GROUND WATER ATLAS OF THE UNITED STATES

SEGMENT 13

ALASKA, HAWAII, PUERTO RICO AND THE U.S. VIRGIN ISLANDS

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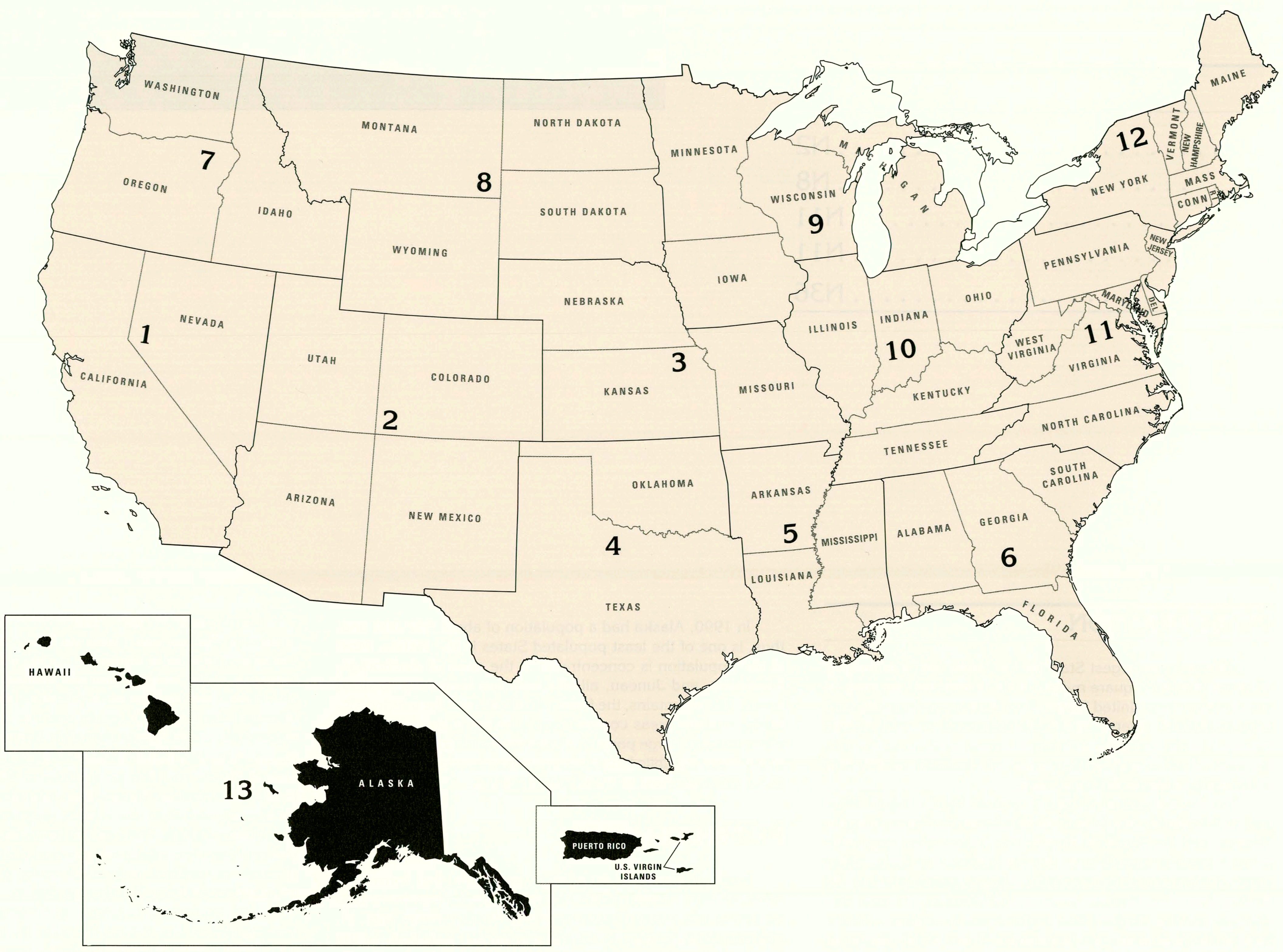

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INTRODUCTION

Alaska is the largest State in the Nation and has an area of about 586,400 square miles, or about one-fifth the area of the conterminous United States. The State is geologically and topographically diverse and is characterized by wild, scenic beauty. Alaska contains abundant natural resources, including ground water and surface water of chemical quality that is generally suitable for most uses.

The central part of Alaska is drained by the Yukon River and its tributaries, the largest of which are the Porcupine, the Tanana, and the Koyukuk Rivers. The Yukon River originates in northwestern Canada and, like the Kuskokwim River, which drains a large part of southwestern Alaska, discharges into the Bering Sea. The Noatak River in northwestern Alaska discharges into the Chukchi Sea. Major rivers in southern Alaska include the Susitna and the Matanuska Rivers, which discharge into Cook Inlet, and the Copper River, which discharges into the Gulf of Alaska. North of the Brooks Range, the Colville and the Sagavanirktok Rivers and numerous smaller streams discharge into the Arctic Ocean.

In 1990, Alaska had a population of about 552,000 and, thus, is one of the least populated States in the Nation. Most of the population is concentrated in the cities of Anchorage, Fairbanks, and Juneau, all of which are located in lowland areas. The mountains, the frozen Arctic desert, the interior plateaus, and the areas covered with glaciers lack major population centers. Large parts of Alaska are uninhabited and much of the State is public land. Ground-water development has not occurred over most of these remote areas.

PHYSIOGRAPHY

Most of Alaska is on a large peninsula that forms the northwestern corner of the North American continent and separates the Arctic Ocean from the Pacific Ocean (**fig. 1**). The southeastern part of the State is on the main body of the continental land mass. Alaska is separated from Russia by the narrow Bering Strait and from the conterminous United States by part of western Canada.

Large areas of high, rugged mountains in northern and southern Alaska are extensions of mountain systems in Canada. The Brooks Range in northern Alaska is the western terminus of the Rocky Mountain System. In southern Alaska, the Alaska and the Boundary Ranges, and the Talkeetna, the Wrangell, the Kenai–Chugach, and the St. Elias Mountains are extensions of the Pacific Mountain System. The south peak of Mount McKinley in the Alaska Range is the highest point in the United States and has an altitude of 20,320 feet above sea level. The Aleutian Range that extends as a long peninsula southwestward from the Alaska mainland is an extension of the Alaska Range. Parts of the summits and upper slopes of the southern mountain ranges and chains are covered with glaciers. In contrast, only small valley glaciers are present in the eastern parts of the Brooks Range.

Low mountains, plateaus, and highlands bound the high mountains and are, in turn, bounded by lowland areas (**fig. 1**). The lowlands are primarily along the courses of major streams and in coastal areas. Most of the cities, towns, and villages in Alaska are in the lowland areas.

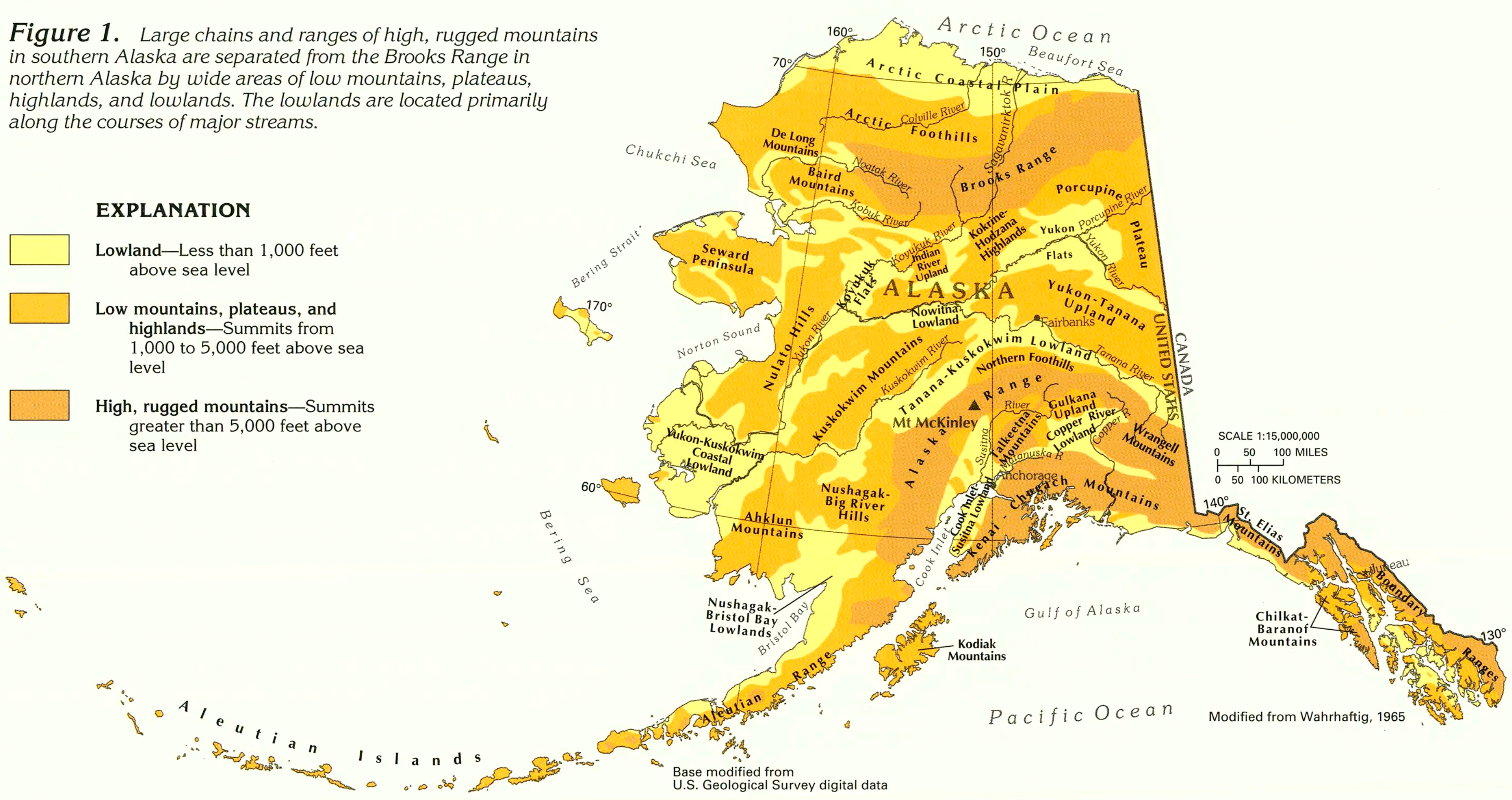


Figure 1. Large chains and ranges of high, rugged mountains in southern Alaska are separated from the Brooks Range in northern Alaska by wide areas of low mountains, plateaus, highlands, and lowlands. The lowlands are located primarily along the courses of major streams.

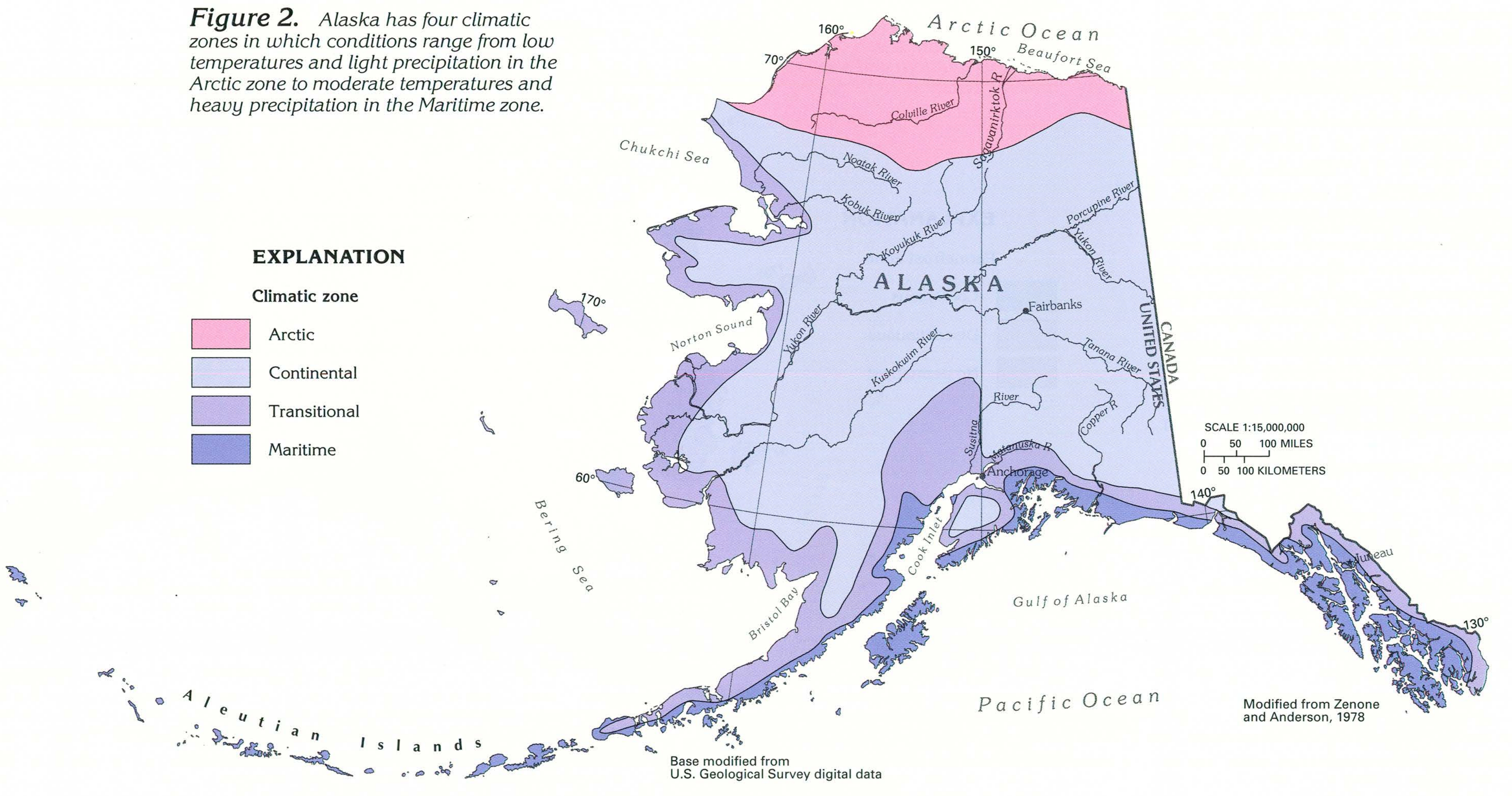


Figure 2. Alaska has four climatic zones in which conditions range from low temperatures and light precipitation in the Arctic zone to moderate temperatures and heavy precipitation in the Maritime zone.

