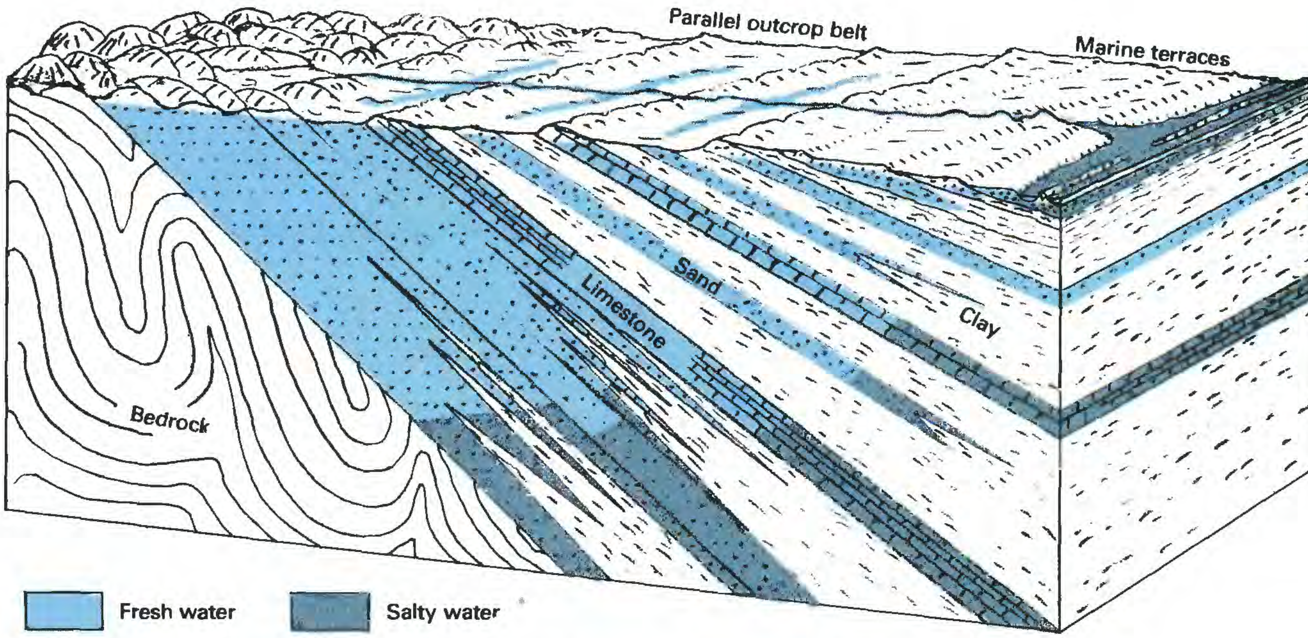


Figure 41. Topographic and geologic features of the Gulf Coastal Plain.

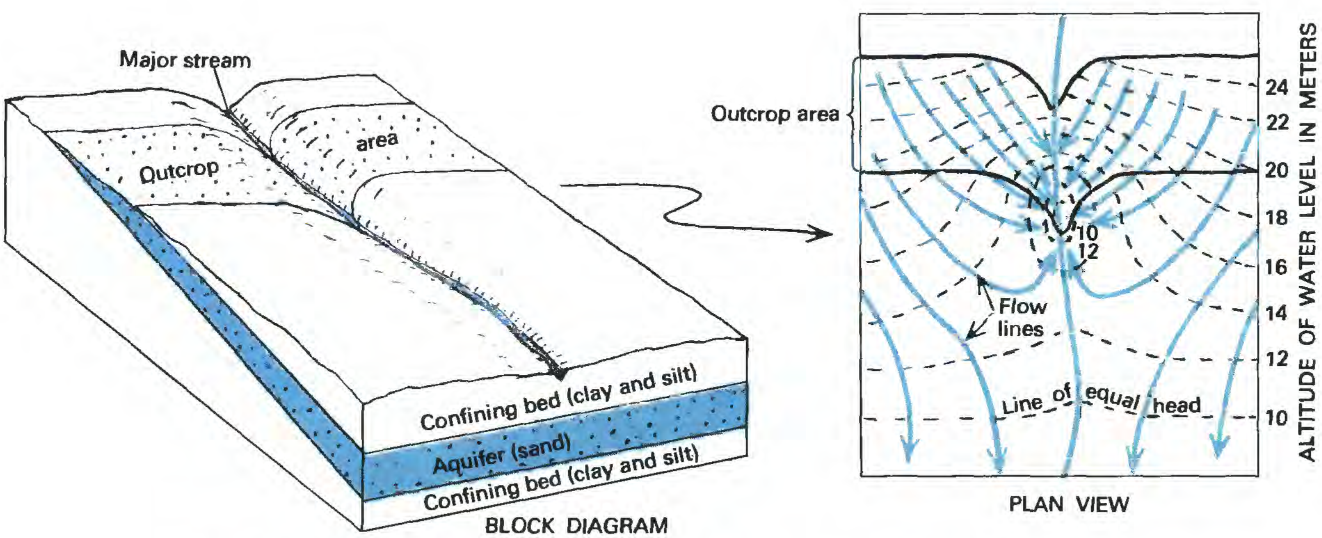


Figure 42. Concentration of ground-water discharge near the downdip part of outcrop areas.

cant distances downdip do not appreciably affect conditions in the outcrop area and thus must be partly or largely supplied from water in storage in the aquifers and confining beds.

The reduction of storage in an aquifer in the vicinity of a pumping well is reflected in a decline in ground-water levels and is necessary in order to establish a hydraulic gradient toward the well. If withdrawals are continued for long periods in areas underlain by thick sequences of unconsolidated deposits, such as the Atlantic and Gulf Coastal Plain, the lowered ground-water levels in the aquifer may result in drainage of water from layers of silt and clay. The depletion of storage in fine-grained beds results in subsidence of the land surface. Subsidence in parts of the Houston area totaled about 9 m as of 1978. Subsidence near pumping centers in the Atlantic Coastal Plain has not yet been confirmed but is believed to be occurring, though at a slower rate than along the Texas Gulf Coast.

The depletion of storage in confining beds is permanent, and subsidence of the land surface that results from such depletion is also permanent. On the other hand, depletion of storage in aquifers may not be fully permanent, depending on the availability of recharge. In arid and semiarid regions, recharge rates are extremely small, and depletion of aquifer storage is, for practical purposes, permanent. Depletion of storage in aquifers in these regions is referred to as *mining*. In humid regions, recharge is sufficient to replace aquifer storage rather quickly, once withdrawals are stopped, so that depletion of aquifer storage in these areas is not considered to be mining. The important point is that depletion of storage in the confining layers of silt and clay in both arid and humid regions is permanent but is not normally considered to be ground-water mining. The term "mining" is applied by most ground-water hydrologists only to areas in which aquifer storage is being permanently depleted.

Depletion of storage in the aquifers underlying large areas of the Atlantic and Gulf Coastal Plain is reflected in long-term declines in ground-water levels (fig. 43). These declines suggest that withdrawals in these areas are exceeding the long-term yield of the aquifers.

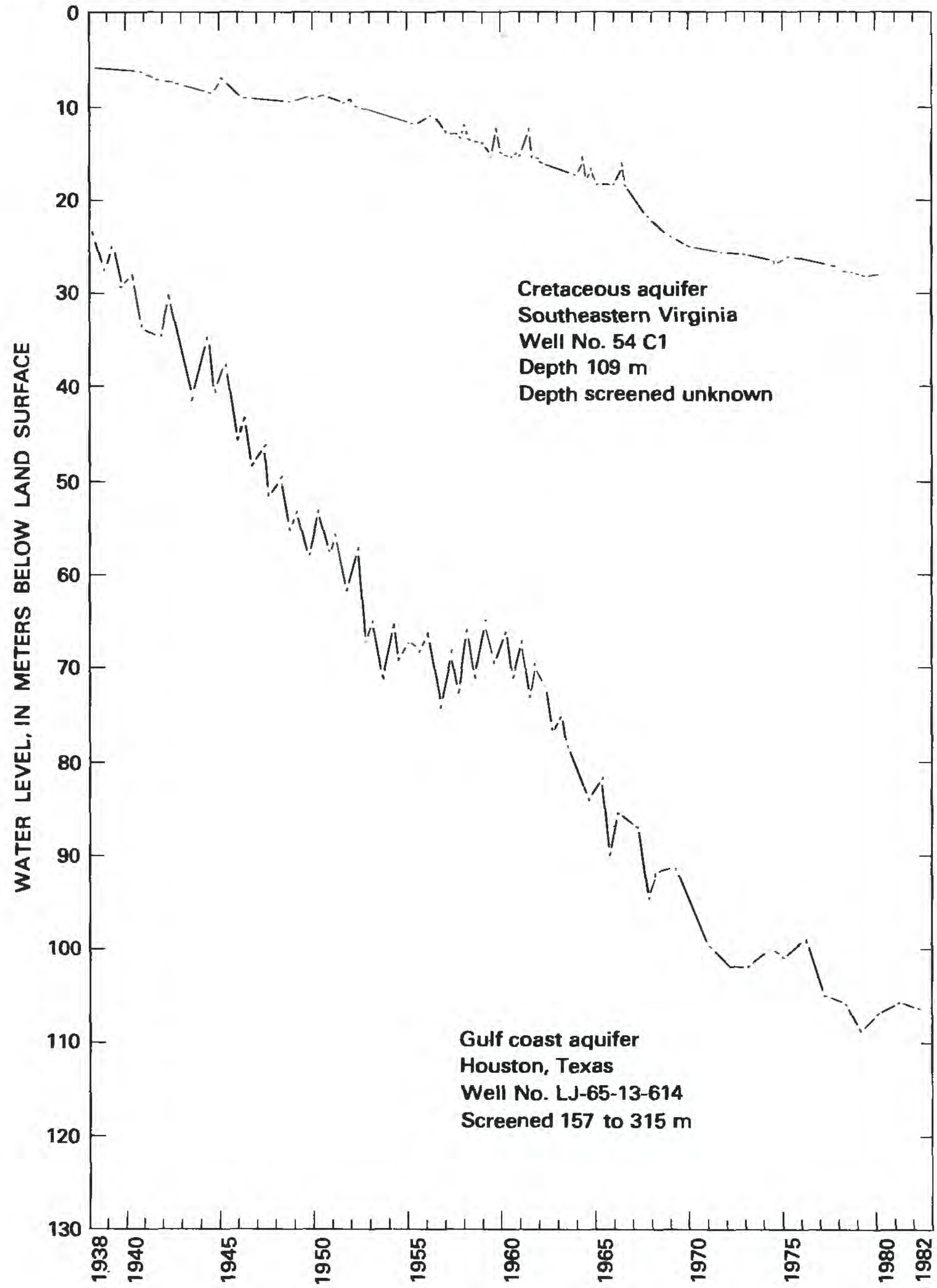


Figure 43. Long-term decline of ground-water levels in the Atlantic and Gulf Coastal Plain.

This is a water-management problem that will become more important as rates of withdrawal and the lowering of water levels increase. Solutions to this problem include (1) concentrating withdrawals as close as possible to outcrop (recharge) areas, (2) dispersing withdrawals in regions remote from the outcrop areas over the widest possible area, and (3) increasing withdrawals from surficial aquifers to the maximum possible extent.

Another problem that affects ground-water development in the region concerns the presence of saline water in the deeper parts of most aquifers. The occurrence of saline water is controlled by the circulation of freshwater which, as noted previously, becomes increasingly slow down the dip of the aquifers. Thus, in some of the deeper aquifers, the interface between freshwater and saltwater is inshore, but in parts of the region, including parts of Long Island, New Jersey, and Mississippi, the interface in the most intensively developed aquifers is a significant distance offshore. Pumping near the interfaces has resulted in problems of saltwater encroachment locally.

Another significant feature of the ground-water system in this region is the presence of "geopressured" zones at depths of 1,800 to 6,100 m in Texas and Louisiana which contain water at a temperature of 80°C to more than 273°C. Water in these zones contains significant concentrations of natural gas, and the water in some zones is under pressures sufficient to support a column of water more than 4,000 m above land surface. Because the elevated temperature, natural gas, and high pressures are all potential energy sources, these zones are under intensive investigation.

11. SOUTHEAST COASTAL PLAIN

(Thick layers of sand and clay over semi-consolidated carbonate rocks)

The Southeast Coastal Plain is an area of about 212,000 km^2 in Alabama, Florida, Georgia, and South Carolina (fig. 44). It is a relatively flat, low-lying area in which altitudes range from sea level at the coast to about 100 m down the center of the Florida peninsula and as much as 200 m on hills in Georgia near the interior boundary of the region. Much of the area, including the Everglades in southern Florida, is a nearly flat plain less than 10 m above sea level.

The land surface of the Southeast Coastal Plain is underlain by unconsolidated deposits of Pleistocene age consisting of sand, gravel, clay, and shell beds and, in southeastern Florida, by semiconsolidated limestone. From the coast up to altitudes of nearly 100 m, the surficial deposits are associated with marine terraces formed when the Coastal Plain was inundated at different times by the sea. In most of the region the surficial deposits rest on formations, primarily of middle to late Miocene age, composed of interbedded clay, sand, and limestone. The most extensive Miocene deposit is the Hawthorn Formation (fig. 45). The formations of middle to late Miocene age and, where those formations are absent, the surficial deposits overlie semiconsolidated limestones and dolomites that are as much as 1,500 m thick. These carbonate rocks range in age from early Miocene to Paleocene and are generally referred to collectively as Tertiary limestones.

The Tertiary limestone that underlies the Southeast Coastal Plain constitutes one of the most productive aquifers in the United States and is the feature that justifies treatment of the region separately from the remainder of the Atlantic and Gulf Coastal Plain. The aquifer, which is known as the Floridan aquifer, underlies all of Florida and southeast Georgia and small areas in Alabama and South Carolina. The Floridan aquifer consists of layers several meters thick composed largely of loose aggregations of shells of foraminifers and fragments of echinoids and other marine organisms interbedded with much thinner layers of cemented and cherty limestone. The Floridan, one of the most productive aquifers in the world, is the principal source of ground-water supplies in the Southeast Coastal Plain region.

In southern Florida, south of Lake Okeechobee, and in a belt about 30 km wide northward along the east coast of Florida to the vicinity of St. Augustine, the water in the Floridan aquifer contains more than 100 mg/L of chloride. In this area, most water supplies are obtained from surficial aquifers, the most notable of which under-

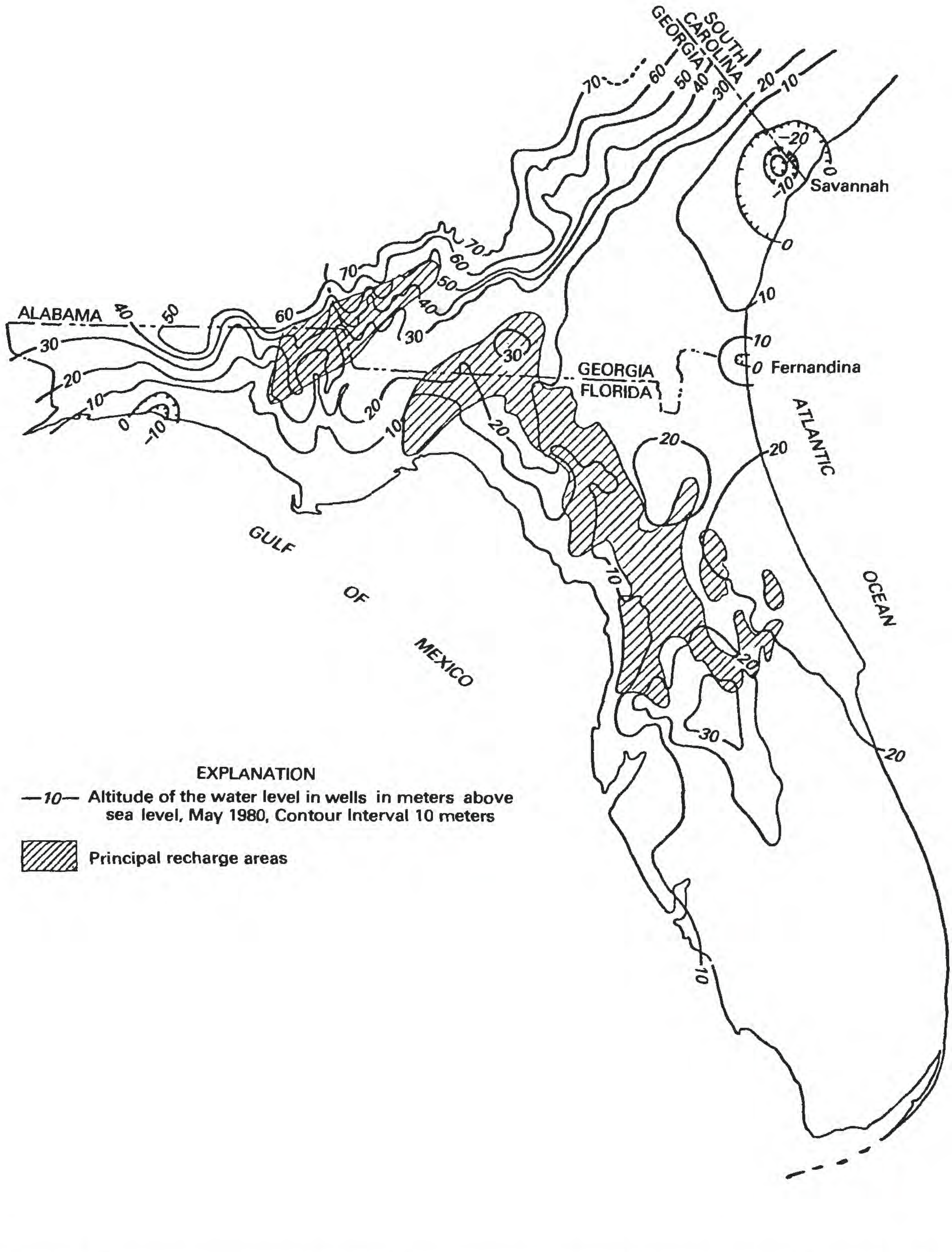


Figure 44. Potentiometric surface for the Floridan aquifer. (Adapted from Johnston, Healy, and Hayes, 1981.)

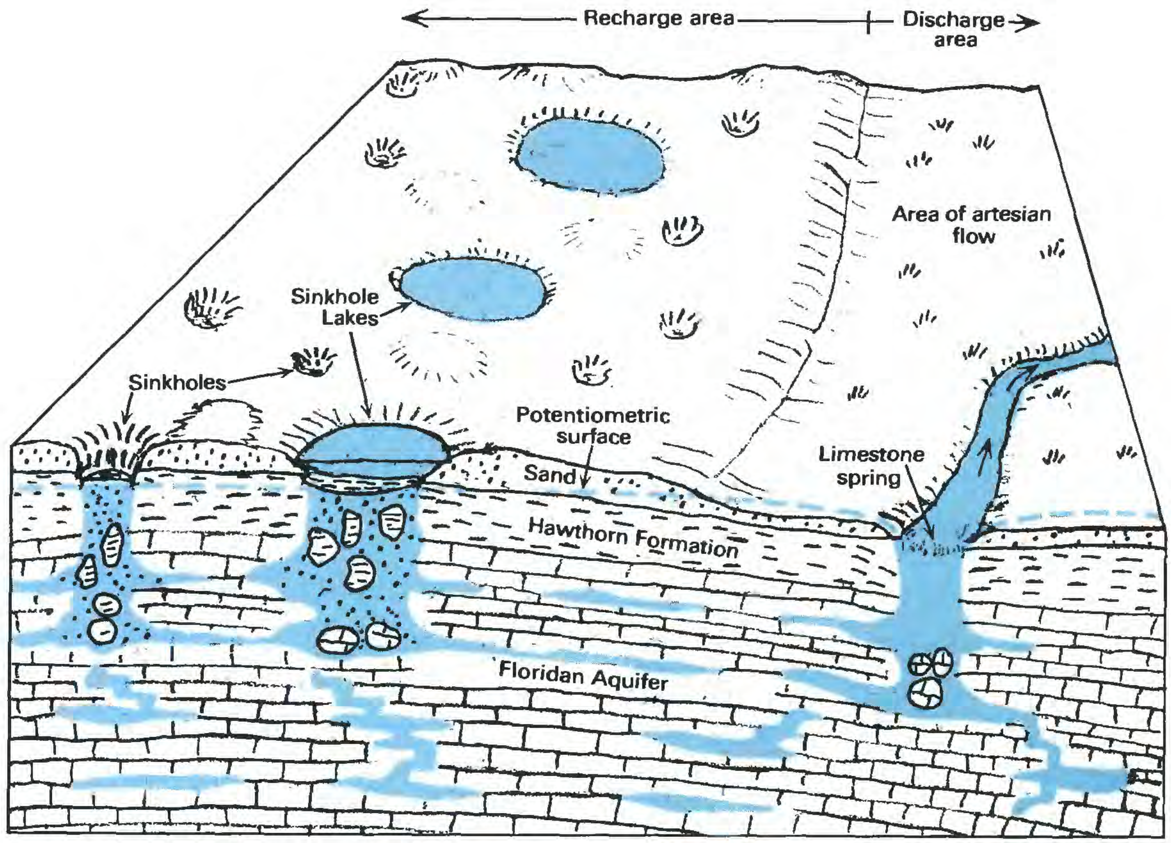


Figure 45. Topographic and geologic features of the Southeast Coastal Plain region.

lies the southeastern part of Florida and which in the Miami area consists of 30 to 100 m of cavernous limestone and sand referred to as the Biscayne aquifer. The Biscayne is an unconfined aquifer which is recharged by local precipitation and by infiltration of water from canals that drain water from impoundments (conservation areas) developed in the Everglades. It is the principal source of water for municipal, industrial, and irrigation uses and can yield as much as $5 m^3 min^{-1}$ (1,300 gal min^{-1}) to small-diameter wells less than 25 m deep finished with open holes only 1 to 2 m in length.

The surficial aquifers in the remainder of the region are composed primarily of sand, except in the coastal zones of Florida where the sand is interbedded with shells and thin limestones. These surficial aquifers serve as sources of small ground-water supplies throughout the region and are the primary sources of ground water where the water in the Floridan aquifer contains more than about 250 mg/L of chloride.

The Floridan aquifer, as noted above, is the principal source of ground water in the region. Ground water in the upper part of the aquifer is unconfined in the principal recharge areas in Georgia and in west-central Florida (fig. 44). In the remainder of the region, water in the aquifer is confined by clay in the Hawthorn Formation and in other beds that overlie the aquifer. Figure 44 shows the *potentiometric surface* of the Floridan aquifer. The contour lines on the map show the altitude, in meters above sea level, at which the water level stood in May 1980 in wells open to the aquifer. This map is an invaluable aid in the identification of recharge and natural discharge areas and in determining the effect of large withdrawals through wells. The principal recharge areas, as identified from the potentiometric-surface map and geologic data, are also shown in figure 44.

Recharge occurs where the potentiometric surface of the Floridan aquifer is lower than the water table in the overlying surficial aquifer. The principal recharge areas include a broad area along the west side of Florida extending from the central part of the peninsula to south-central Georgia and an area extending from west-central Florida through southeast Alabama into southwest Georgia (fig. 44). In these areas, recharge rates are estimated to exceed 120 mm yr^{-1}(5 in. yr^{-1}). Recharge occurs by infiltration of precipitation directly into the limestone, where it is exposed at the land surface, and by seepage through the permeable soils that partly mantle the limestone in the outcrop areas. Considerable recharge also occurs in the higher parts of the recharge areas through permeable openings in the confining beds, where these beds have been breached by the collapse of caverns in the limestone during the process of sinkhole formation (fig. 45). Thus, the land surface in most of Florida north of Lake Okeechobee is marked by thousands of closed depressions ranging in diameter from a few meters to several kilometers. The larger depressions, which represent a more advanced stage of solution of the limestone and collapse of the overlying material, are occupied by lakes generally referred to as sinkhole lakes.

Discharge from the Floridan aquifer occurs through springs and by seepage to streams. Considerable discharge also occurs by diffuse seepage across the overlying confining beds in areas where the potentiometric surface of the aquifer stands at a higher altitude than the water table. In most of these areas, which include the southern third of the Florida peninsula, the east coast area and major stream valleys of Florida, and the coastal zone and major stream valleys of Georgia and South Carolina, wells open to the aquifer will flow at the land surface. Such wells are called "flowing artesian wells." The most spectacular discharge from the Floridan aquifer is through sinkholes exposed along streams and offshore. Florida has 27 springs of the first magnitude at which the average discharge exceeds 2.83 m^3sec^{-1} (100 ft^3sec^{-1}). The largest is Silver Springs, which has an average discharge of 23.2 m^3sec^{-1} (530 million gallons per day) and reached a maximum discharge of 36.5 m^3sec^{-1} on September 28, 1960. Heath and Conover (1981) estimate that the combined discharge from Florida's springs is 357 m^3sec^{-1} (8 billion gallons per day).