CLIMATE

Alaska has a variable climate because of its large size, position between two oceans, high latitude, and range in altitude of the land surface. The State is divided into four climatic zones, based on variations in precipitation and temperature (**fig. 2**). The Arctic zone is characterized by average annual precipitation of less than 20 inches and an average annual temperature of 20 degrees Fahrenheit or less; seasonal variation in temperature is small in this zone. The Continental zone extends over about two-thirds of the State and is characterized by about 20 inches of average annual precipitation and an average temperature of about 22 degrees Fahrenheit. Temperature extremes are greater in the Continental zone than in the other climatic zones. Average annual precipitation in the narrow Transitional zone is about 30 inches, and temperatures average about 27 degrees Fahrenheit annually. The Maritime zone is extremely wet compared to the other three climatic zones; it averages about 70 inches of precipitation annually. Average annual temperature in the Maritime zone is about 42 degrees Fahrenheit. This zone lacks prolonged periods of freezing weather at low altitudes and is characterized by cloudiness and frequent fog. The combination of heavy precipitation and low temperatures at high altitudes in the coastal mountains of southern Alaska accounts for the numerous mountain glaciers.

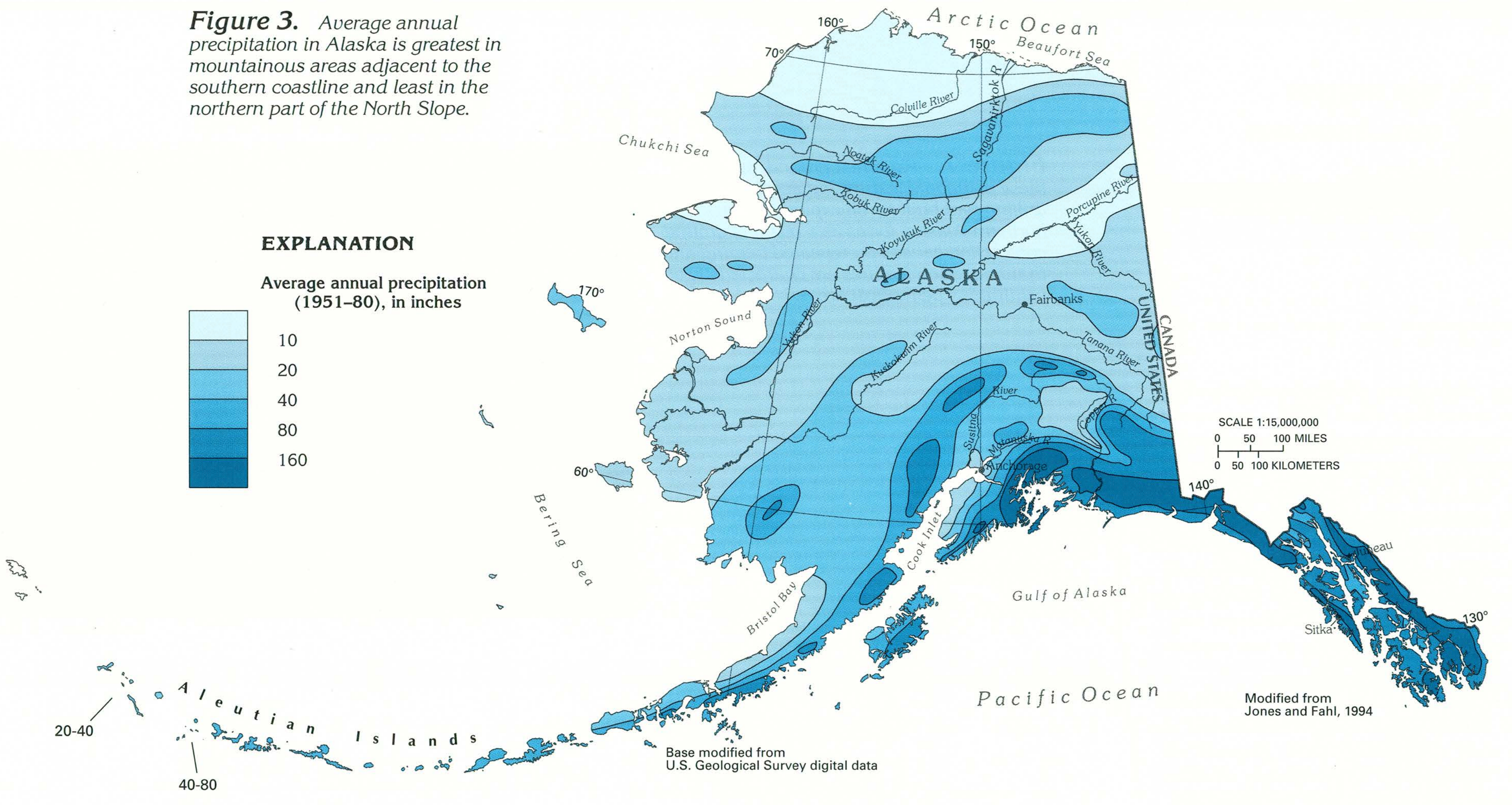


Figure 3. Average annual precipitation in Alaska is greatest in mountainous areas adjacent to the southern coastline and least in the northern part of the North Slope.

PRECIPITATION AND RUNOFF

Average annual precipitation (1951–80) varies greatly in Alaska (**fig. 3**). Areas along the northern part of the North Slope receive less than 10 inches of average annual precipitation, whereas more than 160 inches has been recorded in several places in the southern part of the State, adjacent to the Gulf of Alaska and the Pacific Ocean. Locally, Sitka in the southeastern part of the Maritime climatic zone receives more than 300 inches of precipitation. The amount of precipitation is directly related to topography; high, rugged mountains receive the greatest amounts of precipitation and lowland areas receive least (compare **figs. 1** and **3**).

Much of the precipitation falls as snow from November through March. Snow might fall year-round in the high mountains, where much of it is stored for long periods in glaciers and icefields. The glaciers of Alaska extend over about 17,000 square miles, which is about the size of the combined areas of Massachusetts and New Hampshire; perennial snowfields extend over an additional 13,000 square miles. The water content of the glacial ice is not released until the ice has moved to altitudes sufficiently low to allow the ice to melt. Likewise, water that is stored as snow on the land surface is not released until the spring melt. Several months (in the case of snow) or many years (in the case of glacial ice) may elapse between the time that precipitation falls and the time that it runs off.

Average annual runoff (1951-80) in Alaska ranges from less than 10 inches in large areas of the northern and central parts of the State, and small areas near Cook Inlet and along part of the Copper River, to more than 160 inches in local areas in the southern and southeastern parts of the State (**fig. 4**). The pattern of distribution of runoff is similar to that of precipitation: both are least in lowland areas and greatest in mountainous areas. Average annual runoff over about two-thirds of Alaska is less than 20 inches.

Average annual precipitation minus the total of average annual direct runoff plus evapotranspiration (the combination of evaporation and transpiration by plants) is the amount of water potentially available to infiltrate downward to aquifers in their recharge areas. Although about one-half of Alaska receives less than 20 inches of average annual precipitation (**fig. 3**), conditions of low temperature, high humidity, and cloudy skies that prevail over most of the State minimize the rate of evaporation. Short summers minimize the time during which vegetation actively grows and, thus, negligible amounts of water are returned to the atmosphere by evapotranspiration. The small amount of evapotranspiration that does occur, however, may be a large percentage of the precipitation that falls in northern and western Alaska. Perennially frozen ground, or permafrost, inhibits infiltration of precipitation to underlying aquifers and promotes rapid runoff to streams.

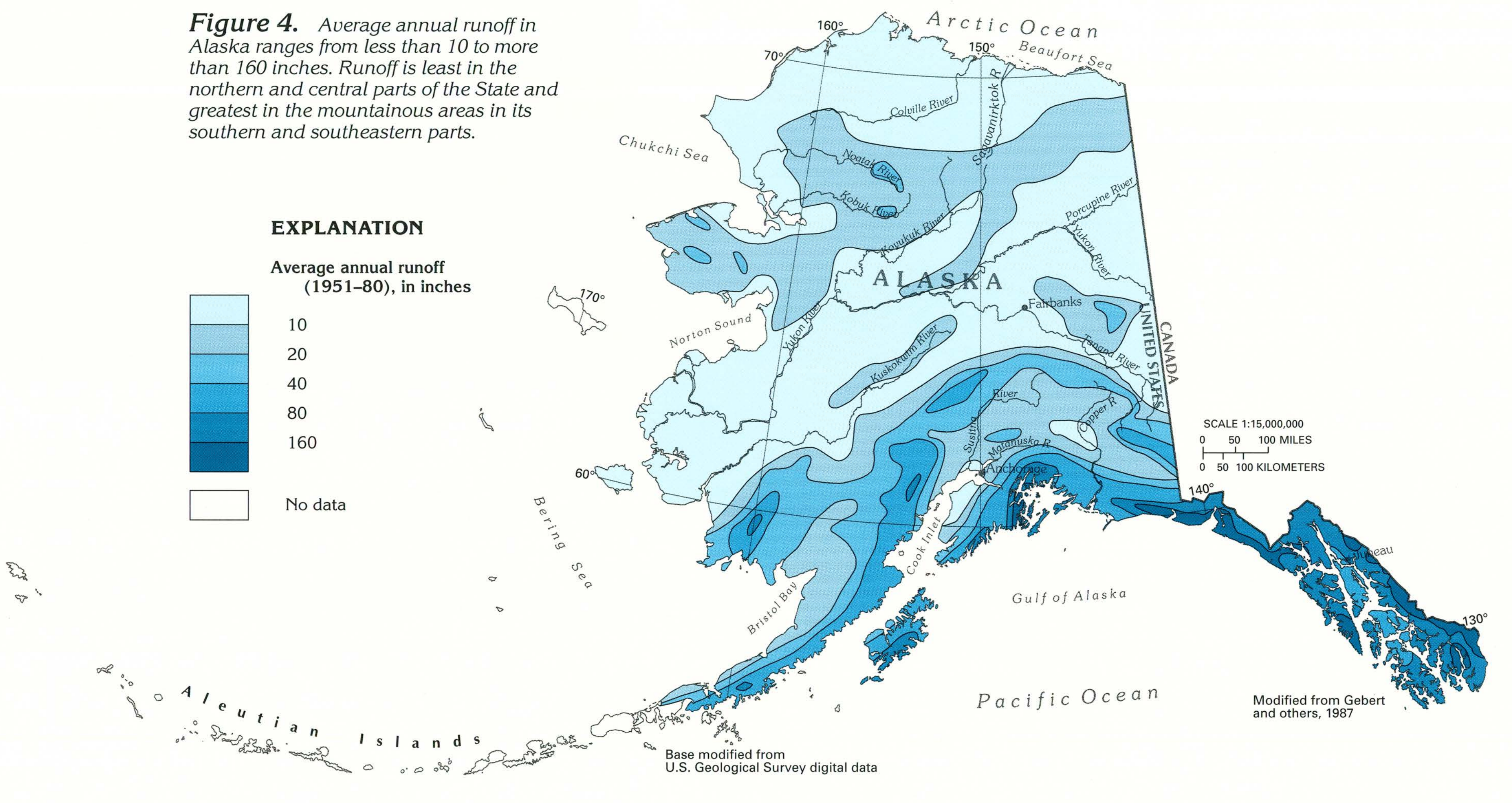


Figure 4. Average annual runoff in Alaska ranges from less than 10 to more than 160 inches. Runoff is least in the northern and central parts of the State and greatest in the mountainous areas in its southern and southeastern parts.

PERMAFROST

Permafrost is soil, unconsolidated deposits, or bedrock that has been continuously at a temperature of 32 degrees Fahrenheit or less for two or more years. The term is synonymous with "perennially frozen ground" but is defined solely on the basis of temperature; locally, permafrost might contain very little water or ice, or might contain highly mineralized water that remains liquid at temperatures less than 32 degrees Fahrenheit. Most permafrost, however, is consolidated by ice.

Permafrost is widespread in Alaska (**fig. 5**), but occurs only in small areas at high altitudes elsewhere in the United States. The thickness and areal continuity of permafrost are greatest in the continuous permafrost zone of northern Alaska and diminish southward. Locally, permafrost extends to depths of 2,000 feet below land surface in parts of the continuous permafrost zone. The wide zone of discontinuous permafrost shown in **figure 5** contains isolated or interconnected unfrozen zones within the permafrost. In this zone, the thickness and lateral continuity of the permafrost decrease southward until only scattered, isolated areas of frozen ground are found near the southern limit of the zone. Areas near the southern and southeastern coasts of Alaska generally contain no permafrost.

The occurrence of permafrost is controlled by the heat balance at the surface of the earth. This balance is affected regionally by the average annual air temperature, which usually must be several degrees below 32 degrees Fahrenheit in order for permafrost to form and persist. The southward increase in average annual air temperature in Alaska is directly reflected by a southward decrease in the thickness and areal continuity of permafrost. The thickness of permafrost is determined by the average annual temperature of the ground surface, thermal properties of the soil and rock, and the geothermal gradient (the natural increase in the temperature of the earth with depth). Where the average annual ground-surface temperature is below freezing, permafrost may form and extend downward until the heat gained from the earth raises the local temperature above the freezing point. Much of Alaska's permafrost is thought to have formed partly during the Pleistocene Epoch, when temperatures were much lower than at present.