Water supplies are obtained from the Floridan aquifer by installing casing through the overlying formations and drilling an open hole in the limestones and dolomites comprising the aquifer. Total withdrawals from the aquifer are estimated to have been about 13×10^6 m^3day^{-1} (3.5 billion gallons per day) in 1978. Large withdrawals also occur from the other aquifers in the region. For example, in 1975 withdrawals for public water supplies in Florida from the Biscayne and other aquifers overlying the Floridan amounted to 2.1×10^6 m^3day^{-1}.

The marked difference in ground-water conditions between the Southeast Coastal Plain and the Atlantic and Gulf Coastal Plain regions is apparent in the response of ground-water levels to withdrawals. In the Atlantic and Gulf region most large withdrawals are accompanied by a pronounced continuing decline in ground-water levels. In the Southeast Coastal Plain, on the other hand, large withdrawals have significantly lowered ground-water levels in only a few areas. The most prominent of these, as shown on figure 44, are in the Savannah area of Georgia and in the Fernandina area near the Florida-Georgia state line.

12. ALLUVIAL VALLEYS

(Thick sand and gravel deposits beneath floodplains and terraces of streams)

In the preceding discussions of ground-water regions, streams and other bodies of surface water were mentioned as places of ground-water discharge. In most areas, ground-water systems and surface streams form a water system so intimately interconnected that a change in one causes a change in the other. For example, withdrawals from ground-water systems reduce discharge to streams and thereby reduce streamflow. If the withdrawals occur near a stream, the hydraulic gradient, which under normal conditions is toward the stream, may be reversed, causing water to move from the stream into the ground-water system. The movement of water from streams into ground-water systems in response to withdrawals, although possible wherever streams receive ground-water discharge under natural conditions, is not a significant feature in most areas because ground-water withdrawals are dispersed over the uplands between streams rather than concentrated near them. An exception to this occurs where stream channels and floodplains are underlain by highly permeable deposits of sand and gravel. The large yields of these deposits, as well as the variability and availability of streamflow, encourage the development of these sand and gravel deposits as sources of ground water and thus encourage the concentration of withdrawals near streams.

Some authors include valleys underlain by productive deposits of sand and gravel in their discussions of the regions in which the valleys occur. However, because these valleys form a distinct ground-water terrane, it is less repetitious and more effective to discuss them as a group. These valleys are referred to in this discussion as alluvial valleys because the sand and gravel, and other associated sediments, were deposited by streams. Such valleys are particularly prevalent in the area covered by ice sheets during the Pleistocene. They also occur in the valleys of the Mississippi River and other streams that received sediment-laden meltwater from the ice sheets or from mountain glaciers that existed during the Pleistocene. The most important alluvial valleys are shown in figure 46. The relation of these valleys to Pleistocene glaciation can be seen by comparing figure 46 and figure 40, which shows areas underlain by glacial deposits.

From the standpoint of ground-water hydrology, three criteria are used to differentiate alluvial valleys from other valleys. These criteria are as follows:

1. The valleys contain sand and gravel deposits thick enough to supply water to wells at moderate to large rates. [Commonly, the water-transmitting capacity of the sand and gravel is at least 10 times larger than that of the adjacent (enclosing) rocks.]
2. The sand and gravel deposits are in hydraulic contact with a perennial stream which serves as a source of recharge and whose flow normally far exceeds the demand from any typical well field.
3. The sand and gravel deposit occurs in a clearly defined band ("channel") that normally does not extend beyond the floodplain and adjacent terraces. (In other words, the width of the deposit is small or very small compared with its length.)

According to these criteria, the valleys of streams that were not affected by glacial meltwater, such as those of the streams that originate in the southern Appalachian Mountains and flow to the Atlantic Ocean or the Gulf of Mexico, are not considered alluvial valleys. The floodplains in these valleys are commonly underlain only by thin deposits of fine-grained alluvium. These criteria also eliminate the "buried" valleys of the glaciated area. The buried valleys, which are relatively common in the North-Central States, contain sand and gravel deposits in well-defined channels that were cut by preglacial streams.

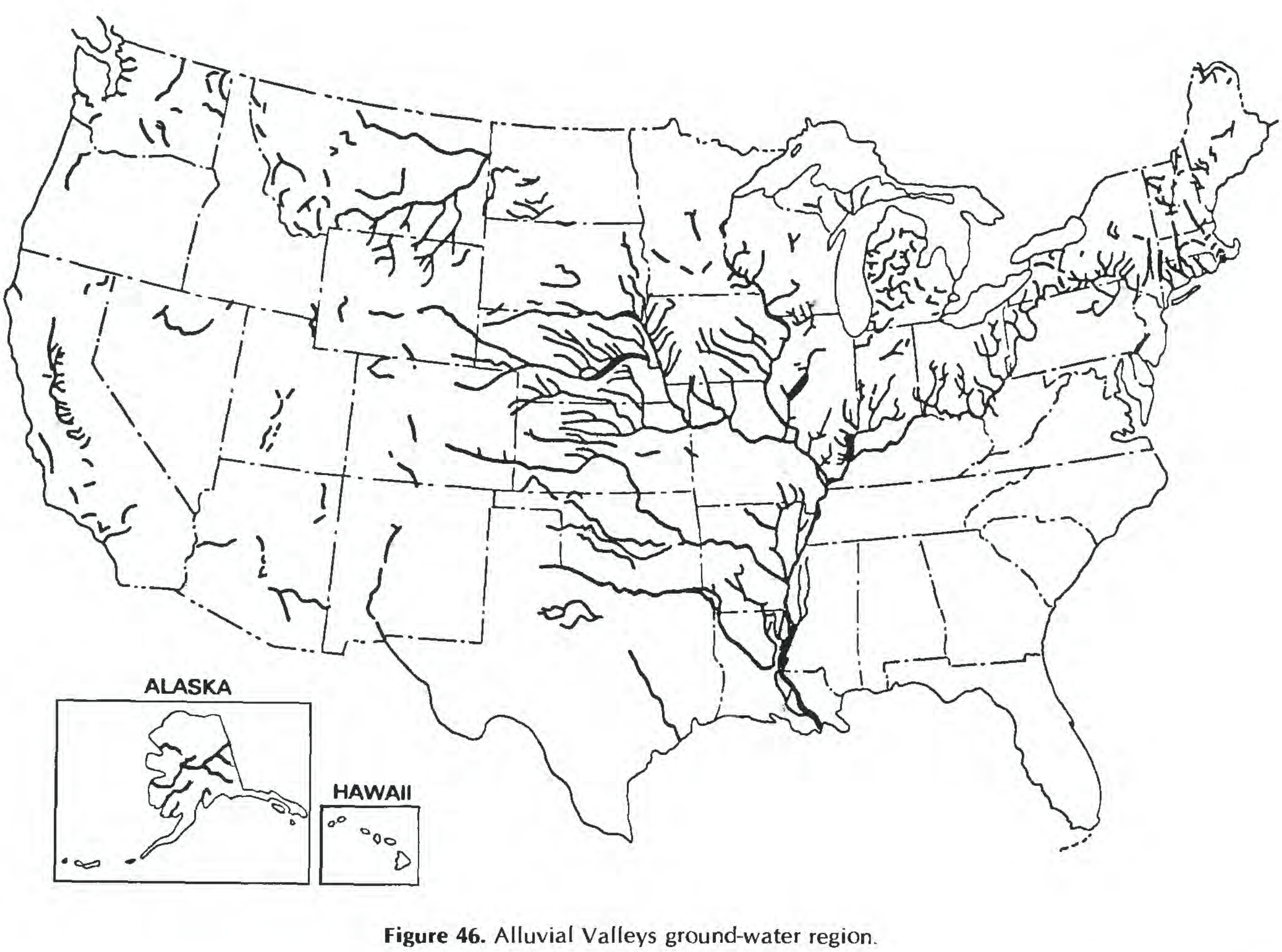


Figure 46. Alluvial Valleys ground-water region.

However, during the advance and retreat of the ice sheets the valleys were filled by less permeable glacial deposits so that they are no longer identifiable from the land surface. Thus, these valleys are said to be "buried." Although the water-transmitting capacity of the sand and gravel in these valleys may be large, the yield to wells in most of them is small because of the limited opportunity for recharge through the surrounding, less-permeable materials.

The alluvial valleys are commonly underlain, in addition to sand and gravel, by deposits of silt and clay. In many of the glaciated valleys in New York and New England the land surface is underlain by a layer of sand and gravel that ranges in thickness from 1 to 2 m to more than 10 m. The bottom of this deposit ranges, from one part of a valley to another, from a position above the water table to several meters below the bottom of streams. This surficial deposit of sand and gravel is commonly underlain by interbedded silt and clay which is, in turn, underlain by a discontinuous "basal" layer of sand and gravel.

The sequence of deposits in the alluvial valleys depends, of course, on the history of deposition in the valleys. The sand and gravel in the valleys of major streams, such as those of the Mississippi (fig. 47), Missouri, and Ohio, are commonly overlain by deposits of clay and other fine-grained alluvium deposited during floods since the end of the glacial period.

Under natural conditions the alluvial deposits are recharged by precipitation on the valleys, by ground water moving from the adjacent and underlying aquifers, by overbank flooding of the streams, and, in some glacial valleys, by infiltration from tributary streams. Water in the alluvial deposits discharges to the streams in the valleys.

The layers of sand and gravel in the alluvial valleys are among the most productive aquifers in the country. They have been extensively developed as sources of water for municipalities, industries, and irrigation. Some of the gravel layers, particularly in the Mississippi, Ohio, and Mohawk River valleys, have hydraulic conductivities nearly as large as those of cavernous limestone. The large yields of the sand and gravel depend not only on their large water-transmitting capacity but also on their hydraulic connection to the streams flowing in the valleys. Large withdrawals from the deposits result in a reduction

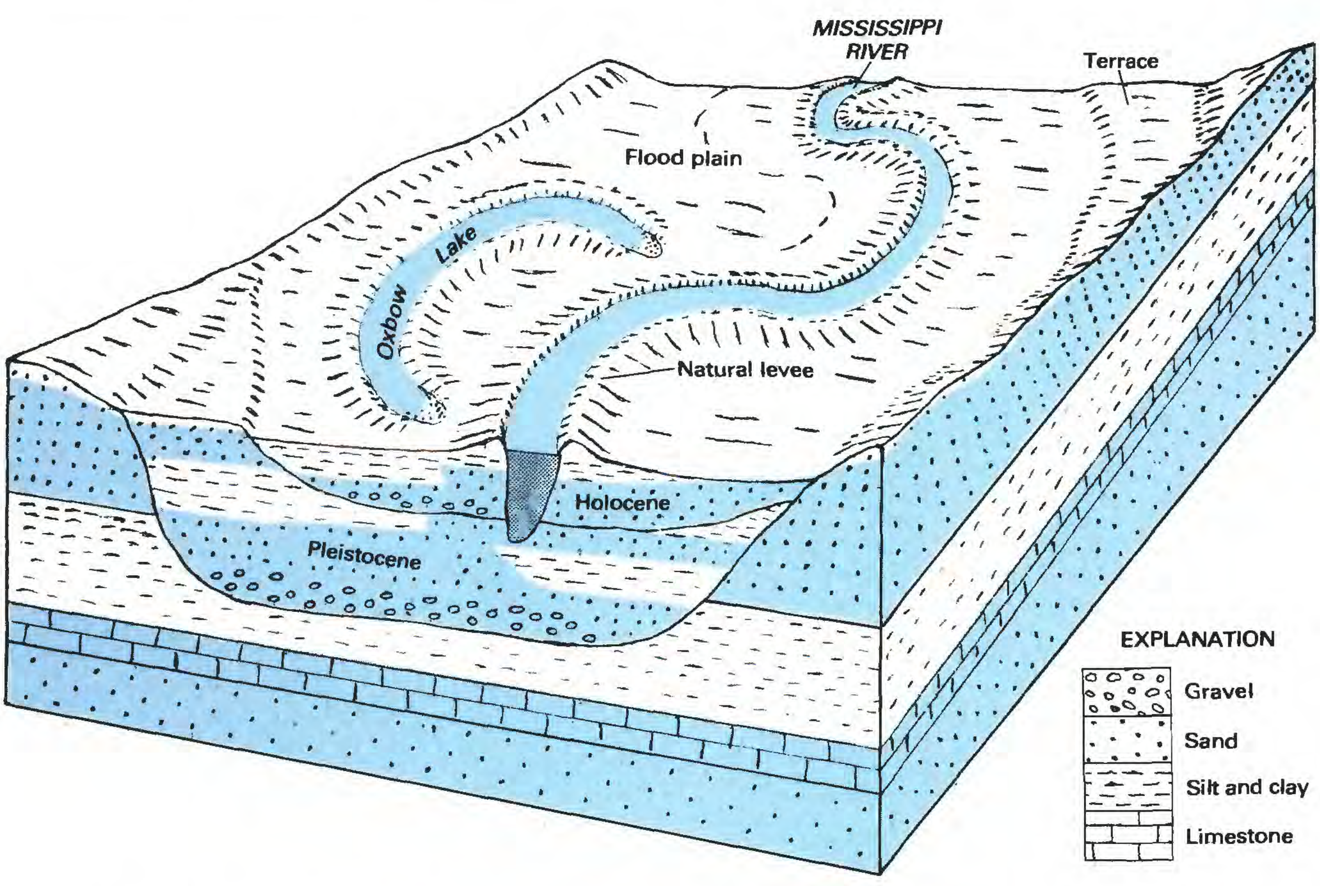


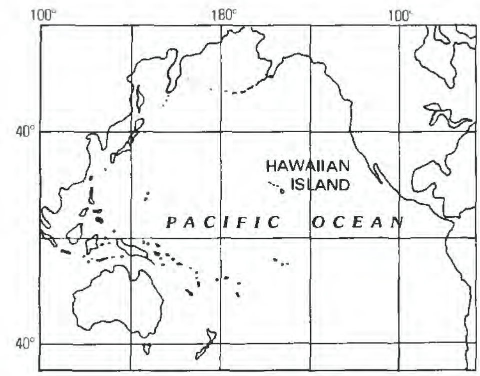
Figure 47. Topographic and geologic features of a section of the alluvial valley of the Mississippi River.

in ground-water discharge to the streams and, if large enough, cause infiltration of water from the streams into the deposits.