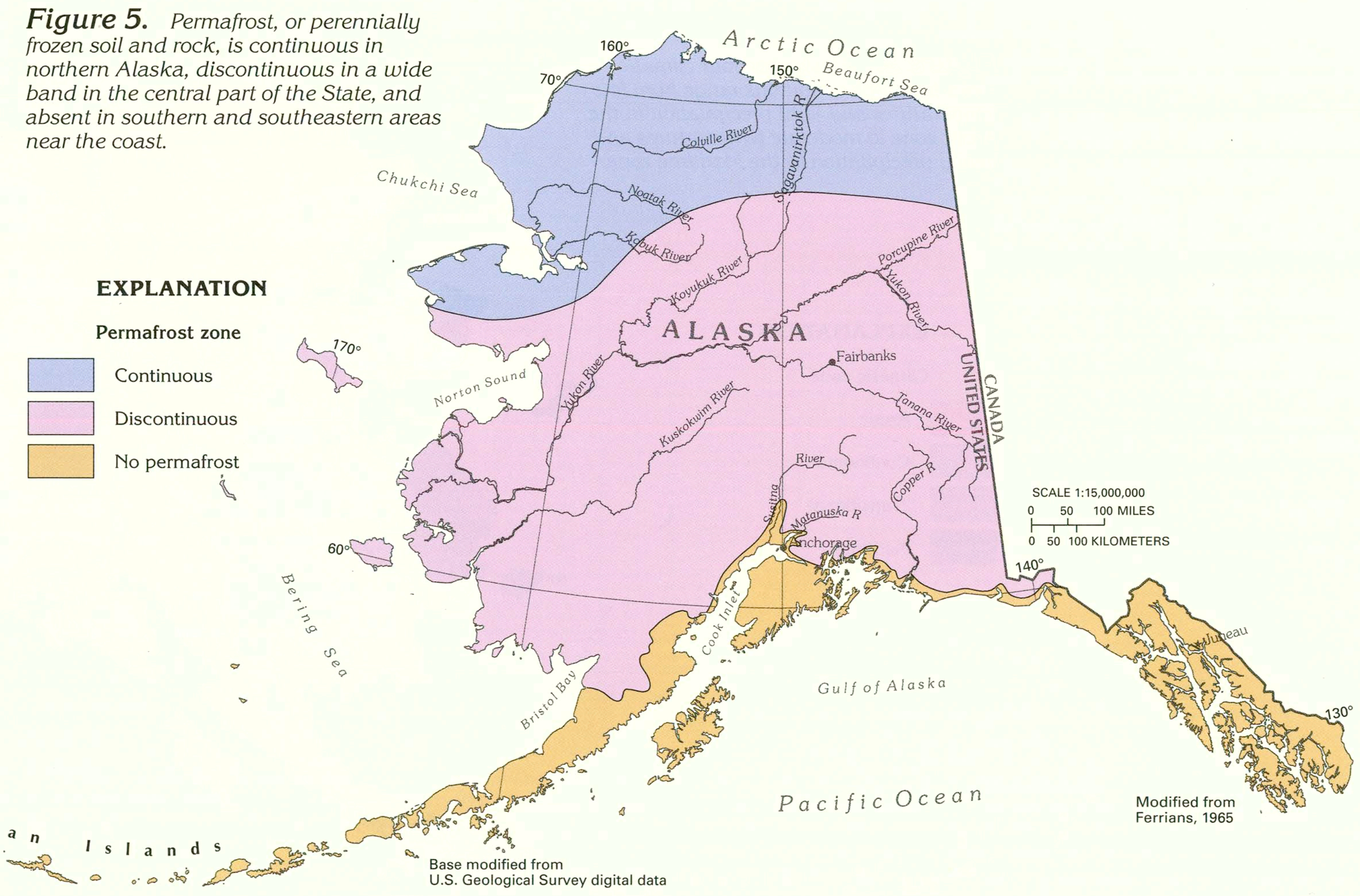


Figure 5. Permafrost, or perennially frozen soil and rock, is continuous in northern Alaska, discontinuous in a wide band in the central part of the State, and absent in southern and southeastern areas near the coast.

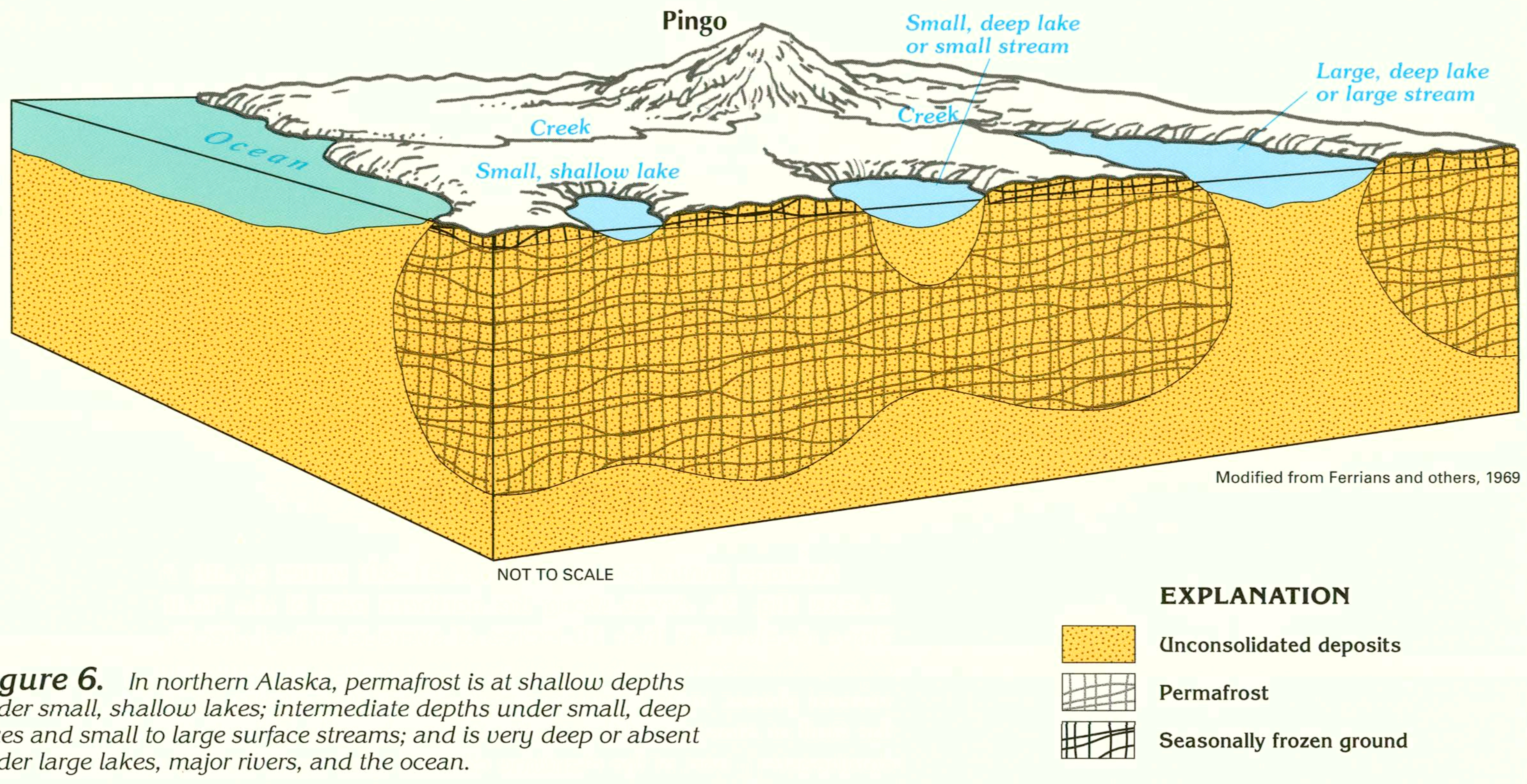


Figure 6. In northern Alaska, permafrost is at shallow depths under small, shallow lakes; intermediate depths under small, deep lakes and small to large surface streams; and is very deep or absent under large lakes, major rivers, and the ocean.

Factors that locally affect the surface heat balance, and thus, the presence and thickness of permafrost, include soil and rock type, relief, slope aspect (steepness and the direction which the slope faces), vegetation, snow cover, and the presence of surface-water bodies or flowing ground water. Different types of soils and rocks conduct heat at different rates and, thus, affect the depth and thickness of permafrost. Unvegetated soils may be warmer than vegetated soils because they lack the shading effect of the vegetation. In areas underlain by intrusive igneous rocks, the geothermal gradient may be higher than normal, thus limiting the thickness of permafrost, and where thermal springs issue from such rocks, they provide enough heat to locally thaw the permafrost. In the zone of discontinuous permafrost, silt in the alluvial and glacial deposits in lowlands is more likely to contain permafrost than sand and gravel interbedded with the silt. The sand and gravel beds might contain moving ground water that conducts sufficient heat to melt the permafrost. The insulating effect of thick snow tends to prevent the formation of permafrost locally; thick snow accumulations are more likely to form on gentle slopes than on steep slopes. Southward-facing slopes receive more solar radiation and, thus, are less likely to be underlain by permafrost than are northward-facing slopes. The warming effect of streams, rivers, lakes, and the ocean may extend to a depth of several hundred feet and result in local areas where permafrost is thin or absent.

The relation of surface-water bodies to the depth and thickness of permafrost in the zone of continuous permafrost is shown in **figure 6**. Beneath the ocean, large, deep lakes, or large streams, permafrost is thin or might be absent. Beneath small, deep lakes or streams that are perennially ice-free, an unfrozen zone overlies the permafrost but is bounded by it on the sides. The water in such an unfrozen zone commonly is highly mineralized. Beneath small, shallow lakes or creeks that completely freeze during the winter, permafrost is present only a few feet below the bottom of the surface-water body. In the discontinuous permafrost zone, the permafrost is thinner, and most lakes and large rivers are underlain by unfrozen zones that perforate the permafrost.

Human activities can affect the local thickness of permafrost because changes in ground surface temperature of only a few degrees can change permafrost thickness. Removing natural vegetation and its insulating effect in the process of clearing land causes increased solar absorption, a rise in surface temperature, and thinning of permafrost. Conversely, adding fill during road building or other construction projects increases the thickness of insulating material above the permafrost and under these insulated roadways the permafrost is less likely to melt. Heat radiating from the floors of buildings constructed directly on the land surface can cause thinning of permafrost, whereas the shading effect of buildings constructed on pilings creates a less likely chance of the permafrost melting.

Permafrost is reflected by distinctive geomorphic features at the land surface. Small lakes are common to abundant in permafrost areas. In the zone of discontinuous permafrost, many of these lakes are "thaw lakes" that occupy shallow depressions and are unfrozen only in summer. Beaded drainage, or streams along which small pools appear to be connected like beads on a string, is an indicator of permafrost areas. Patterned (polygonal) ground such as that shown in **figure 7** forms in permafrost areas where the ground freezes and then contracts on further cooling. Cracks that open during the contraction propagate downward well into the permafrost, where the temperature remains below freezing even during the melt season. When spring melt occurs at the surface, water runs down into the crack and refreezes at depth. This cycle of freezing, contraction, melting, and freezing again occurs each year, adding annual growth margins to the wedges, which intersect to form polygons. Pingos, or isolated, steep-sided, circular to oval hills (**fig. 8**) that range from 10 to more than 100 feet in height, form in permafrost areas. One way in which pingos form is by freezing of thawed and saturated sediments of drained lake basins. The sediments freeze inward from the sides of the basin and downward from the surface, and expand as they freeze. Water may be expelled from the sediments due to the volume expansion created by the freezing. The water pressure pushes upward an area of thin frozen sediment to form the core of a pingo. A few feet of silt, sand, and peat overlie the ice core.

Figure 7. Patterned ground, such as these polygonal features adjacent to a drilling pad built for oil exploration in northern Alaska, forms as a result of ground contraction caused by repeated freezing and thawing. Such features are characteristic of continuous permafrost areas.

George Gryc, U. S. Geological Survey, 1985

Figure 8. Some pingos, or low, circular hills such as the two shown here, form in the basins of abandoned lakes in permafrost areas. Upward expansion of water under pressure from ice that freezes inward from the basin margins forms the cores of the pingos.

George Gryc, U. S. Geological Survey, 1985

RELATION OF PERMAFROST AND GROUND WATER

The principles of ground-water recharge, movement, and discharge are, in general, as valid in permafrost areas as in more temperate regions. However, ground-water flow systems in permafrost areas are affected by cold climate and the presence of perennially frozen ground. The generalized diagram of permafrost conditions shown in **figure 9** is representative of the northern and middle parts of the zone of discontinuous permafrost. The top of perennially frozen ground is called the permafrost table. Above the permafrost table is the active layer, a zone that freezes in winter and thaws in summer; permeable, saturated parts of the active layer constitute suprapermafrost aquifers. These aquifers are seasonal and are primarily useful as a summer water supply where they contain water of usable chemical quality. Suprapermafrost aquifers are a source of freshwater for some villages near the Arctic Ocean. In recent years, however, water pumped from freshwater lakes in summer and stored in heated tanks for winter use is a more likely source of supply. The permafrost table forms a basal confining unit for the suprapermafrost aquifers.

Permeable material below the base of permafrost constitutes subpermafrost aquifers. In the zone of continuous permafrost, these aquifers consist mostly of consolidated rock; in the discontinuous permafrost zone, they commonly consist of unconsolidated deposits. Subpermafrost aquifers are used as sources of water supply in parts of the basins of the Yukon and Tanana Rivers where the aquifers contain freshwater. However, subpermafrost aquifers in parts of northern and western Alaska and in the Copper River Lowland contain highly mineralized water.

Permafrost affects ground-water recharge, movement, and discharge. The frozen ground blocks the downward percolation of rainfall or meltwater, and thus restricts recharge to subpermafrost aquifers. Where the permafrost table is shallow, it can perch water near the land and surface. Permafrost also blocks the lateral movement of ground water, and acts as a confining unit for water in subpermafrost aquifers. Discharge of water confined beneath the permafrost is possible only through unfrozen zones, or taliks, that perforate the permafrost layer. Although a huge quantity of water is stored in the permafrost, the water cannot be obtained and the presence of thick, continuous permafrost greatly limits the usefulness of most shallow aquifers.