Where the alluvium contains highly permeable sand and gravel deposits, long-term yields of wells depend primarily on the effectiveness of the hydraulic connection between the sand and gravel and the stream. In many valleys where the upper part of the alluvial deposits is fine grained, the hydraulic connection is relatively ineffective. This problem has been partly solved in some valleys by placing production wells as close as possible to the streams, so that the maximum hydraulic gradient can be developed across the fine-grained alluvium between the stream bottom and the aquifer. Another solution is to equip wells with screens or slotted pipe that is extended horizontally in the alluvium beneath the stream.

13. HAWAIIAN ISLANDS

(Lava flows segmented in part by dikes, interbedded with ash deposits, and partly overlain by alluvium)



The Hawaiian Islands region encompasses the State of Hawaii and consists of eight major islands occupying an area of 16,706 km^2 in the Pacific Ocean 3,700 km southeast of California. The islands are the tops of volcanoes that rise from the ocean floor and stand at altitudes ranging from a few meters to more than 4,000 m above sea level. Each island was formed by lava that issued from one or more eruption centers. The islands have a hilly to mountainous appearance resulting from erosion that has carved valleys into the volcanoes and built relatively narrow plains along parts of the coastal areas (fig. 48).

Each of the Hawaiian Islands is underlain by hundreds of distinct and separate lava flows, most of which are composed of basalt. The lavas issued in repeated outpourings from narrow zones of fissures, first below sea level, then above it. The lavas that extruded below the sea are relatively impermeable. Those formed above sea level tend to be highly permeable, with interconnected openings that formed as the lava cooled, cavities and openings that were not filled by the overlying flow, and lava tubes (tunnels). The central parts of the thicker flows tend to be more massive and less permeable; the most common water-bearing openings are joints and faults that formed after the lava solidified. Thin layers of ash and weathered volcanic rock occur irregularly between some of the flows that formed above sea level. The lava flows in valleys and parts of the coastal plains are covered by a thin layer of alluvium consisting of coral (limestone) fragments, sand-size fragments of basalt, and clay (fig. 48).

The fissures through which the lava erupted tend to cluster near eruption centers. Flows from the fissures moved down depressions on the adjacent slopes (fig. 49) to form layers of lava that dip at angles of 4 to 10 degrees toward the margins of the volcanoes. The result, prior to modification by erosion, is a broad, roughly circular, gently convex mountain similar in shape to a warrior's shield. Thus, volcanoes of the Hawaiian type are referred to as shield volcanoes. When eruption along a fissure ceases, the lava remaining in the fissure solidifies to form a dike (fig. 48).

All of the islands have sunk, to some extent, as a result of a downward flexing of the Earth's crust caused by the weight of the volcanoes. This has resulted in flows that formed above sea level being depressed below sea level. The upper parts of these flows contain freshwater that serves as an important source of water.

In mineral composition and nature of the water-bearing openings, the lavas that form the Hawaiian Islands are very similar to those in the Columbia Plateau region. Thus, from these two standpoints, these regions could be combined into one. There is, however, one important difference that justifies their treatment as separate regions. This difference relates to the presence of seawater around and beneath the islands, which significantly affects the occurrence and development of water supplies.

From the standpoint both of description and of development, it is useful to divide the ground-water system of the Hawaiian Islands into three parts (fig. 50). The

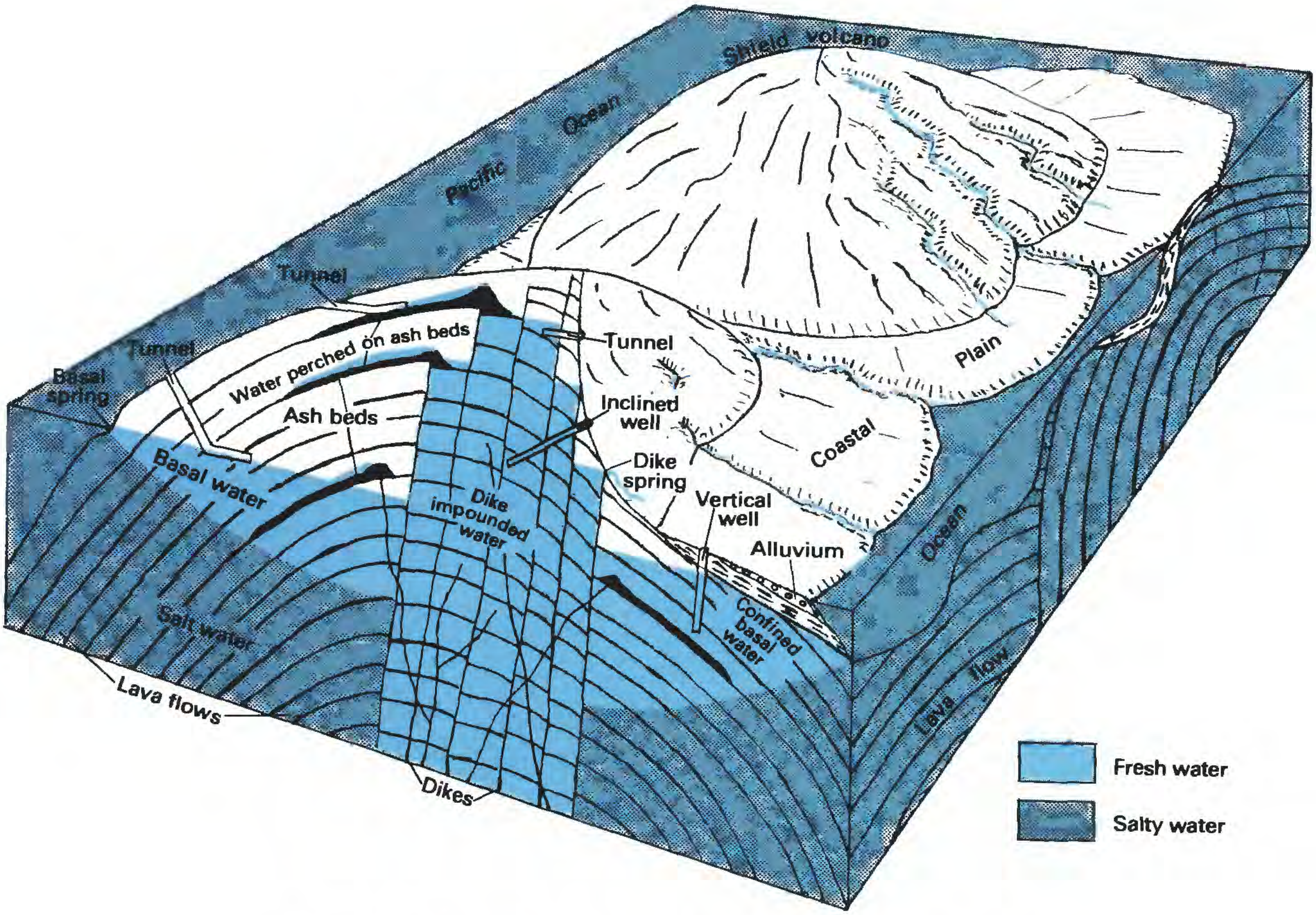


Figure 48. Topographic and geologic features of an Hawaiian island.

first part consists of the higher areas of the islands in the vicinity of the eruption centers. The rocks in these areas are formed into a complex series of vertical compartments surrounded by dikes developed along eruption fissures. The ground water in these compartments is referred to as dike-impounded water. The second, and by far the more important, part of the system consists of the lava flows that flank the eruption centers and that contain fresh ground water floating on saline ground water. These flank flows are partially isolated hydraulically from the vertical compartments developed by the dikes that surround the eruption centers (fig. 48). The fresh ground water in these flows is referred to as basal ground water. In parts of the coastal areas the basal water is confined by the overlying alluvium. The third part of the system consists of fresh water perched, primarily in lava flows, on soils, ash, or thick impermeable lava flows above basal ground water.

The ground-water system is recharged by precipitation which ranges annually from about 160 mm to more than 11,000 mm. This wide range in precipitation reflects the effect of the islands on the moist northeast trade winds. As the moisture-laden winds are deflected upward by the mountains, precipitation falls on the higher elevations. Precipitation is heaviest on mountains below 1,000 m and lightest in the coastal areas on the leeward side of the islands and at elevations above 1,000 m on the islands of Maui and Hawaii. The average annual precipitation on the islands is estimated to be about 1,800 mm. Because of the highly permeable nature of the volcanic soils, it is estimated that about 30 percent of the precipitation recharges the ground-water system (fig. 51).

Some discharge of dike-impounded ground water doubtless occurs through fractures in the dikes into the flanking lava flows. This movement must be small, however, because water stands in the compartments at levels hundreds of meters above sea level and the principal discharge occurs as springs on the sides and at the heads of valleys where erosion has removed parts of the dikes. Both the basal ground water and the perched ground water in the lava flows surrounding the dike-bounded compartments is recharged by precipitation and by streams leaving the dike-bounded area. Discharge is to streams and to springs and seeps along the coast.

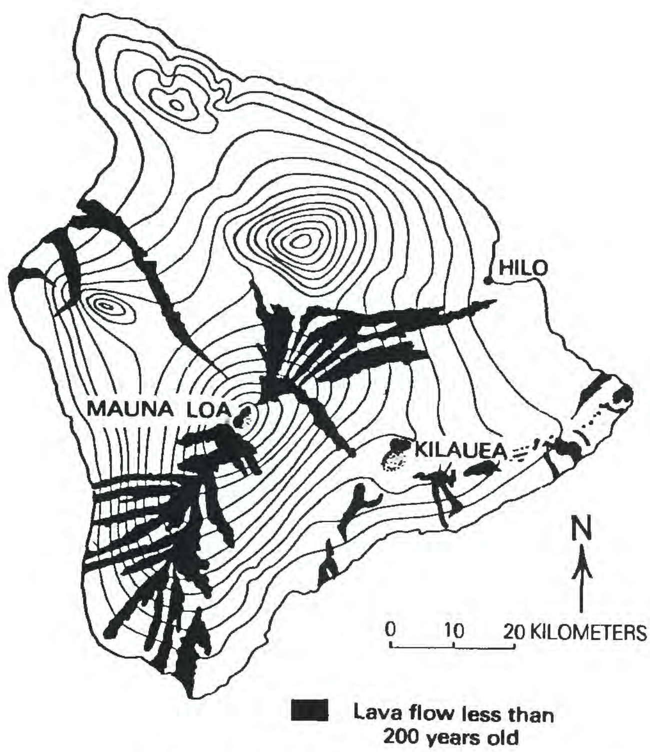


Figure 49. Recent lava flows on the Island of Hawaii

The basal water is the principal source of ground water on the islands (fig. 48). Because the freshwater is lighter (less dense) than seawater, it floats as a lens-shaped body on the underlying seawater. The thickness of the freshwater zone below sea level essentially depends on the height of the freshwater head above sea level. Near the coast the zone is thin, but several kilometers inland from the coast on the larger islands it reaches thicknesses of at least a few hundred meters (fig. 48). In parts of the coastal zone, and especially on the leeward side of the islands, the basal ground water is brackish (fig. 50).

Forty-six percent of the water used in Hawaii in 1975, or 3.1 x 10^6 m^3day^{-1}, was ground water. It is obtained through horizontal tunnels and through both vertical and inclined wells (fig. 48). Tunnels are used to obtain supplies of basal water near the coast where the freshwater zone is thin. Tunnels are also used to tap dike-impounded water. These tunnels encounter large flows of water when the principal impounding dike is penetrated and it is necessary to drain most of the water in the saturated zone above the tunnel before construction can be completed. Thereafter, the yield of the tunnel reflects the rate of recharge to the compartment tapped by the tunnel. To avoid a large initial waste of water and to preserve as much storage as possible, the Honolulu Board of Water Supply has begun to construct inclined wells to obtain dike-impounded water. Vertical wells are used to obtain basal water and perched ground water in inland areas where the thickness of the freshwater zone permits the use of such wells.

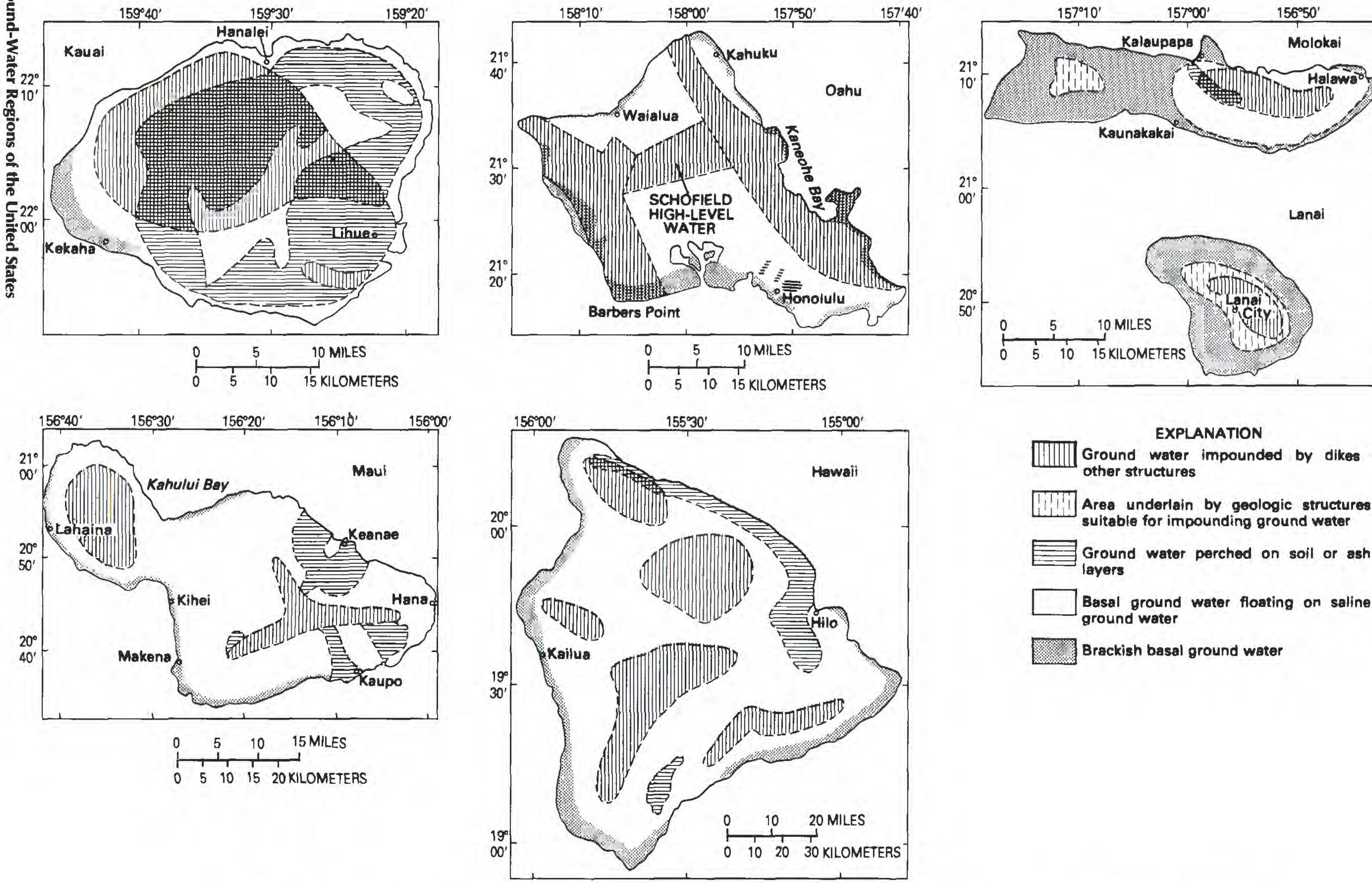


Figure 50. Approximate outline of the different ground-water areas on the principal Hawaiian islands. (From Takasaki, 1977.)

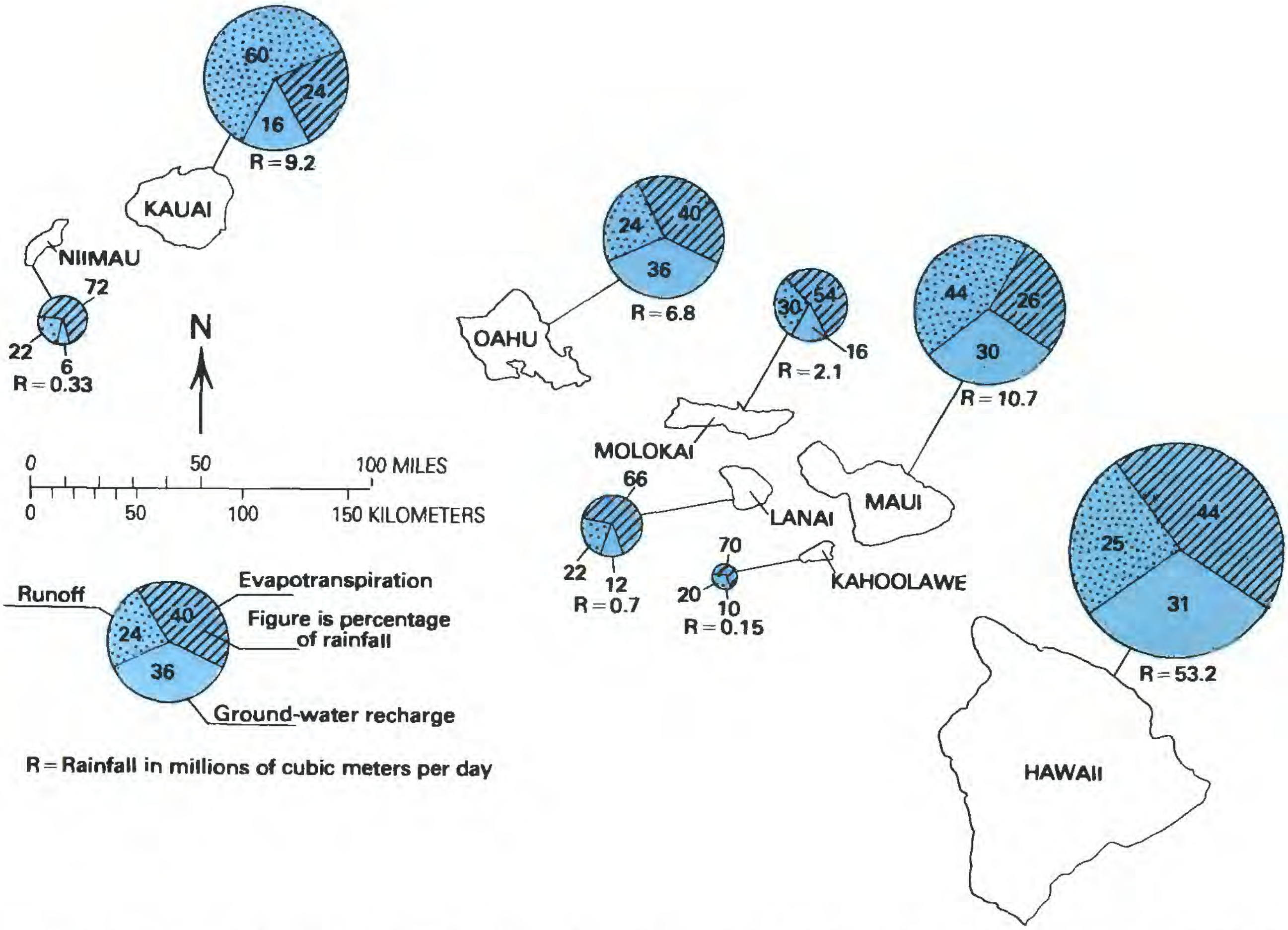


Figure 51. Simplified water budgets of the Hawaii Islands. (From U.S. Geological Survey Professional Paper 813-M.)

14. ALASKA

(Glacial and alluvial deposits, occupied in part by permafrost, and overlying crystalline, metamorphic, and sedimentary rocks)

The Alaska region encompasses the State of Alaska, which occupies an area of 1,519,000 km^2 at the northwest corner of North America. Physiographically, Alaska can be divided into four divisions—from south to north, the Pacific Mountain System, the Intermontane Plateaus, the Rocky Mountain System, and the Arctic Coastal Plain (fig. 52). The Pacific Mountain System is the Alaskan equivalent of the Coast Range, Puget Sound Lowland, and Cascade provinces of the Washington-Oregon area. The Intermontane Plateaus is a lowland area of plains, plateaus, and low mountains comparable to the area between the Cascades-Sierra Nevada and the Rocky Mountains. The Rocky Mountain System is a continuation of the rocky Mountains of the United States and Canada, and the Arctic Coastal Plain is the geologic equivalent of the Great Plains of the United States and Canada. The coastal areas and lowlands range in altitude

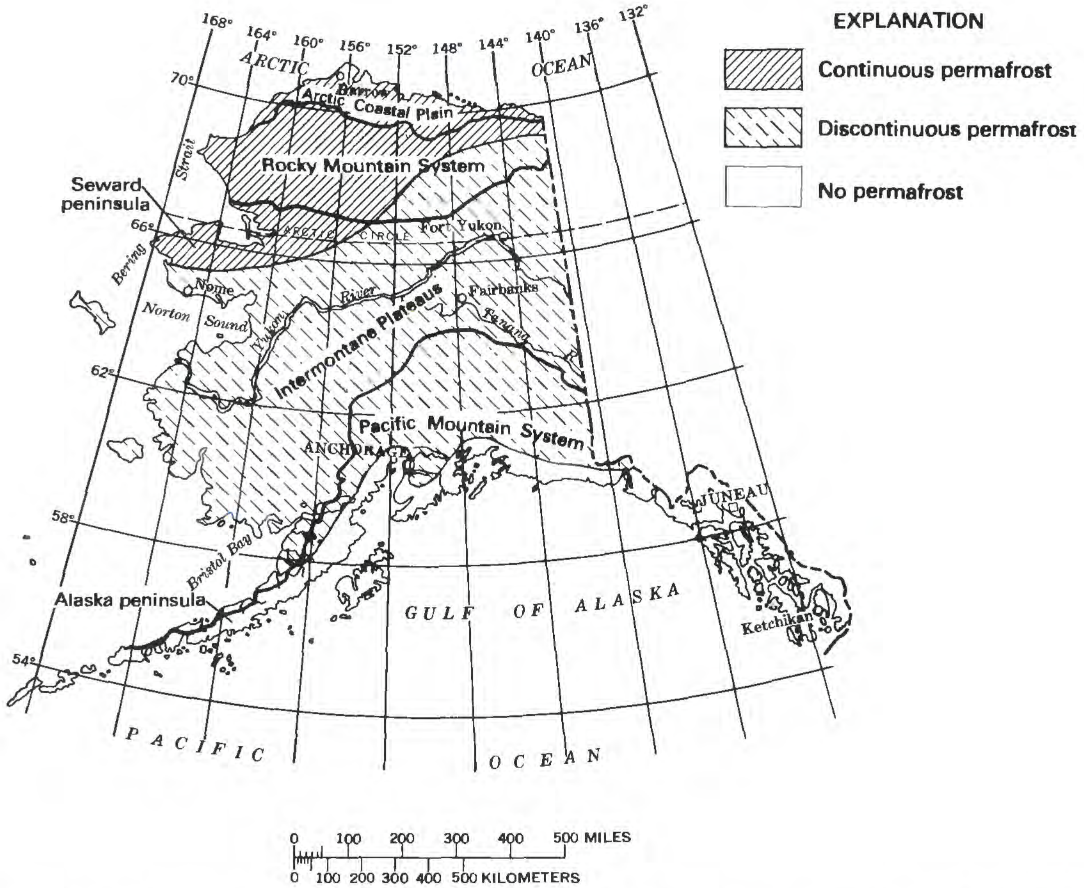


Figure 52. Physiographic divisions and permafrost zones of Alaska. (Physiography after Wahrhaftig, 1965; permafrost zones from Williams, 1970.)

from sea level to about 300 m, and the higher mountains reach altitudes of 1,500 to 3,000 m. Mt. McKinley in the Pacific Mountain System is the highest peak in North America, with an altitude of about 6,200 m.