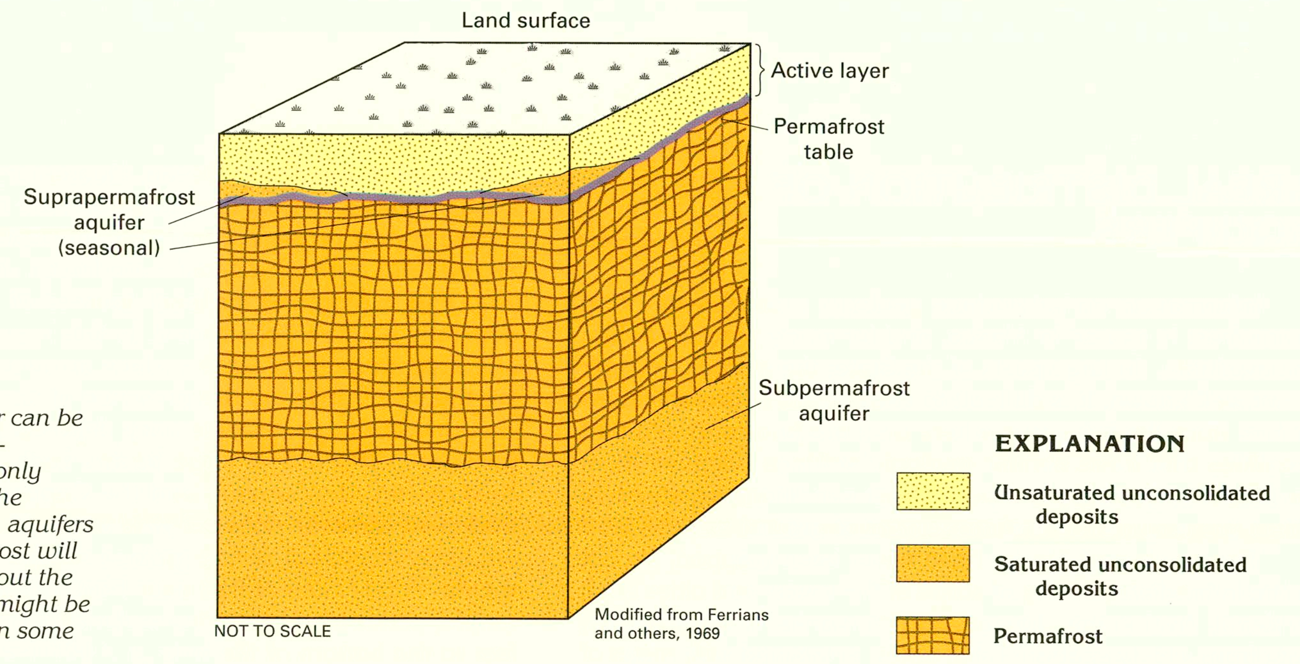


Figure 9. *Water can be obtained from suprapermafrost aquifers only seasonally, during the summer. In contrast, aquifers beneath the permafrost will yield water throughout the year, but the water might be highly mineralized in some areas of Alaska.*

GEOLOGY

The rocks and unconsolidated deposits exposed in Alaska range in age from Precambrian to Holocene. The distribution of major categories of rock types is shown by a generalized geologic map (**fig. 10**). Within each major mapped category, rocks younger or older than those represented by the category might crop out, but are not shown because of the map scale. Glacial drift deposited during the Pleistocene Epoch by large valley glaciers mantles mountain flanks and adjacent lowland areas in most of the mountainous areas of Alaska. These drift deposits and large areas of windblown silt (called loess) derived from glacial deposits are likewise not shown on the map. Although consolidated bedrock locally yields water to wells, especially where the bedrock is fractured or contains large solution openings, most ground water is withdrawn from permeable Quaternary deposits.

Modern interpretations of the complex geology of Alaska are based on the concept that the State is a mosaic of geologic terranes. A terrane is a body of rock of regional extent that is bounded by faults, and whose geologic history is different than that of adjacent terranes. All the terranes in Alaska represent blocks of the Earth's crust that have moved large or small distances relative to each other. The movement might have been translational (lateral movement without rotation) or rotational or both. Some of the terranes may have moved only a short distance, whereas others may have moved laterally for several hundred miles or rotated as much as 135 degrees. The pattern of terranes in Alaska reflects the interactions of oceanic crustal plates with the North American plate; large-scale lateral and rotational movements, rifting, and volcanic activity result from these interactions. A detailed discussion of Alaskan terrane theory and evidence is beyond the scope of this Atlas; an excellent summary of the topic can be found in Plafker and Berg (1994), listed in the References section of this atlas. Some of the large faults shown in figure 10 separate terranes.

Lower Paleozoic and Precambrian metamorphic rocks underlie most of central Alaska and much of the Seward Peninsula, the Yukon–Tanana Upland, the Kokrine–Hodzana Highlands, and the southern flank of the Brooks Range (compare **fig. 10** with **fig. 1**). These rocks are primarily gneiss, schist, phyllite, and quartzite, but locally include argillite, marble, and several kinds of metasedimentary rocks. Local areas of Lower Paleozoic and/or Precambrian sandstone, limestone, shale, and chert in the northeast Brooks Range are mapped in this category. In the eastern part of the Yukon–Tanana Upland, Paleozoic intrusive and volcanic rocks of various kinds intrude, overlie, or are faulted against lower Paleozoic and Precambrian metamorphic rocks in an area of complex geology.

Cambrian through Devonian sedimentary rocks are widespread in the Brooks Range, the northwestern part of the Yukon–Tanana Upland, the northwestern and eastern parts of the Kuskokwim Mountains, the northeastern part of the Nushagak–Big River Hills, and southeastern Alaska. Smaller areas of these rocks are exposed in the easternmost part of the Alaska Range and in the Northern Foothills that border that range. These rocks consist mostly of sandstone, shale, and siltstone, but also include beds of limestone, dolomite, and chert. Cambrian through Devonian sedimentary rocks are complexly folded and faulted in the Brooks Range and are less deformed elsewhere.

Mississippian through Permian sedimentary rocks crop out mostly along the northern flanks of the Brooks Range, in the eastern part of the Porcupine Plateau (compare **fig. 10** and **fig. 1**), in the northern and eastern parts of the Alaska Range, in the Wrangell Mountains and the northeastern part of the Kenai-Chugach Mountains, and locally in southeastern Alaska. These rocks are mostly limestone, shale, siltstone, and sandstone, but include beds of conglomerate, dolomite, and chert. Locally, marble, argillite, and metasedimentary and metavolcanic rocks are mapped in this category.

Upper Paleozoic metamorphic, sedimentary, and igneous rocks are exposed mostly in southeastern Alaska, the western parts of the Ahklun Mountains, and the southern part of the Nulato Hills. Metamorphic rock types mapped in this category include schist, gneiss, phyllite, and slate; sedimentary rocks include limestone, dolomite, chert, tuff, and volcaniclastic rocks; and igneous rocks include gabbro and basaltic to andesitic lava flows.

Mesozoic sedimentary rocks underlie large parts of the Arctic Foothills and the Arctic Coastal Plain, the Baird Mountains and the Indian River Upland south of the Brooks Range, most of the Nulato Hills, the Nushagak–Big River Hills, the Kuskokwim and the Ahklun Mountains, and the southern part of the Alaska Range. Smaller exposures of these rocks are in the Wrangell and the Talkeetna Mountains, the northern part of the Aleutian Range, the Kodiak Mountains, and the Chilkat–Baranof Mountains (compare **fig. 10** with **fig. 1**). These rocks are mostly shale, siltstone, and sandstone, but locally include limestone and large deposits of coal.

Mesozoic volcanic rocks crop out in large areas of central Alaska, from the eastern side of the Seward Peninsula to the westernmost part of the Yukon-Tanana Upland to the northern part of the Kuskokwim Mountains. Smaller areas of these rocks are exposed in the Nulato Hills, the western part of the Ahklun Mountains, the Talkeetna and the Wrangell Mountains, and southeastern Alaska. These rocks range in composition from andesite to basalt.

Mesozoic intrusive rocks crop out in smaller areas than the Mesozoic volcanic rocks, but are widespread in central, southern, and southeastern Alaska. These rocks are mostly in upland and mountainous areas and range in composition from granite to gabbro. The widespread occurrence of these rocks, along with that of the Mesozoic volcanic rocks, shows that igneous activity was greatest in Alaska during Mesozoic time.

Mesozoic metamorphic, volcanic, and igneous intrusive rocks underlie large parts of the Kenai–Chugach Mountains and a small part of the Kodiak Mountains. These rocks consist of greenstone, limestone, chert, granodiorite, schist, and layered gabbro. Their contacts and extent are incompletely known because of glacial cover in many places.

Tertiary sedimentary rocks crop out mostly in the northeastern part of the Arctic Coastal Plain, near Cook Inlet and the northern part of the Gulf of Alaska, and in the northern part of the Aleutian Range. Smaller exposures of these rocks are along part of the Northern Foothills that flank the Alaska Range, and on the south-central flank of the Alaska Range. These rocks are primarily sandstone, siltstone, and shale, but also contain beds of coal, mudstone, and conglomerate.

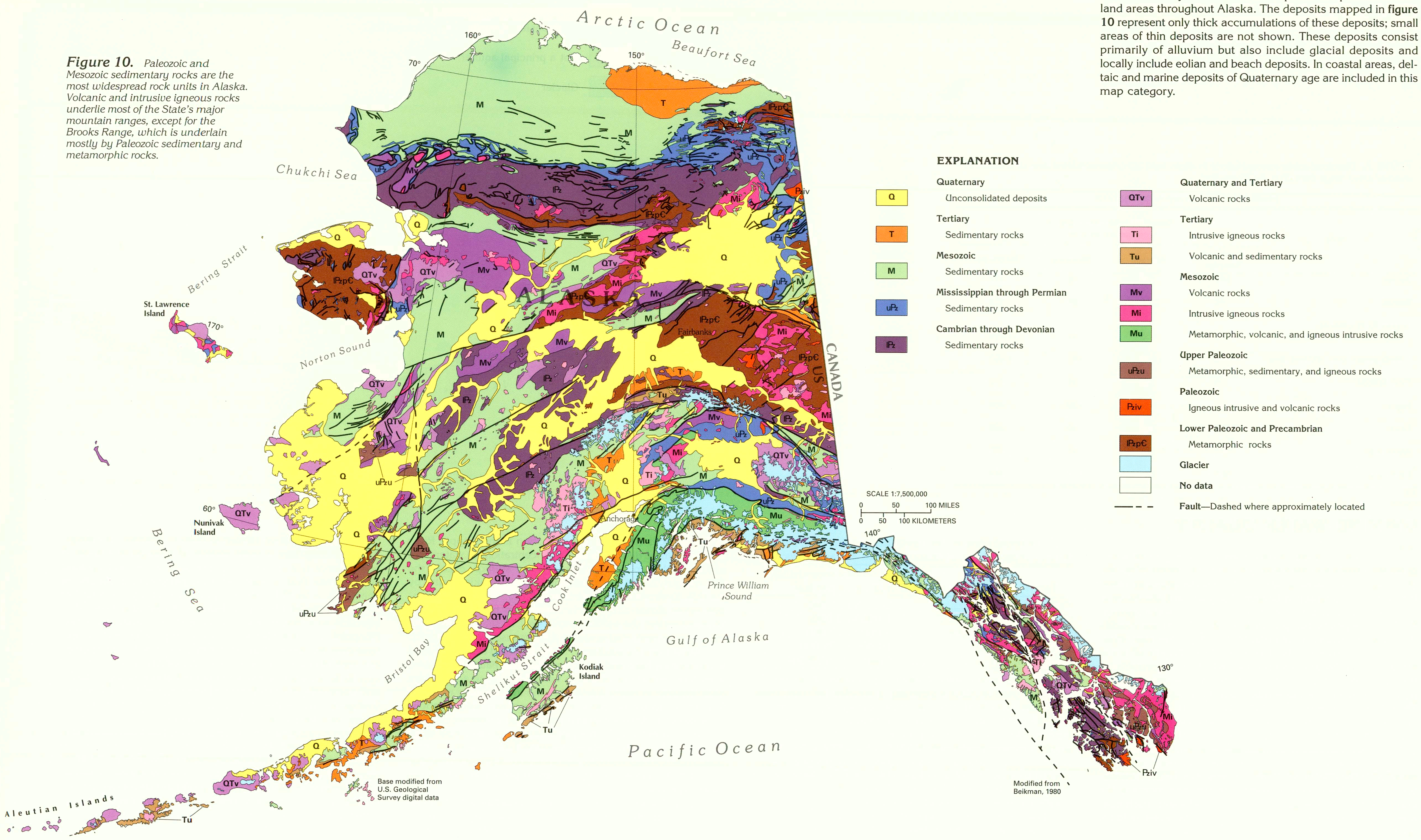
Tertiary intrusive igneous rocks are prominent in the southern part of the Alaska Range and in the Talkeetna Mountains. Smaller exposures of these rocks are found in the eastern part of the Yukon–Tanana Upland, the Kodiak Mountains, and on some of the Aleutian Islands. These rocks range in composition from gabbro to granite.

Tertiary volcanic and sedimentary rocks are exposed mostly in the area around Prince William Sound, the southeastern side of Kodiak Island, and in the Aleutian Islands. These rocks consist of complexly interbedded sedimentary and volcanic rocks of early Tertiary (Paleocene through Oligocene) age.

Quaternary and Tertiary volcanic rocks ranging in composition from rhyolite to basalt are prominent in large parts of central and southern Alaska and in the Aleutian Islands. Volcanic eruptions continue along Cook Inlet, on the Alaska Peninsula, and in the Aleutian Islands at the present time.

Quaternary unconsolidated deposits are present in lowland areas throughout Alaska. The deposits mapped in **figure 10** represent only thick accumulations of these deposits; small areas of thin deposits are not shown. These deposits consist primarily of alluvium but also include glacial deposits and locally include eolian and beach deposits. In coastal areas, deltaic and marine deposits of Quaternary age are included in this map category.

Figure 10. *Paleozoic and Mesozoic sedimentary rocks are the most widespread rock units in Alaska. Volcanic and intrusive igneous rocks underlie most of the State's major mountain ranges, except for the Brooks Range, which is underlain mostly by Paleozoic sedimentary and metamorphic rocks.*



AREAL DISTRIBUTION OF AQUIFERS

Information on subsurface geology, ground water, and permafrost is sparse in Alaska, and for many places no data are available. In large parts of the State, the surface geology is not well known. It is difficult to extrapolate hydrologic conditions from the few areas where they are known to different localities that have similar geologic settings because local variations in geologic and permafrost conditions significantly affect the occurrence and movement of ground water.

The aquifers of Alaska have never been mapped, except in the immediate vicinity of some of the towns and cities such as Kenai, Anchorage, Juneau, and Fairbanks. In other places, data from widely scattered drill holes, combined with maps of the surficial geology, allow some inference about the availability of ground water. The distribution of coarse-grained, unconsolidated alluvial and glacial-outwash deposits of Quaternary age is shown in **figure 11**. In many areas, such as the Tanana River basin, these deposits comprise thick aquifers that yield large quantities of water to wells. In other areas, such as the Copper River basin, widespread Quaternary deposits consist mostly of lacustrine silt and clay that are underlain by saline water and do not comprise aquifers. In the coastal area between Norton Sound and Bristol Bay, Quaternary deposits extend over large areas but are generally too fine grained to yield significant amounts of water. However, sand and gravel deposits such as those that provide the water supply for Bethel locally form productive aquifers. From the Brooks Range northward to the Arctic Ocean, Quaternary deposits contain continuous permafrost and, therefore, are not aquifers. In the northern part of the zone of discontinuous permafrost, the alluvial and outwash deposits are frozen during much of the year and exploration for local sources of ground water has generally not been conducted. In this region, however, scattered occurrences of large surface accumulations of ice during the winter indicate the presence of local aquifers.

Unconsolidated Quaternary deposits may locally be as thick as 1,000 feet in large basins such as the Yukon, the Kuskokwim, the Tanana, and the Copper River. The entire thickness, however, does not yield water. At depth, the deposits are likely to consist of fine grained marine or lacustrine sediments. A test hole drilled near Fort Yukon in 1994, for example, penetrated lacustrine sediments from a depth of 600 feet to the bottom of the hole at 2,000 feet.

Igneous, metamorphic, and sedimentary rocks underlie about 70 percent of Alaska. Although these rocks generally yield smaller amounts of water to wells than coarse-grained alluvial and outwash deposits, they are important aquifers in some parts of the State. In the Fairbanks area, approximately half the residents obtain water from wells completed in bedrock. Large springs that issue from carbonate rocks in the eastern part of the Brooks Range are reported to discharge as much as 16,000 gallons per minute. Carbonate bedrock on Admiralty Island in southeastern Alaska also yields large quantities of water from well-developed cave systems. In general, the water-yielding capability of bedrock in Alaska is not well known, however, and bedrock aquifers are not mapped in **figure 11**.

Figure 11. *Coarse-grained alluvial and glacial-outwash deposits of Quaternary age are present in many of the lowland areas of Alaska and are known to yield large quantities of water in such places as Fairbanks and Anchorage. These coarse grained deposits are likely to yield water in other places, if the deposits are unfrozen.*

Table 1. *Dissolved-solids concentrations in water from the unconsolidated-deposit aquifers in selected areas range from 26 to 3,490 per liter*

[Modified from Zenone and Anderson, 1978]

Area	Dissolved-solids concentration (milligrams per liter)			
	Number of Samples	Average	Minimum	Maximum
Juneau	141	199	26	372
Haines	14	209	66	352
Copper River Lowland:				
Wells less than 100 feet deep	11	535	55	1,015
Wells greater than 100 feet deep	13	1,936	382	3,490
King Salmon	16	158	94	222
Homer	27	314	139	489
Kenai	140	209	50	368
Anchorage	567	159	93	225
Fairbanks	502	227	112	342

GROUND-WATER QUALITY

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

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

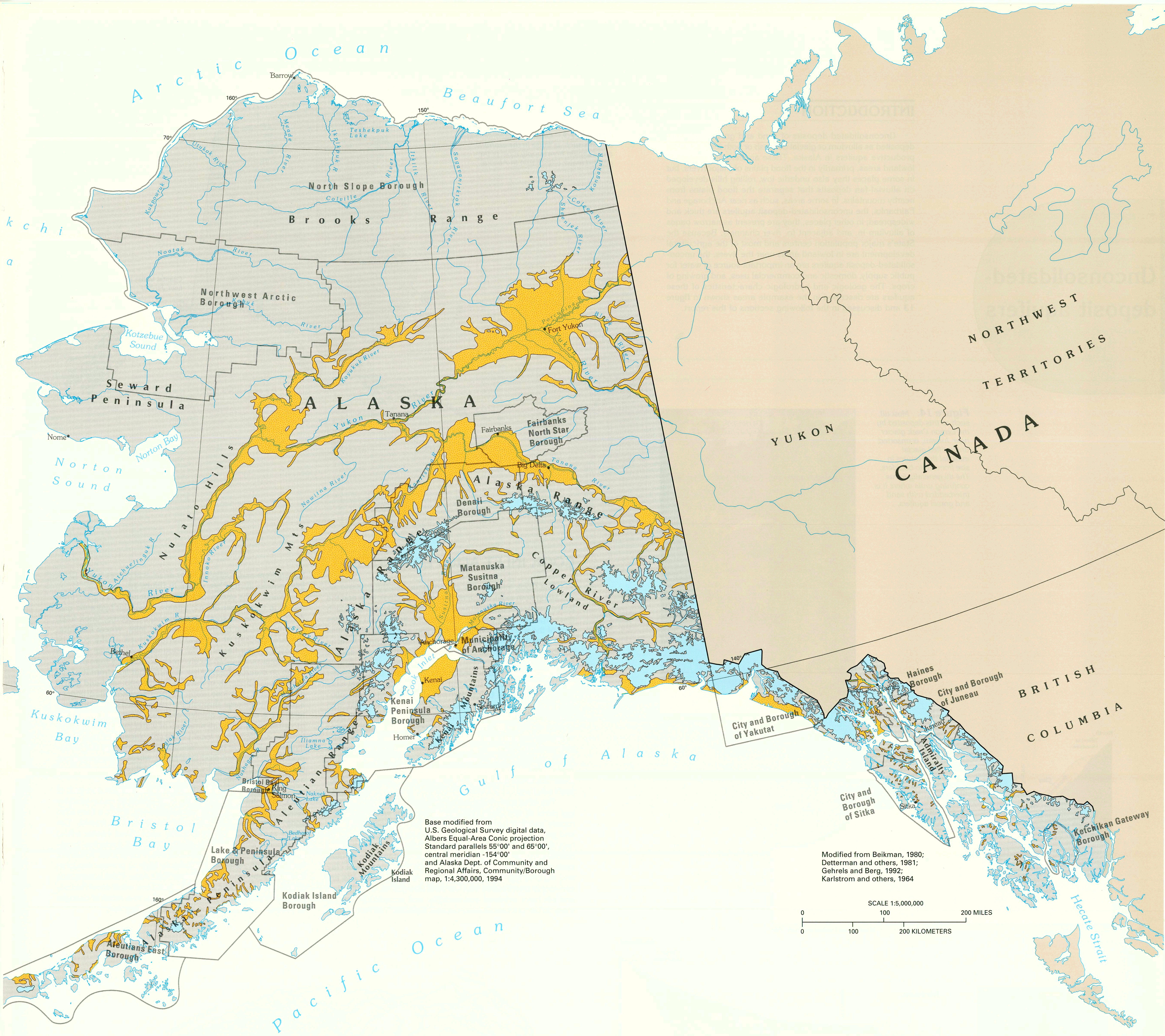
Term	Dissolved-solids concentration, in milligrams per liter
Freshwater	Less than 1,000
Slightly saline water	1,000 to 3,000
Moderately saline water	3,000 to 10,000
Very saline water	10,000 to 35,000
Brine	Greater than 35,000

The chemical quality of water from aquifers in unconsolidated deposits in Alaska generally is suitable for most uses. The water, classified by the dominant dissolved ions it contains, is a calcium bicarbonate or calcium magnesium bicarbonate type in inland areas. Locally, in areas near the coast, these aquifers contain moderately saline to very saline water in their downgradient parts, where the aquifer is hydraulically connected to seawater of a sodium chloride type. Water in the mixing zone between fresh and saline water in these coastal aquifers commonly is a sodium bicarbonate type.

Dissolved-solids concentrations in water from unconsolidated-deposit aquifers are less than 400 milligrams per liter in most places (**table 1**). An exception is the Copper River Lowland, where dissolved-solids concentrations in water from shallow and deep wells, and from some springs, exceed the 500 milligrams per liter recommended for drinking water by the U.S. Environmental Protection Agency. The large concentrations of dissolved solids in water from the Copper River Lowland reflect the upward movement of saline water from marine sediments that underlie the unconsolidated deposits.

Water from the aquifers in unconsolidated deposits is hard to moderately hard and, thus, may require treatment for some uses. Concentrations of iron in water from these aquifers are objectionable in many places, but the iron is easily removed from the water by inexpensive treatment. Iron concentrations in excess of 1,000 micrograms per liter are common; concentrations greater than 300 micrograms per liter can cause staining of laundry and porcelain plumbing fixtures, and impart a taste to the water. Locally, excessive concentrations of dissolved manganese and arsenic are reported in water from these aquifers.

Ground-water contamination from human activities can take place rapidly, and shallow aquifers such as those in unconsolidated deposits are particularly susceptible to contamination. Contamination related to human activities is categorized as being from a point source or a nonpoint source. A point source is a specific local site such as an underground storage tank that contains wastes, petroleum products, or chemicals; a landfill; a storage pond, pit, or lagoon; a spill of hazardous chemicals or petroleum products; or a disposal or injection well that receives municipal or industrial wastes. Nonpoint contamination sources are large-scale and can extend over hundreds of acres. Examples of nonpoint sources are: agricultural activities, such as applying fertilizer or chemicals to fields; urban areas with concentrations of septic tanks and cesspools; encroachment of saltwater or highly mineralized geothermal water; mining operations; oilfields and associated tank farms; and salt from highway deicing. Nitrate, a common contaminant from septic tanks, has been reported in ground water near Fairbanks in concentrations greater than the recommended Federal drinking-water standard of 10 milligrams per liter. These large nitrate concentrations, however, were present in places before significant development occurred, and are thought to result in part from the addition of nitrogen to the soil by plants such as alders.



The chemical quality of water from bedrock aquifers in Alaska is known from a few areas where dispersed residential wells have been drilled away from centralized water-distribution systems. In the vicinity of Fairbanks, water from wells completed in bedrock is generally a calcium bicarbonate type and usually is hard, especially on the lower slopes. Locally, concentrations of arsenic and nitrate in excess of the recommended Federal drinking-water standards are reported. Water of chemical quality suitable for most uses is reported from wells completed in bedrock aquifers in the Anchorage–Eagle River area and in coastal communities bordering the Kenai and the Kodiak Mountains. However, water from wells completed in coal-bearing Tertiary strata in the Cook Inlet Basin commonly contains objectionable concentrations of iron and hydrogen sulfide.

FRESH GROUND-WATER WITHDRAWALS

Although surface water is abundant in Alaska, many of the streams, rivers, and lakes are covered with ice for much of the year. In addition, streams that are fed by glaciers transport glacial silt which gives the water a milky appearance and renders it unsuitable for many uses unless the silt is removed by flocculation. Accordingly, ground water is an important source of supply, especially in the zones where permafrost is discontinuous or absent.

During 1990, ground water provided 23 percent of the total freshwater withdrawn in Alaska, but supplied 37 percent of the water withdrawn for public supply and 90 percent of that withdrawn for rural domestic use. Fairbanks, Juneau, and about 50 smaller communities depend almost entirely on ground water for supply. About 50 percent of the State's population is supplied by ground water.

The Municipality of Anchorage withdrew ground water at a rate of 11 million gallons per day during 1969, and withdrawals increased to more than 20 million gallons per day during 1985. Since 1985, however, Anchorage has constructed a new pipeline to Eklutna Lake north of the city. This lake and Ship Creek, which flows through the city, now supply most of the water needed by the municipality.

Most of the ground water in the Anchorage and Juneau areas is withdrawn from aquifers in unconsolidated deposits. Wells completed in unconsolidated deposits provide about one-half of the water withdrawn in the Fairbanks area; the remaining one-half is obtained from wells completed in bedrock. Bedrock supplies water to a significant number of wells in the hillside areas of Anchorage, on Kodiak Island, and on the Kenai Peninsula.

Total fresh ground-water withdrawals in Alaska during 1990 were about 63 million gallons per day (**fig. 12**). About 54 percent of this amount, or about 34 million gallons per day, was withdrawn for public supply. About 15 million gallons per day, or about 24 percent of the total withdrawals, were pumped for domestic and commercial use. Withdrawals for industrial, mining, and thermoelectric power use accounted for almost all the remainder of the water pumped. Only about 0.2 million gallons per day, or less than one-half of one percent, of the water withdrawn was used for agricultural purposes. About 48 million gallons per day of saline ground water was withdrawn for mining use during 1990.