As would be expected of any area its size, Alaska is underlain by a diverse assemblage of rocks. The principal mountain ranges have cores of igneous and metamorphic rocks ranging in age from Precambriam to Mesozoic. These are overlain and flanked by younger sedimentary and volcanic rocks. The sedimentary rocks include carbonates, sandstones, and shales. In much of the region the bedrock is overlain by unconsolidated deposits of gravel, sand, silt, clay, and glacial till (fig. 53).

Climate has a dominant effect on hydrologic conditions in Alaska. Mean annual air temperatures range from -12°C in the Rocky Mountain System and the Arctic Coastal Plain to about 5°C in the coastal zone adjacent to the Gulf of Alaska. The present climate and the colder climates that existed intermittently in the past have resulted in the formation of permafrost, or perennially frozen ground. Permafrost is present throughout the State except in a narrow strip along the southern and southeastern coasts (fig. 52). In the northern part of the Seward Peninsula, in the western and northern parts of the Rocky Mountain System, and in the Arctic Coastal Plain, the permafrost extends to depths as great as 600m and is continuous except beneath deep lakes and in the alluvium beneath the deeper parts of the channels of streams (fig. 54). South of this area and north of the coastal strip, the permafrost is discontinuous and depends on exposure, slope, vegetation, and other factors. The permafrost is highly variable in thickness in this zone but is generally less than 100 m thick.

Much of the water in Alaska is frozen for at least a part of each year: that on the surface as ice in streams and lakes or as snow or glacier ice and that below the surface as winter frost and permafrost. Approximately half of Alaska, including the mountain ranges and adjacent parts of the lowlands, was covered by glaciers during the Pleistocene (fig. 55). About 73,000 km^2, or one-twentieth of the region, is still occupied by glaciers, most of which are in the mountain ranges that border the Gulf of Alaska. Precipitation, which ranges from about 130 mm yr^{-1} in the Rocky Mountain System and the Arctic Coas-

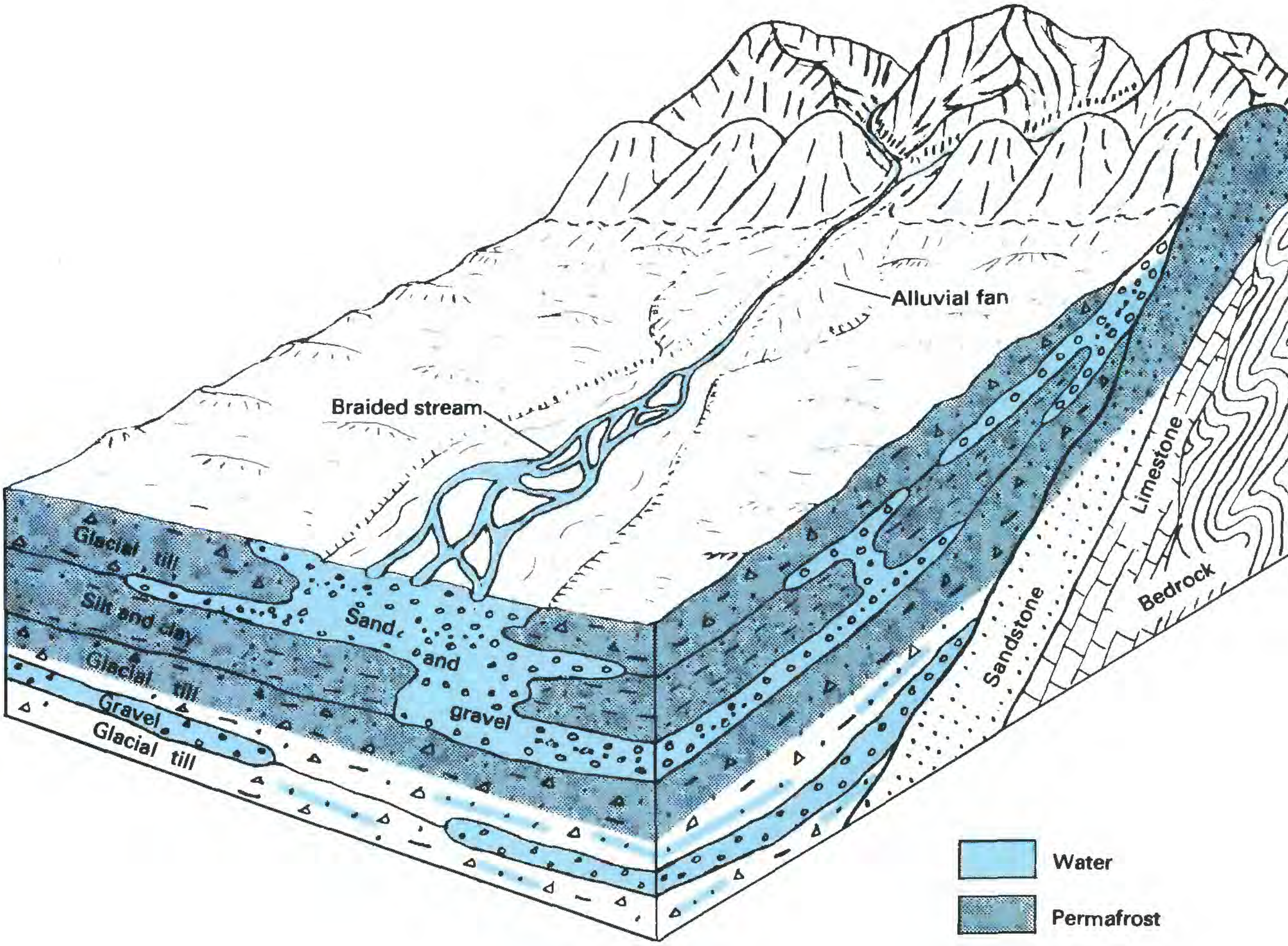


Figure 53. Topographic and geologic features of parts of Alaska.

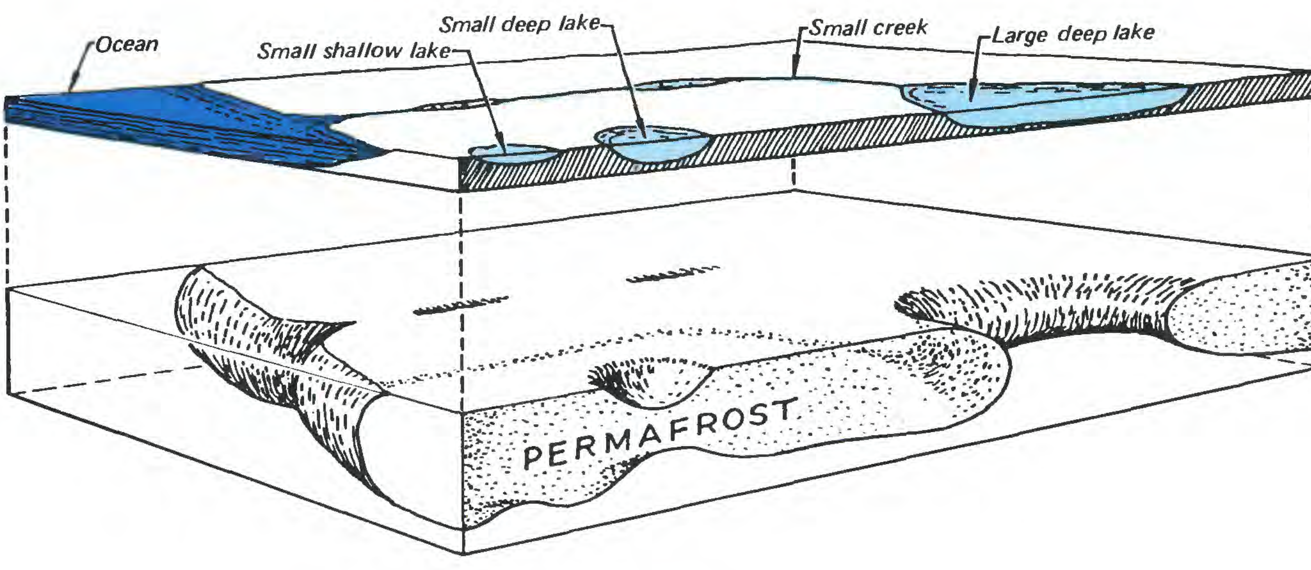


Figure 54. Effect of surface water on permafrost in the zone of continuous permafrost. (Modified from Lachenbruch and others, 1962.)

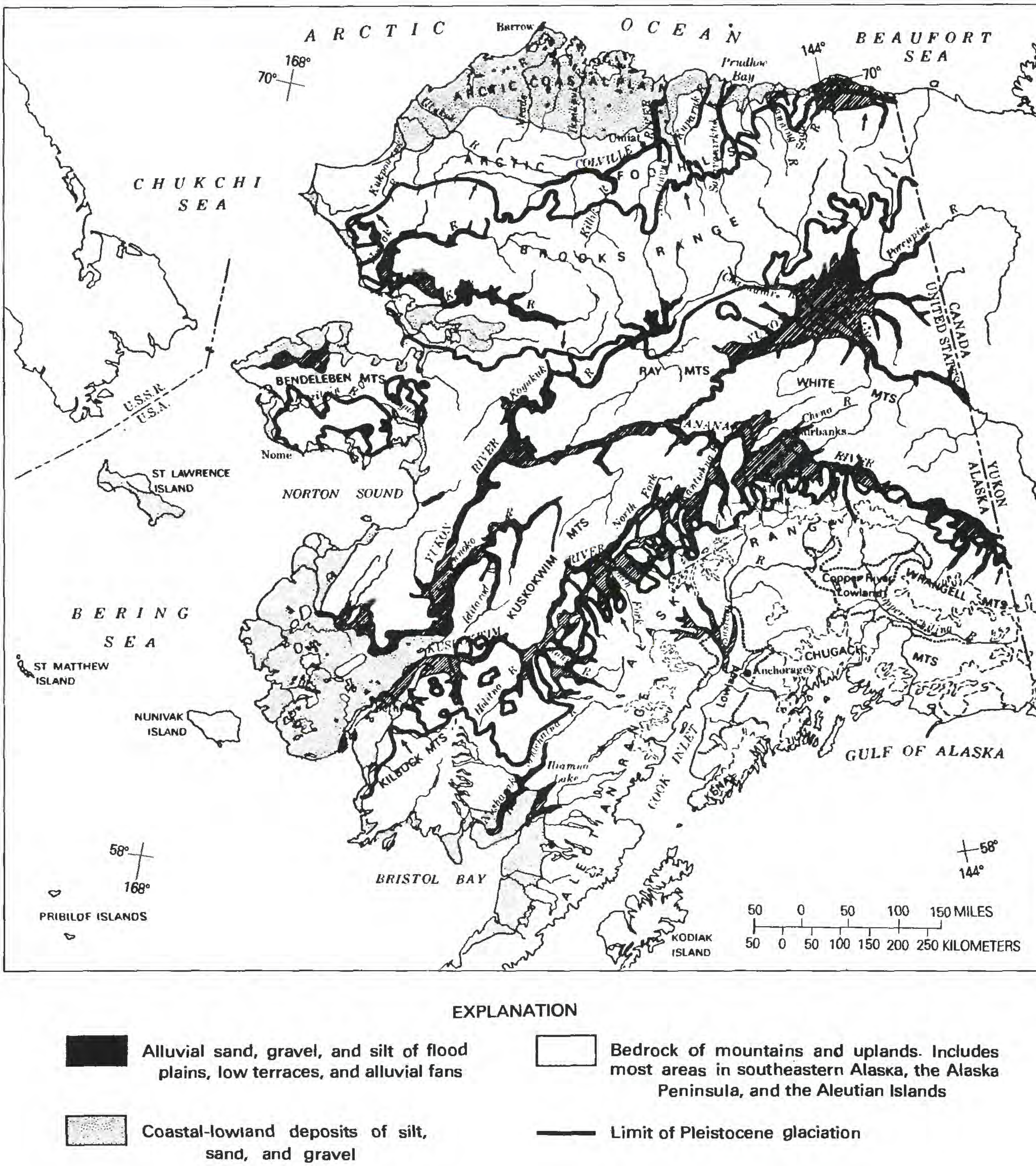


Figure 55. Major hydrogeologic environments of Alaska. (From Williams, 1970.)

tal Plain to about 7,600 mm yr^{-1} along the southeast coast, falls as snow for 6 to 9 months of the year and even year-round in the high mountain regions. The snow remains on the surface until thawing conditions begin, in May in southern and central Alaska and in June in the arctic zone. During the period of subfreezing temperatures, there is no overland runoff, and many streams and shallow lakes not receiving substantial ground-water discharge are frozen solid.