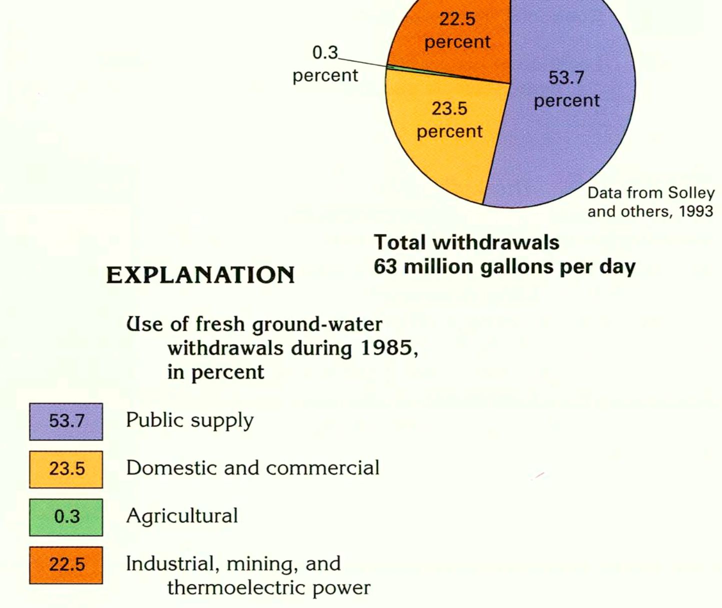


Figure 12. *More than one-half of the fresh ground water withdrawn in Alaska during 1990 was used for public supply. Domestic and commercial withdrawals were the second largest category of water use.*

Unconsolidated-deposit aquifers

INTRODUCTION

Unconsolidated deposits of sand and gravel that were deposited as alluvium or glacial outwash or both form the most productive aquifers in Alaska. These aquifers are present in lowland areas, primarily in the flood plains of major rivers, but in some places they also underlie low, rolling hills developed on alluvial-fan deposits that separate the flood plains from nearby mountains. In some areas, such as near Anchorage and Fairbanks, the unconsolidated-deposit aquifers are thick and widespread; in other places, they are present as narrow bands of alluvium in, and adjacent to, river channels. Because the State's major population centers and most of the agricultural development are in lowland areas near the rivers, the unconsolidated-deposit aquifers are an important source of water for public supply, domestic and commercial uses, and growing of crops. The geologic and hydrologic characteristics of these aquifers are described in the example areas shown in **figure 13** and discussed in the following sections of this report.

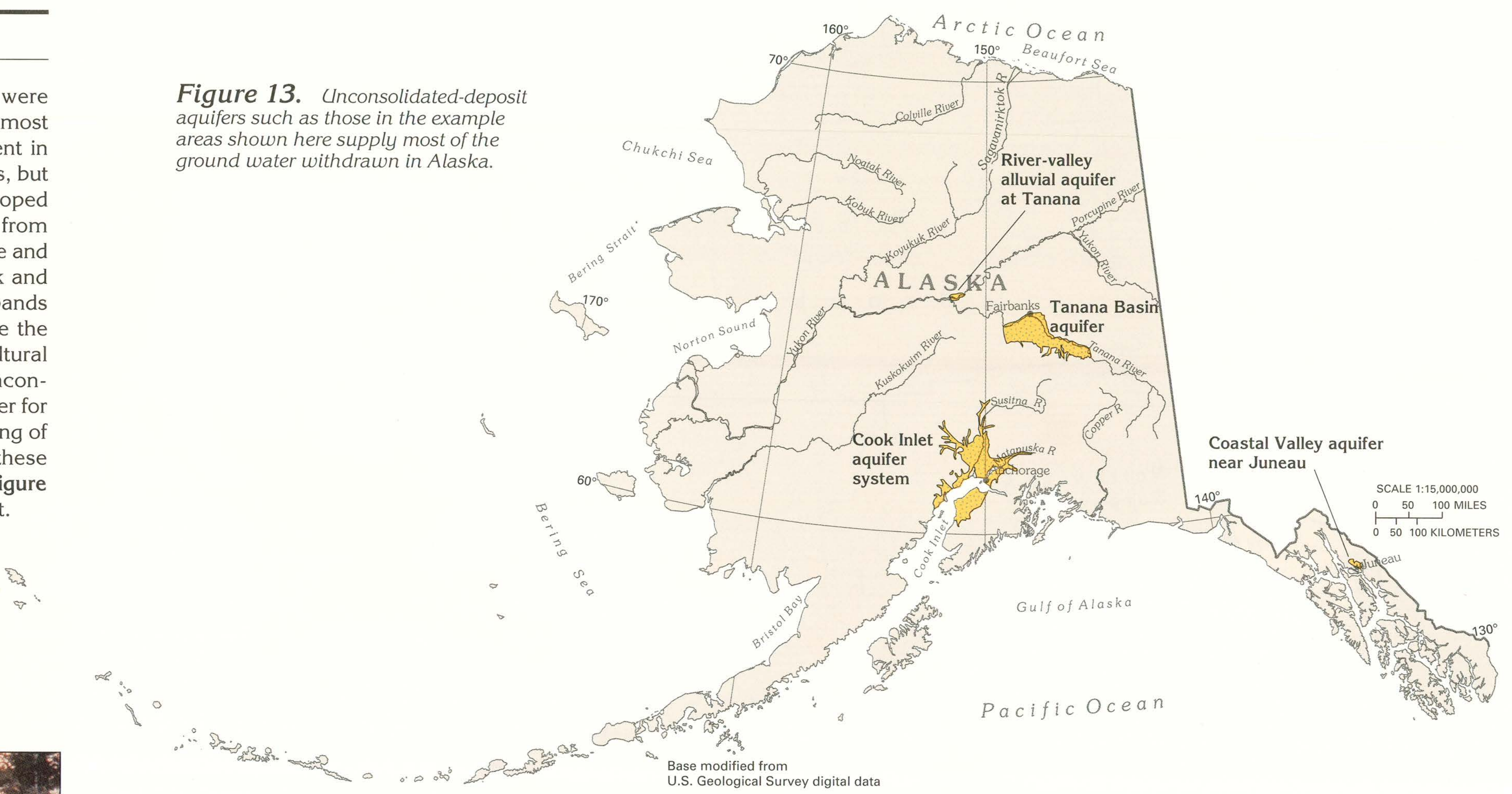
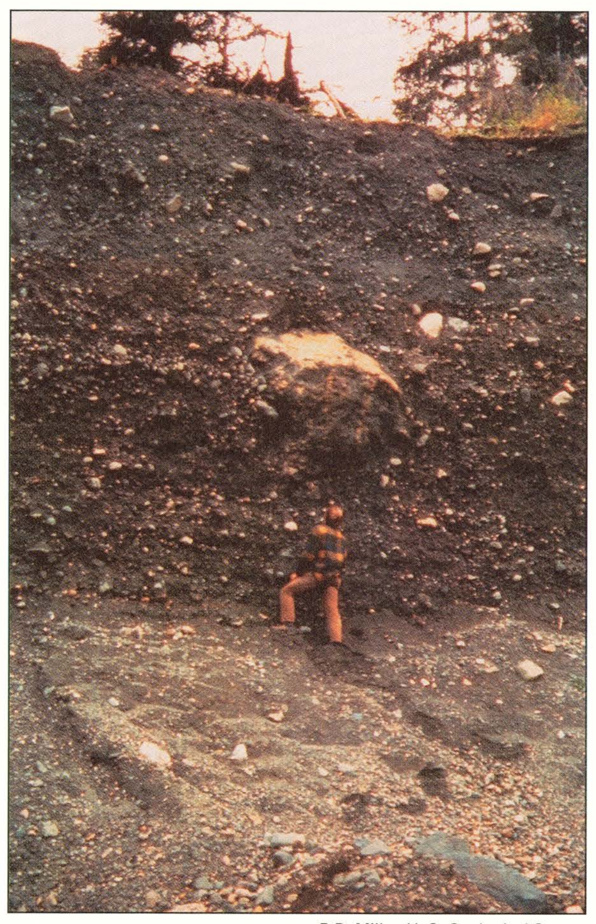


Figure 13. *Unconsolidated-deposit aquifers such as those in the example areas shown here supply most of the ground water withdrawn in Alaska.*



R.D. Miller, U. S. Geological Survey

Figure 14. *Most till, such as this deposited by the Lemon Creek glacier near Juneau, is unsorted, unstratified glacial material that ranges in size from silt to boulders. The till generally forms confining units where it is interbedded with sand and gravel aquifers.*

COOK INLET AQUIFER SYSTEM

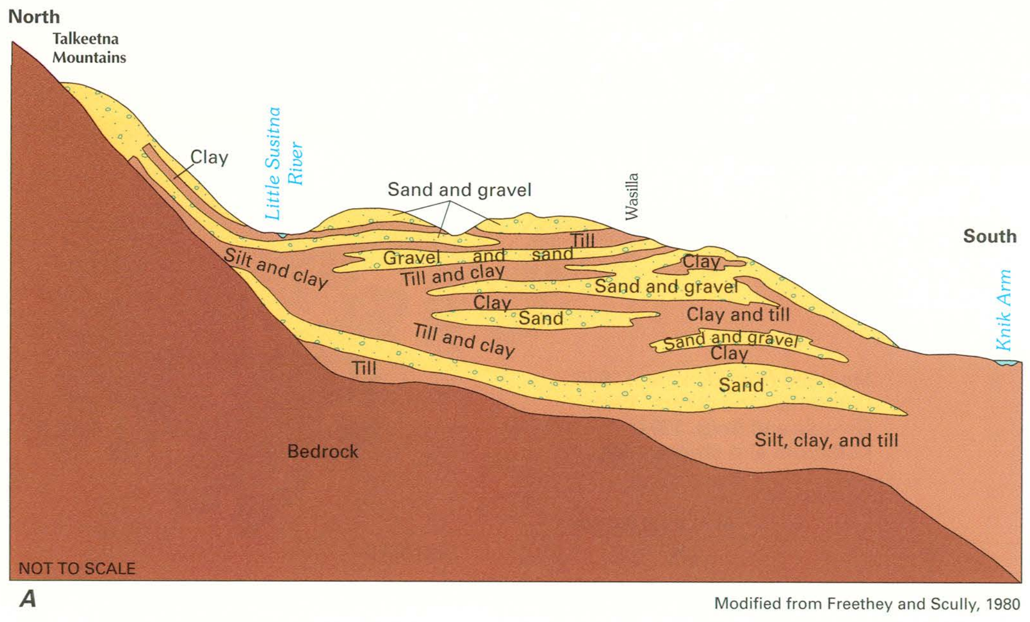
The Cook Inlet aquifer system underlies the lowland areas along both sides of the northern part of Cook Inlet and the lower reaches of the Susitna and the Matanuska Rivers which discharge into the inlet (**fig. 13**). The aquifer system provides part of the water supply for Anchorage and for smaller cities and towns including Palmer, Kenai, and Soldotna. A large number of domestic wells also obtain water from the aquifer system.

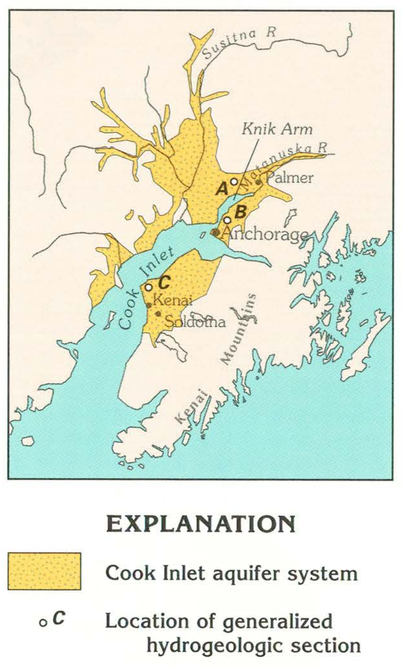
The unconsolidated sediments that make up the aquifer system consist of clay, silt, sand, gravel and boulders that were deposited primarily by glaciers but also by alluvial and colluvial processes. The sediments are complexly interbedded, with lenses and thin beds of sand and gravel interfingering with beds of clay, silt, and till. The stratigraphic complexity and great variability in grain size of the sediments causes discontinuity and variability in their hydraulic characteristics. Low-permeability sedimentary and metamorphic rocks underlie the aquifer system; locally, small volumes of water might move through these rocks and discharge upward to the unconsolidated-deposit aquifers.

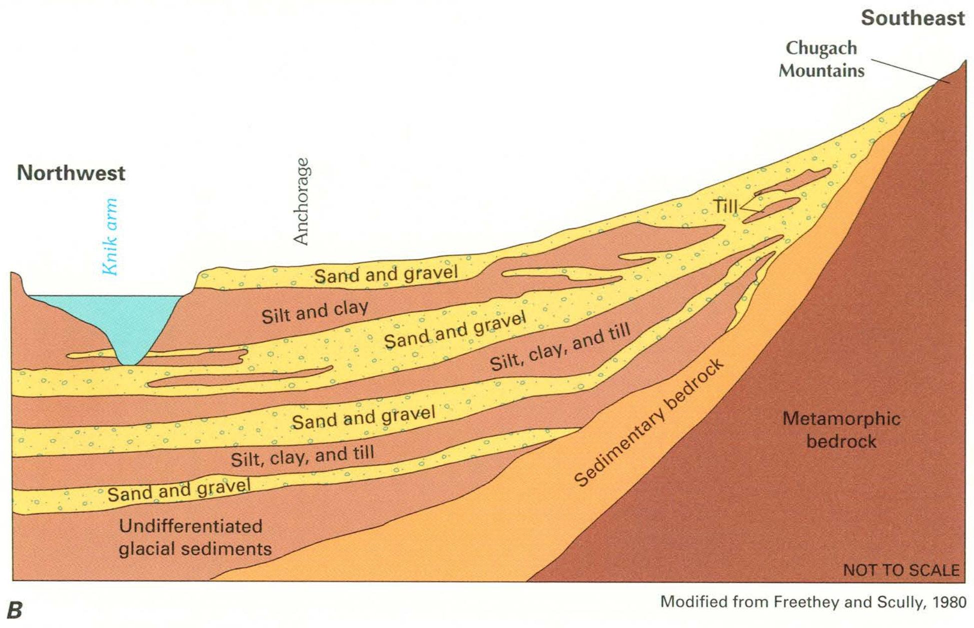
The sand and gravel beds that compose the water-yielding parts of the Cook Inlet aquifer system were deposited mostly as glacial outwash. Locally, alluvial deposits of sand and gravel are present in the upper parts of the aquifer system. Sand and gravel of colluvial origin flank the bedrock hills bordering the sedimentary basin that contains the aquifer system. Poorly sorted, unstratified till (**fig. 14**) or beds of clay and silt that represent glacial-lake or estuarine deposits are commonly interbedded with the sand and gravel. The till, clay, and silt have minimal permeability and commonly confine water in the unconsolidated-deposit aquifers. The relations of the aquifers and confining units at several places in the Cook Inlet aquifer system are shown in **figure 15**.

Water in the unconsolidated-deposit aquifers moves from recharge areas near the mountains, down the hydraulic gradient to discharge areas beneath major streams, Cook Inlet, or Knik Arm, the northern fork of the inlet. Where the aquifers are exposed at the land surface, such as the colluvial deposits on the flanks of the mountains or alluvial deposits near streams, they can receive recharge directly from precipitation on outcrop areas. Also, streams that flow from the low-permeability bedrock of the mountains onto sand and gravel deposits (**fig. 16**) lose water to the unconsolidated-deposit aquifers by leakage through the stream beds. The principal recharge areas for the aquifers are, thus, near the flanks of the mountain ranges. Small amounts of water might leak upward into the aquifers from local permeable zones in the underlying bedrock. Water moves laterally in the unconsolidated-deposit aquifers toward discharge areas, where it moves upward. Some water discharges by evapotranspiration from unconfined aquifers and withdrawals from wells.

The aquifers near Anchorage are the best known part of the Cook Inlet aquifer system. Two principal water-yielding zones contain most of the ground water (**fig. 15B**); a deep third zone is present in some places but is not well known. The upper zone contains water under unconfined (water table) conditions, whereas a fine-grained unit that underlies it creates confined (artesian) conditions in the lower zone. Hydraulic heads in both zones are sufficiently high to prevent intrusion of saline water from Cook Inlet or Knik Arm. Tidal fluctuations of as much as 37 feet in the inlet produce water-level fluctuations of as much as 4 feet in some wells, as a result of changes in pressure created by the rising and falling tide.







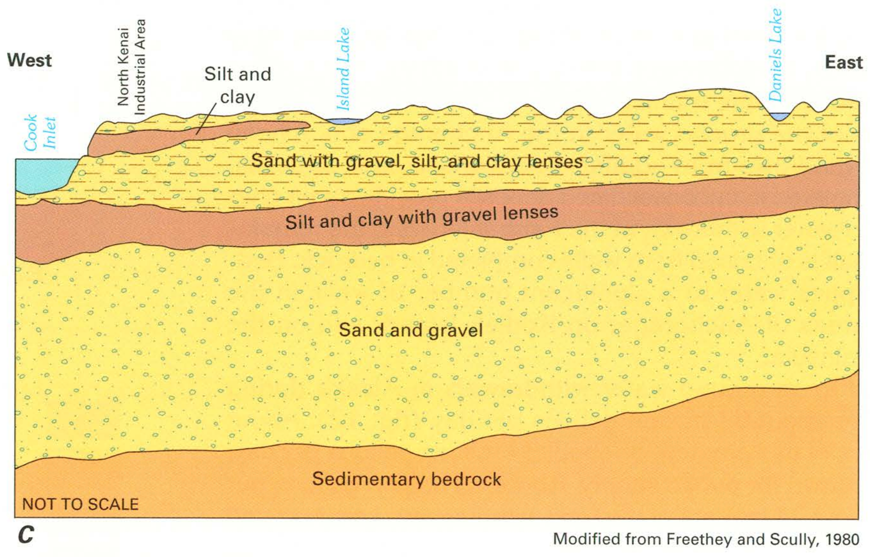


Figure 15. *The sediments of the Cook Inlet aquifer system are complexly interbedded near Wasilla (**A**), where numerous aquifers and confining units are present. Interbedding is somewhat less complex near Anchorage (**B**), but at least four water-yielding beds exist in some places. On the northern part of the Kenai Peninsula (**C**), stratification is still less complex and three fairly well-defined aquifers are present.*

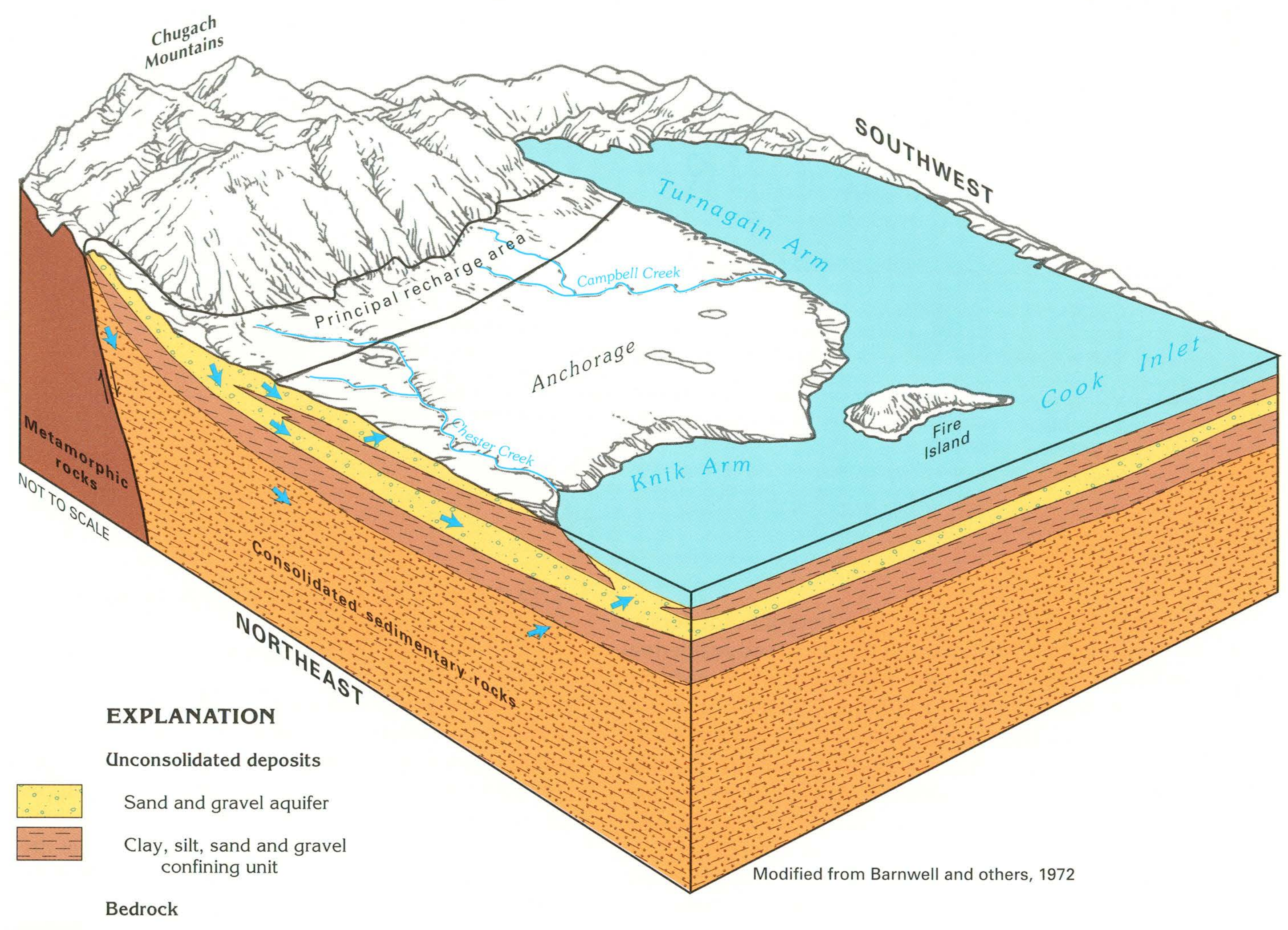
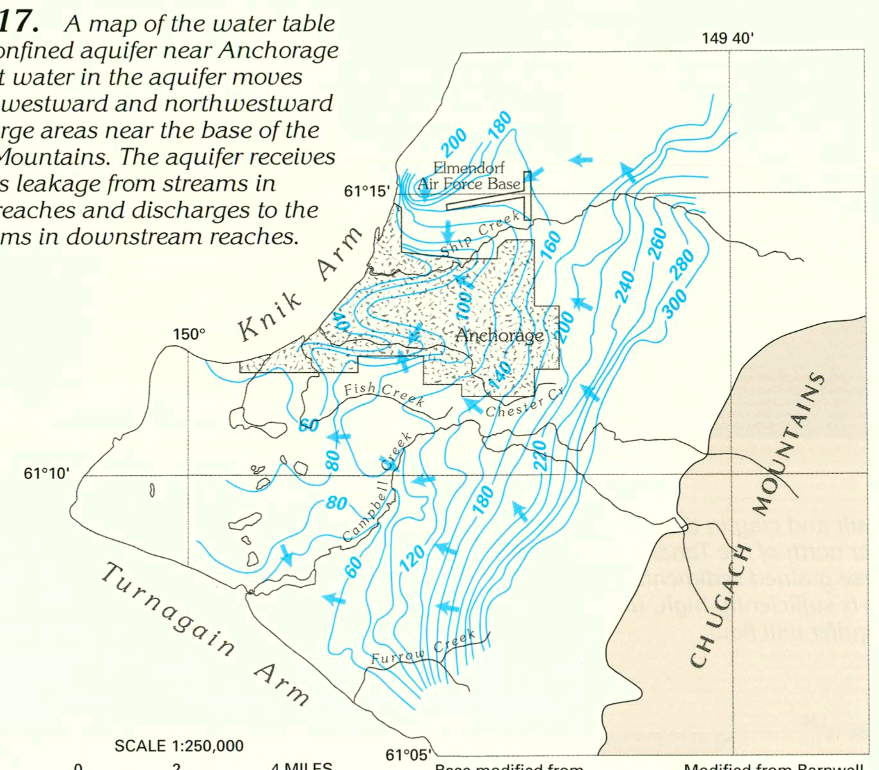


Figure 16. *Water movement in the unconsolidated-deposit aquifers of the Cook Inlet aquifer system is summarized on this generalized cross section of the Anchorage area. The water moves regionally from recharge areas near the flanks of the mountains toward Knik Arm of Cook Inlet. Locally, much of the water discharges as base flow to streams in downgradient areas.*

Figure 17. A map of the water table of the unconfined aquifer near Anchorage shows that water in the aquifer moves regionally westward and northwestward from recharge areas near the base of the Chugach Mountains. The aquifer receives recharge as leakage from streams in upstream reaches and discharges to the same streams in downstream reaches.



Base modified from U.S. Geological Survey, Tyonek, 1958 and Anchorage, 1962

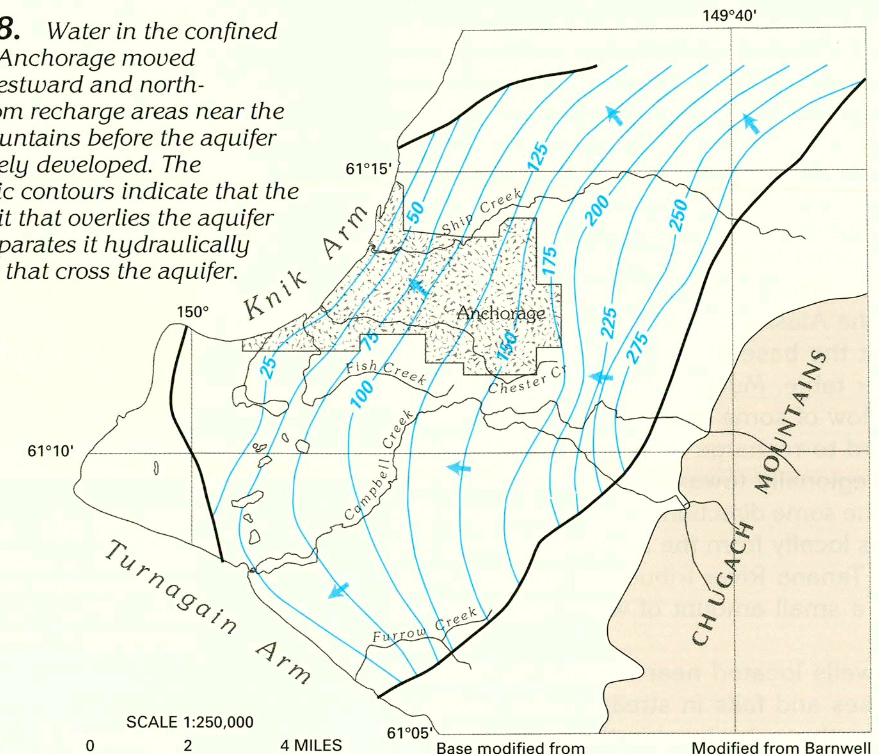
Modified from Barnwell and others, 1972; and Brabets and others, 1999

EXPLANATION

—200— **Water-table contour**—Shows altitude of water table in part of Cook Inlet aquifer system in 1955. Contour interval 20 feet. Datum is sea level

→ **Direction of ground-water movement**

Figure 18. Water in the confined aquifer near Anchorage moved regionally westward and northwestward from recharge areas near the Chugach Mountains before the aquifer was intensively developed. The potentiometric contours indicate that the confining unit that overlies the aquifer effectively separates it hydraulically from streams that cross the aquifer.