From the standpoint of ground-water availability and well yields, Alaska is divided into three zones. In the zone of continuous permafrost, ground water occurs beneath the permafrost and also in small, isolated, thawed zones that penetrate the permafrost beneath large lakes and deep holes in the channels of streams (fig. 54). In the zone of discontinuous permafrost, ground water occurs below the permafrost and in sand and gravel deposits that underlie the channels and floodplains of major streams (fig. 53). In the zone of discontinuous permafrost, water contained in silt, clay, glacial till, and other fine-grained deposits usually is frozen. Thus, in this zone the occurrence of ground water is largely controlled by hydraulic conductivity. In the zone not affected by permafrost, which includes the Aleutian Islands, the western part of the Alaska Peninsula, and the southern and southeastern coastal areas, ground water occurs both in the bedrock and in the relatively continuous layer of unconsolidated deposits that mantle the bedrock.

Relatively little is known about the occurrence and availability of ground water in the bedrock. Permafrost extends into the bedrock in both the zones of continuous and discontinuous permafrost, but springs that issue from carbonate rocks in the Rocky Mountain System indicate the presence of productive water-bearing openings. Small supplies of ground water have also been developed from sandstones, from volcanic rocks, and from faults and fractures in the igneous and metamorphic rocks.

Recharge of the aquifers in the Alaska region occurs when the ground is thawed in the areas not underlain by permafrost. This period generally lasts only from June through September. Because the ground, even in nonpermafrost areas, is still frozen when most snowmelt runoff occurs, relatively little recharge occurs in interstream areas by infiltration of water across the unsaturated zone. Instead, most recharge occurs through the channels of streams where they flow across the alluvial fans that fringe the mountainous areas and in alluvial deposits for some distance downstream. Because of the large hydraulic conductivity of the sand and gravel in these areas, the rate of infiltration is large. Seepage investigations along Ship Creek near Anchorage indicate channel losses of 0.07 m^3sec^{-1} km^{-1}, which gives an infiltration rate through the wetted perimeter of about 0.4 m day^{-1}.

Discharge from aquifers occurs in the downstream reaches of streams and through seeps and springs along the coast. The winter flow of most Alaskan streams is sustained by ground-water discharge. In the interior and northern regions, this discharge is evidenced by the buildup of ice (referred to locally as "icings") in the channels of streams and on the adjacent flood plains.

In the Arctic Coastal Plain and other areas underlain by very deep permafrost, ground water under the permafrost tends to contain a relatively large concentration of dissolved substances. Objectionable concentrations of iron also are present in shallow aquifers in most parts of the region.

15. PUERTO RICO AND VIRGIN ISLANDS

(Alluvium and limestones overlying and bordering fractured igneous rocks)

Puerto Rico, its outlying islands of Culebra and Vieques, and the Virgin Islands of St. Croix, St. Thomas, and St. John, are in the Caribbean Sea about 1,500 km southeast of Florida (fig. 56). The total land area of the region is 9,340 km^2, of which 8,990 km^2 are in the Commonwealth of Puerto Rico. Puerto Rico and the Virgin Islands are marked by considerable topographic relief. A mountainous area with ridge tops reaching altitudes of 1,200 m extends in an east-west direction nearly the entire length of Puerto Rico. The mountains are bordered to the north and south by steep-sided hills and ridges separated by relatively narrow valleys. The hilly areas, in turn, are

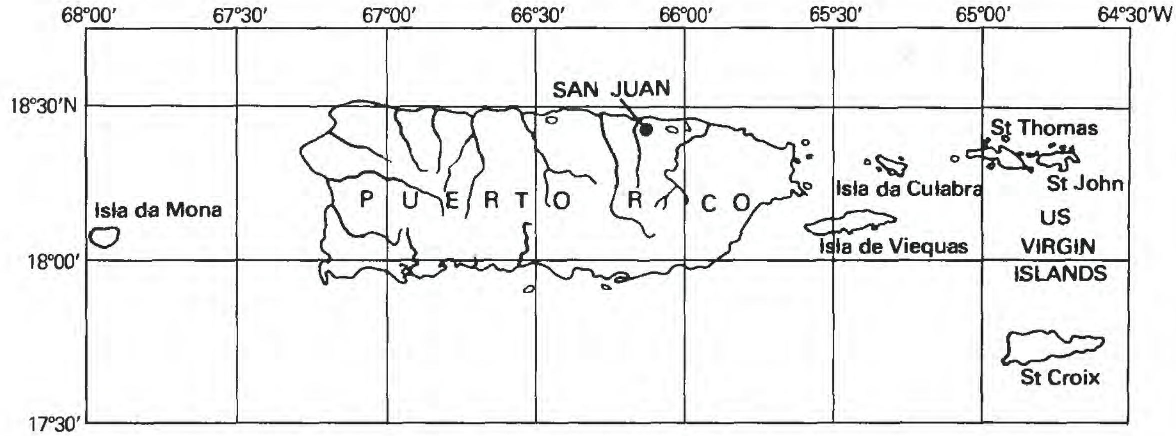


Figure 56. Puerto Rico and the Virgin Islands.

bordered by relatively narrow coastal plains. The Virgin Islands represent the tops of mountains left standing above the sea when the crustal block on which Puerto Rico and the adjacent islands are located was tilted downward to the northeast. Thus, peaks on the Virgin Islands are much lower than those on Puerto Rico, with highest altitudes of less than 500 m.

Most of Puerto Rico and the Virgin Islands are underlain by volcanic and intrusive igneous rocks of Late Cretaceous and early Tertiary age (fig. 57). In Puerto Rico, these rocks are bordered to the north and south by limestones of Oligocene and Miocene age (figs. 57 and 58). In parts of the coastal plain and in the valleys of the larger streams, the limestones and igneous rocks are overlain by alluvial deposits composed, in part, of fragments of volcanic rocks (fig. 58). About half of St. Croix, including a broad area extending from the southwest coastal area through the center of the island, is underlain by limestone, clayey limestone (marl), and alluvium. The remainder of the island is underlain by volcanic and other igneous rocks. Only about 10 percent of St. Thomas and 5 percent of St. John are underlain by limestone and alluvium, the remainder being underlain by volcanic and igneous rocks (fig. 57).

The alluvium, limestones, and volcanic rocks underlying Puerto Rico and the Virgin Islands are all water bearing. These are the types of rocks that make up the most productive aquifers in the other ground-water regions. Thus, at first glance, it would seem that these Caribbean islands would be especially favorable areas for ground-water development. This, however, is not the case.

In comparison to the Hawaiian Islands, in which the volcanic rocks form highly permeable lava flows, the volcanic rocks in the Caribbean are composed largely of ash layers and fragmental material formed during explosive eruptions. In early Tertiary time these rocks were compressed, folded, and metamorphosed and thereby were converted to hard, dense rocks that now contain interconnected openings only along fractures and faults (fig. 58). Thus, the hydraulic properties of the volcanic and other igneous rocks that underlie Puerto Rico, the islands of Culebra and Vieques, and the Virgin Islands resemble those of the crystalline rocks in the Piedmont and Blue Ridge region.

The limestones and the overlying alluvial deposits make up the most productive aquifers. The most extensive and thickest section of these underlie the north coastal area of Puerto Rico (figs. 57, 58). This area is as much as 20 km wide and is underlain, at places along the coast, by more than 1,600 m of limestone and alluvium. The upper part of the limestone has been extensively modified by solution and has the largest hydraulic conductivity. The extent of solution is suggested by the topography of the limestone belt, which shows three distinct stages (fig. 58). The youthful stage is marked by a plateau-like surface slightly pitted with shallow, closed depressions. The next, or mature stage, is represented by steep, conical hills separated by star-shaped depressions that have steep convex sides and slightly concave floors. The third, or old stage, is marked by conical hills rising out of a nearly flat plain underlain by blanket sand deposits. The deeper part of the limestone section has been affected by solution less than the upper part and, therefore, has a much lower hydraulic conductivity. The limestones underlying the remaining coastal areas of Puerto Rico and the Virgin Islands form the most productive aquifers in those areas, but, because they are generally thin, their yields are small.

Deposits of alluvium composed of gravel, sand, silt, and clay, up to 100 m thick, occur in stream valleys and as a relatively continuous blanket of coalescing alluvial fans in southern Puerto Rico. Alluvium more than 600 m thick has been penetrated along the southern coast of Puerto Rico. The alluvium and limestones, where both are present, are hydraulically connected and, where both

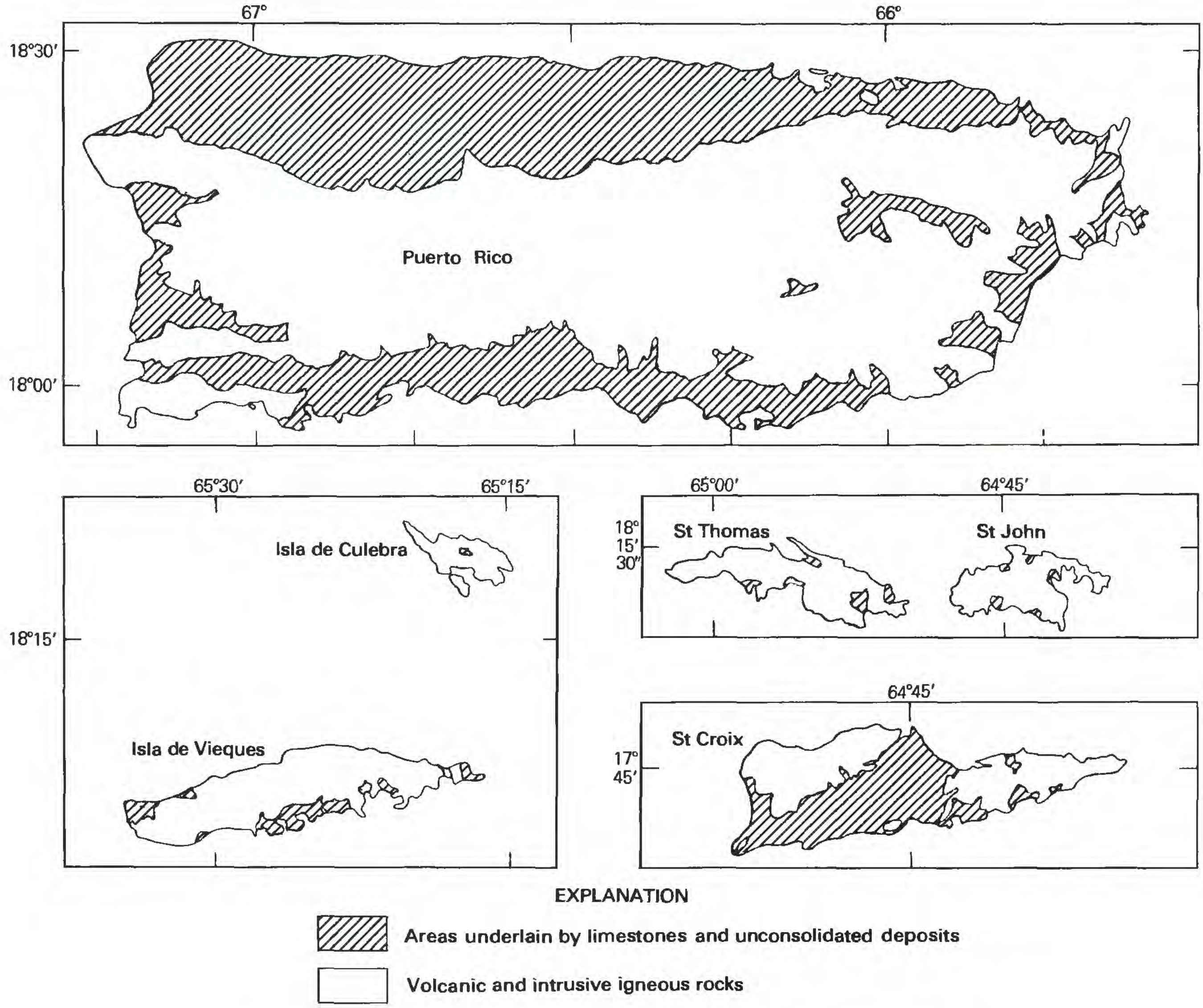


Figure 57. Generalized geology of Puerto Rico and the Virgin Islands.

are saturated, effectively form a single water-bearing unit (fig. 58).

Recharge of the ground-water system is from precipitation, which averages 1,800 mm per year in Puerto Rico and about 1,060 mm per year in the Virgin Islands. Because the islands lie in the belt of easterly trade winds, precipitation is higher on the eastern and northern sides of the islands and is strongly affected by land-surface altitudes. Thus, annual precipitation ranges from about 5,000 mm in the mountains in the northeastern part of Puerto Rico to about 730 mm on the smaller islands and along the southwestern coast of Puerto Rico. Because of the tropical climate, about 60 percent of the precipitation on Puerto Rico and as much as 90 percent of that on the Virgin Islands may be lost to evapotranspiration. The remainder either runs off on the surface or percolates to the water table. Discharge from the ground-water system occurs to streams, to coastal wetlands, and to offshore springs and seeps.

The northern coastal area of Puerto Rico is the most favorable area in the region for large ground-water developments. This area is underlain by thick, permeable aquifers and receives abundant precipitation. However, this area, as is true of the other coastal areas in the region underlain by productive aquifers, contains fresh ground water in direct contact with seawater, and large ground-water developments, especially near the coast, are confronted with the potential problem of seawater encroachment (fig. 58). The higher inland areas of Puerto Rico and the Virgin Islands are most favorably situated with respect to precipitation and freedom from seawater encroachment. Unfortunately, these areas are underlain

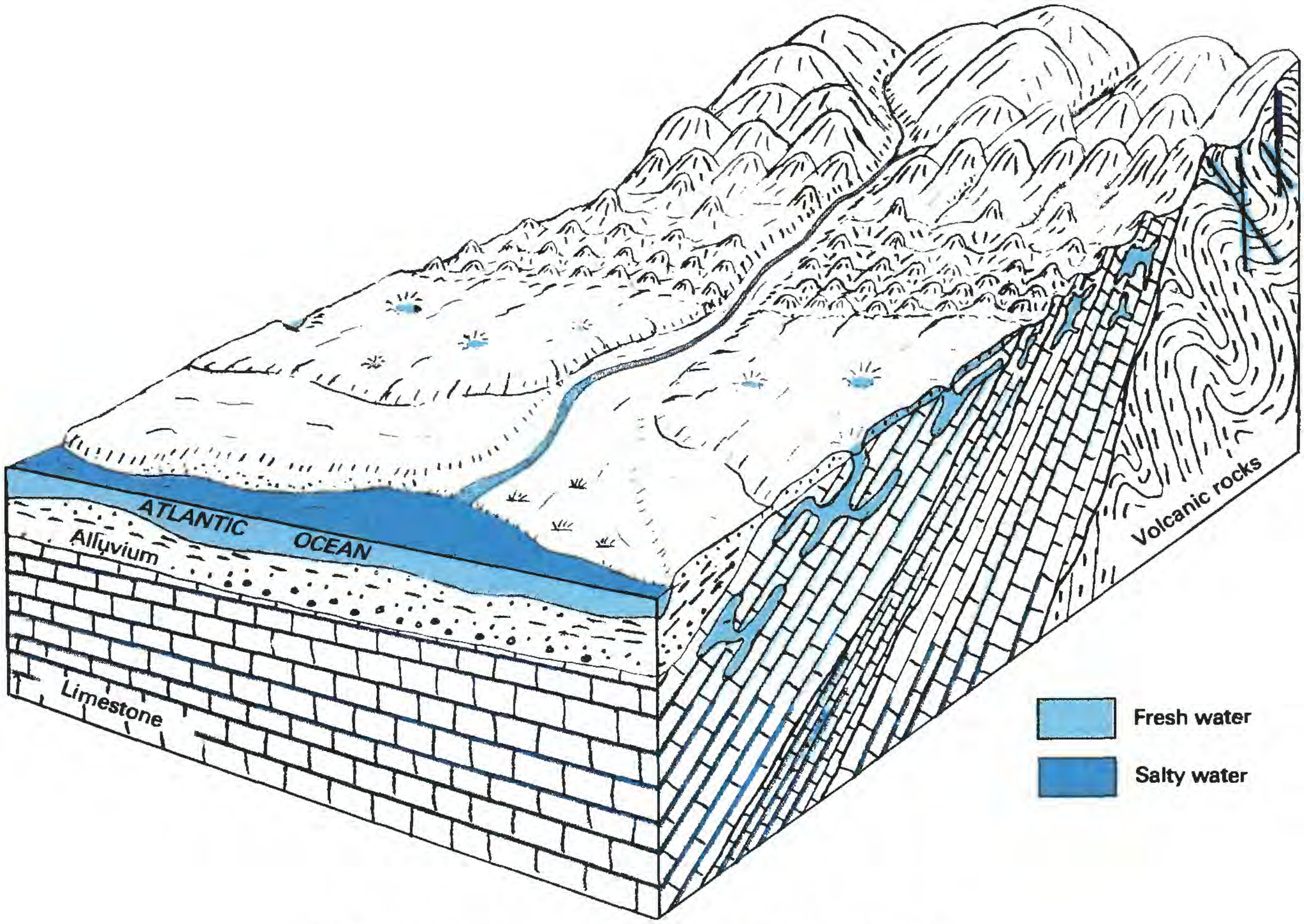


Figure 58. Topographic and geologic features of Puerto Rico.

by rocks of very low permeability which have a small storage capacity and small well yields. Steep slopes in these areas also produce large rates of runoff during heavy rains.

Part of the water needs of the Virgin Islands are being met by desalting seawater, and studies have been made to determine the feasibility of recharging aquifers with treated waste water. Meeting the increasing water needs in the region will require water management that takes advantage of the most advanced technology and that involves unusually effective water conservation.

REFERENCES

A large number of publications were consulted, for both general and specific information, in the preparation of this paper. Specific reference to these publications generally is omitted in the text, both to avoid interruption of the discussions and to save space. Publications that served as primary references are listed below, under the categories of general references and references to regional discussions. General references include publications that were used both for background information on the classification of ground-water systems and for general information on the regions. References to the regional discussions include publications that served as a source of additional information on the individual regions.

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Chapter	*Water-Resources Region*	*Authors*
A	Ohio	R.M. Bloyd, Jr.
B	Upper Mississippi	R.M. Bloyd, Jr.
C	Upper Colorado	Don Price and Ted Arnow
D	Rio Grande	S.W. West and W.L. Broadhurst
E	California	H.E. Thomas and D.A. Pheonix
F	Texas-Gulf	E.T. Baker, Jr., and J.R. Wall
G	Great Basin	T.E. Eakin, Don Price, and S.R. Harrill
H	Arkansas, White, Red	M.S. Bedinger and R.T. Sniegocki
I	Mid-Atlantic	Allen Sinnott and E.M. Cushing
J	Great Lakes	W.G. Weist, Jr.
K	Souris-Red-Rainy	H.O. Reeder
L	Tennessee	Ann Zurawski
M	Hawaii	K.J. Takasaki
N	Lower Mississippi	J.E. Terry, R.L. Hosman, and C.T. Bryant
O	South Atlantic-Gulf	D.J. Cederstrom, E.H. Boswell, and G.R. Tarver
P	Alaska	Chester Zenone and G.S. Anderson
Q	Missouri Basin	O.J. Taylor
R	Lower Colorado	E.S. Davidson
S	Pacific-Northwest	B.L. Foxworthy
T	New England	Allen Sinnott
U	Caribbean	F. Gomez-Gomez and J.E. Heisel

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The regional descriptions and the table listing the common ranges in the hydraulic characteristics of the regions (table 6) were reviewed by the following:

1. Western Mountain Ranges—W.E. Price
2. Alluvial Basins—T.W. Anderson and W.D. Nichols
3. Columbia Lava Plateau—B.L. Foxworthy, G.F. Lindholm, R.L. Nace, R.F. Novitch, William Meyer, and Ann Zurawski
4. Colorado Plateau and Wyoming Basin—J.S. Gates and J.W. Hood
5. High Plains—E.D. Gutentag, W.F. Lichtler, H.E. McGovern, and J.B. Weeks
6. Nonglaciated Central—A.E. Becker, R.J. Faust, M.V. Marcher, and C.R. Wood
7. Glaciated Central—M.S. Garber, Allan Randall, and R.M. Waller
8. Piedmont and Blue Ridge—C.C. Daniel, III
9. Northeast and Superior Uplands—M.H. Frimpter and D.I. Siegel
10. Atlantic and Gulf Coastal Plain—E.H. Boswell, G.T. Cardwell, M.S. Garber, R.L. Hosman, Harold Meisler, and R.L. Wait
11. Southeast Coastal Plain—P.W. Bush, C.S. Conover, and R.H. Johnston
12. Alluvial Valleys—M.H. Frimpter, M.S. Garber, W.F. Lichtler, H.E. McGovern, Allan Randall, and R.M. Waller
13. Hawaii—B.L. Jones
14. Alaska—C.E. Sloan
15. Puerto Rico and Virgin Islands—C.B. Bentley, F. Gomez-Gomez, and D.G. Jordan

Units and Conversions

Metric to inch-pound units		Inch-pound to metric units
	Length	
1 millimeter (mm) = 0.001 m = 0.03937 inches		1 inch (in) = 25.4 mm = 2.54 cm = 0.0254 m
1 centimeter (cm) = 0.01 m = 0.3937 inches = 0.0328 feet		1 foot (ft) = 12 in = 30.48 cm = 0.3048 m
1 meter (m) = 39.37 inches = 3.28 feet = 1.09 yards		1 yard (yd) = 3 ft = 0.9144 m = 0.0009144 km
1 kilometer (km) = 1,000 m = 0.62 miles		1 mile (mi) = 5,280 ft = 1,609 m = 1.609 km
	Area	
1 cm^2 = 0.155 $inches^2$		1 in^2 = 6.4516 cm^2
1 m^2 = 10.758 $feet^2$ = 1.196 $yards^2$		1 ft^2 = 929 cm^2 = 0.0929 m^2
1 km^2 = 247 acres = 0.386 $miles^2$		1 mi^2 = 2.59 km^2
	Volume	
1 cm^3 = 0.061 $inches^3$		1 in^3 = 0.00058 ft^3 = 16.39 cm^3
1 m^3 = 1,000 liters = 264 U.S. gallons = 35.314 $feet^3$		1 ft^3 = 1,728 in^3 = 0.02832 m^3
1 liter (l) = 1,000 cm^3 = 0.264 U.S. gallons		1 gallon = 231 in^3 = 0.13368 ft^3 = 0.00379 m^3
	Mass	
1 microgram (μg) = 0.000001 g		
1 milligram (mg) = 0.001 g		1 pound (lb) = 16 oz = 0.4536 kg
1 gram (g) = 0.03527 ounces = 0.002205 pounds		1 ounce (oz) = 0.0625 lb = 28.35 gm
1 kilogram (kg) = 1,000 grams = 2.205 pounds		

Relation of Units of Hydraulic Conductivity, Transmissivity, Recharge Rates, and Flow Rates

Hydraulic Conductivity (K)

Meters per day (m day^{-1})	Centimeters per second (cm sec^{-1})	Feet per day (ft day^{-1})	Gallons per day per square foot (gal day^{-1}ft^{-2})
ONE	1.16×10^{-3}	3.28	2.45×10^{1}
8.64×10^{2}	ONE	2.83×10^{3}	2.12×10^{4}
3.05×10^{-1}	3.53×10^{-4}	ONE	7.48
4.1×10^{-2}	4.73×10^{-5}	1.34×10^{-1}	ONE

Transmissivity (T)

Square meters per day (m^{2}day^{-1})	Square feet per day (ft^{2}day^{-1})	Gallons per day per foot (gal day^{-1}ft^{-1})
ONE	10.76	80.5
0.0929	ONE	7.48
0.0124	0.134	ONE

Recharge Rates

Unit depth per year	Volume		
	m^{3}day^{-1}km^{-2}	ft^{3}day^{-1}mi^{-2}	gal day^{-1}mi^{-2}
mm	2.7	251	1,874
in	70	6,365	47,738

Flow Rates

m^{3}sec^{-1}	m^{3}min^{-1}	m^{3}day^{-1}	ft^{3}sec^{-1}	ft^{3}min^{-1}	gal min^{-1}
ONE	60	86,400	35.3	2,120	15,800
0.0167	ONE	1,440	0.588	35.3	264
0.0283	1.70	2,448	ONE	60	449
0.000472	0.0283	40.75	0.0167	ONE	7.48
0.000063	0.00379	5.348	0.0023	0.134	ONE