Base modified from U.S. Geological Survey, Tyonek, 1958 and Anchorage, 1962

Modified from Barnwell and others, 1972

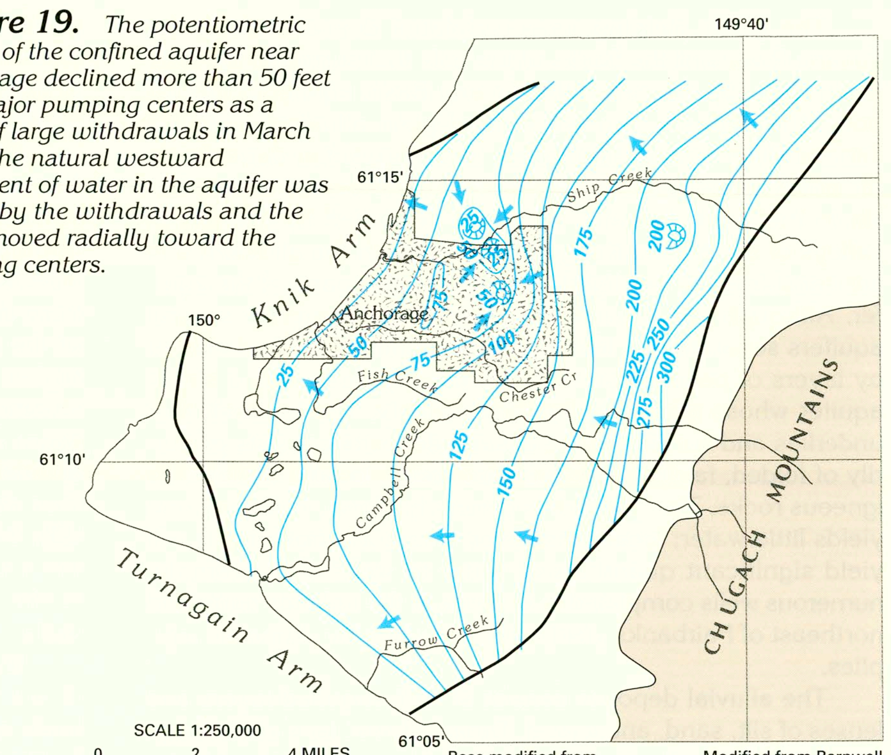
EXPLANATION

—200— **Potentiometric contour**—Shows altitude at which water level would have stood in tightly cased wells completed in the confined aquifer in 1955. Contour interval 25 feet. Datum is sea level

→ **Direction of ground-water movement**

—— **Approximate limit of confining unit**

Figure 19. The potentiometric surface of the confined aquifer near Anchorage declined more than 50 feet near major pumping centers as a result of large withdrawals in March 1969. The natural westward movement of water in the aquifer was altered by the withdrawals and the water moved radially toward the pumping centers.



Base modified from U.S. Geological Survey, Tyonek, 1958 and Anchorage, 1962

Modified from Barnwell and others, 1972

EXPLANATION

—200— **Potentiometric contour**—Shows altitude at which water level would have stood in tightly cased wells completed in the confined aquifer on March 21, 1969. Hachures indicate depressions. Contour interval 25 feet. Datum is sea level

→ **Direction of ground-water movement**

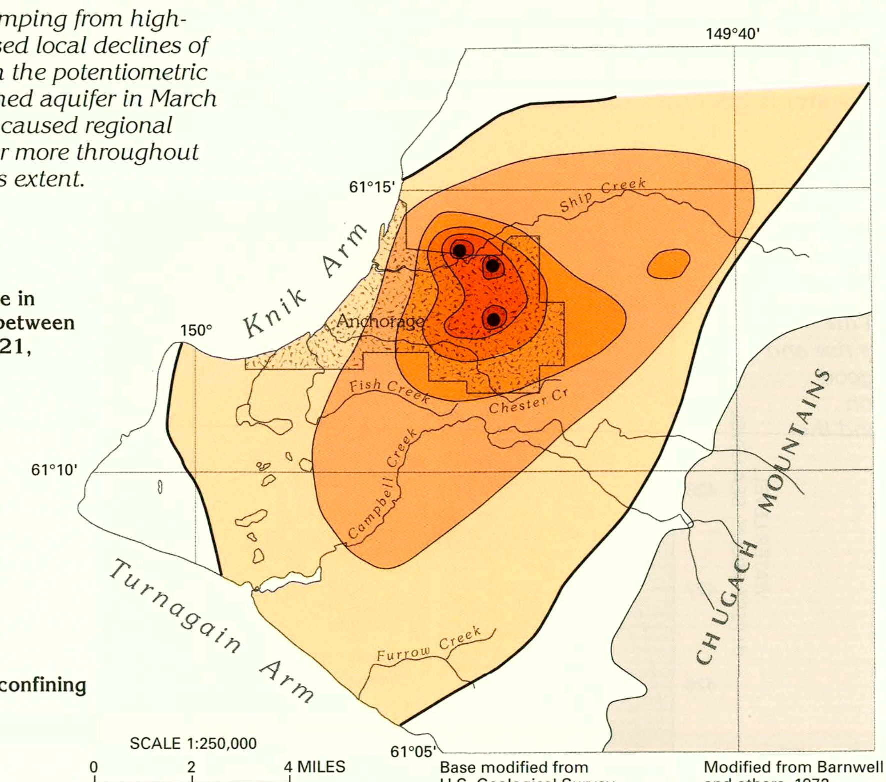
—— **Approximate limit of confining unit**

A map of the water table in the shallow, unconfined aquifer in the Anchorage area (**fig.17**) shows that water in this aquifer moves generally westward and northwestward from recharge areas at the eastern limit of the aquifer system. The configuration of the water table generally corresponds to the configuration of the land surface, but the water table contours are irregular where they cross streams. These irregularities reflect the hydrologic relations between the stream and the aquifer. Ship Creek, north of Anchorage, is a good example of these relations. Eastward from the airstrip at Elmendorf Air Force Base, the water-table contours bend downstream where they cross Ship Creek, indicating that the creek is losing water to the aquifer. Farther westward, the contours point upstream where they cross Ship Creek, indicating that the creek is gaining water from the aquifer in this area. Discharge from the aquifer to other streams is indicated by the shape of the water-table contours where they cross the downstream reaches of Chester Creek and Campbell Creek: the contours bend upstream in both areas.

Before large ground-water withdrawals began, water in the confined aquifer near Anchorage moved regionally from recharge areas near the Chugach Mountains toward discharge areas at Cook Inlet and Knik Arm (**fig. 18**). The regional direction of movement was similar to that of water in the unconfined aquifer (compare **figs. 17** and **18**). However, the potentiometric surface of the confined aquifer indicates little or no hydraulic connection between the aquifer and streams that cross it. The fine-grained sediments that overlie this aquifer form an effective confining unit that hydraulically separates the aquifer not only from the streams, but also from the overlying unconfined aquifer. The effectiveness of the confining unit is also shown by the difference in altitude between the water table and the potentiometric surface of the confined aquifer. Water levels in the unconfined aquifer are 20 to 30 feet higher than the potentiometric levels of the confined aquifer everywhere the confining unit is present (compare **figs. 17** and **18**).

Withdrawal of water from high-capacity wells completed in the confined aquifer causes a decline in artesian pressure in the aquifer that is reflected by depressions on the aquifer's potentiometric surface (**fig. 19**). Large withdrawals from pumping centers near Elmendorf Air Force Base and the Glenn Highway caused the potentiometric surface of the aquifer to decline more than 50 feet by March 1969. Most of the ground water withdrawn in the Anchorage area is pumped from the confined aquifer. Withdrawals were sufficient to cause declines of 10 feet or more over an area of more than 40 square miles in March 1969 (**fig. 20**).

Figure 20. Pumping from high-capacity wells caused local declines of more than 50 feet in the potentiometric surface of the confined aquifer in March 1969. Withdrawals caused regional declines of 10 feet or more throughout most of the aquifer's extent.



Base modified from U.S. Geological Survey, Tyonek, 1958 and Anchorage, 1962

Modified from Barnwell and others, 1972

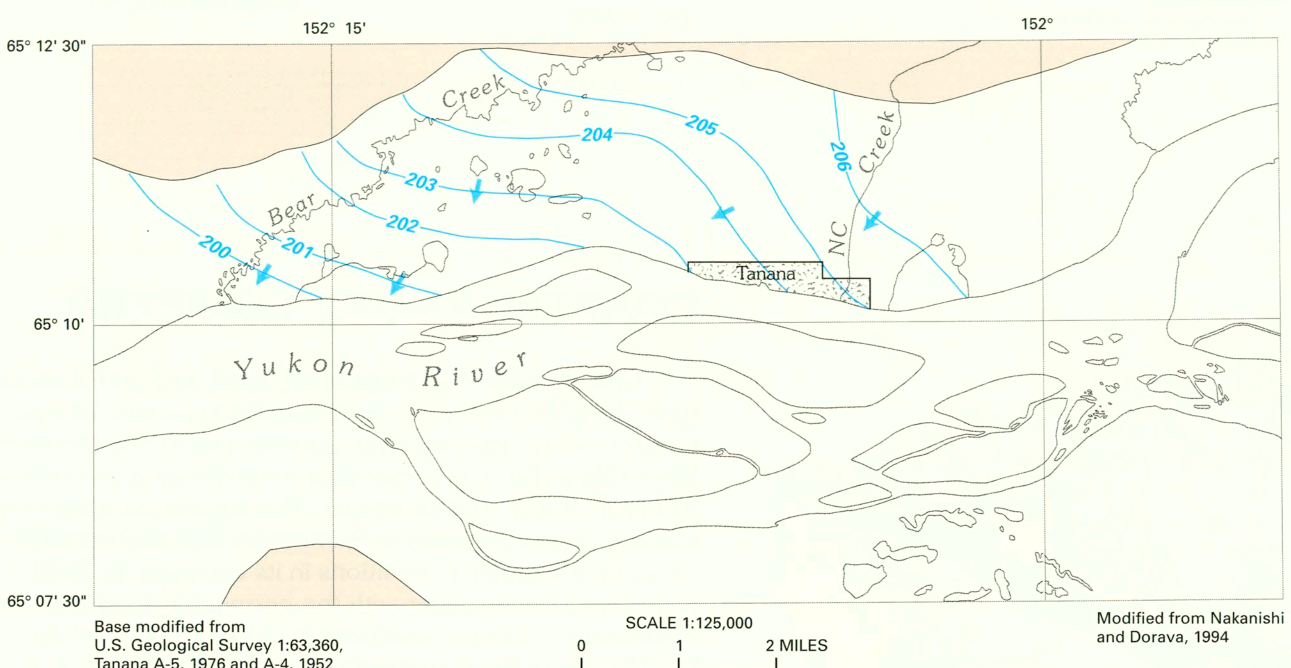
EXPLANATION

Net water-level decline in confined aquifer between 1955 and March 21, 1969, in feet

- Less than 10
- 10 to 20
- 20 to 30
- 30 to 40
- 40 to 50
- Greater than 50

—— **Approximate limit of confining unit**

● **High-capacity well**



Base modified from U.S. Geological Survey 1:63,360, Tanana A-5, 1976 and A-4, 1952

Modified from Nakanishi and Dorava, 1994

EXPLANATION

—203— **Water-table contour**—Shows altitude of water table, summer 1993. Contour interval 1 foot. Datum is sea level

→ **Direction of ground-water movement**

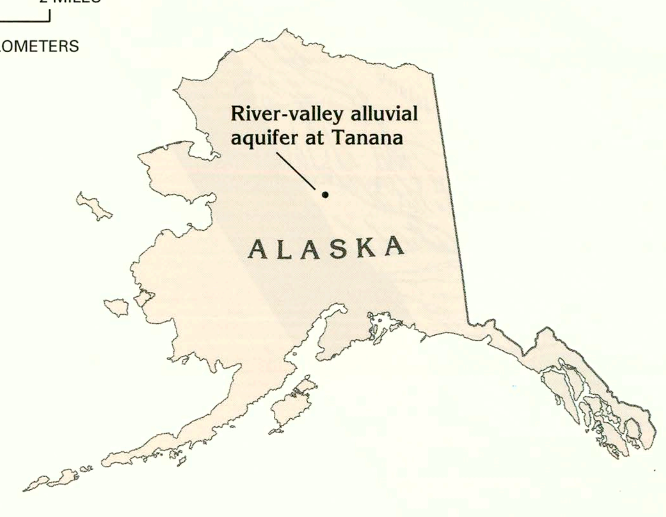


Figure 21. Water in the alluvial aquifer at Tanana moves from recharge areas beneath Bear and NC Creeks southward and southwestward to discharge into the Yukon River. Regional movement of the water is parallel to the direction of flow of the river.

RIVER-VALLEY ALLUVIAL AQUIFERS

Alluvial deposits of sand and gravel that are present in the flood plains and terraces of the major river valleys in Alaska, and that are not connected to large alluvial fans, are called river-valley alluvial aquifers in this report. The permeable sand and gravel contain lenses and beds of silt and clay, rich in organic material in some places, that retard the movement of ground water. The alluvial deposits are present mostly in the zone of discontinuous permafrost but also occur in the parts of the State where permafrost is absent. Where present, the permafrost acts as an impermeable barrier to ground-water flow, and creates confined conditions for water that might be in unfrozen permeable beds beneath it. Permafrost is absent beneath the beds of the major streams and in the alluvium adjacent to the streams; thus, the alluvial aquifers are in hydraulic connection with the streams and the movement and level of ground water are directly influenced by the direction of streamflow and the stage of the stream.

The aquifer in deposits of thick alluvium in the flood plain of the Yukon River at Tanana (**fig. 13**) is an example of a river-valley alluvial aquifer. The alluvial deposits at Tanana consist of sandy gravel and sandy silt, bordered at the sides of the river valley by silty deposits of colluvium that locally contain poorly sorted sand and gravel. Discontinuous permafrost is present in the alluvium except beneath the bed of the river and the flood plain immediately adjacent to it, where the warming effect of the river prevents permanent freezing of the ground. Adjacent to the river, therefore, ground water can move into and out of the riverbanks and stream bed, depending on the elevation of water in the river relative to the water level in the aquifer. Water levels in the aquifer at Tanana rise and fall in response to rises and falls of river level.

Field observations and computer simulation indicate that the movement of ground water near Tanana is toward the Yukon River from the valley walls of the river (**fig. 21**). Water recharges the aquifer by seepage through the beds of Bear and NC Creeks, and moves locally southward and southwestward to discharge to the Yukon River. Regionally, ground water moves westward, in the same direction as the flow of the river. The local movement of ground water is probably more complex than that shown in the figure because permafrost was assumed to be absent in the computer simulations; the general movement of the water, however, is thought to be correct.

TANANA BASIN AQUIFER

The water-yielding unconsolidated deposits along the Tanana River and the flanks of the hills that surround the river basin (**fig. 13**) are called the Tanana Basin aquifer in this report. The deposits consist of flood-plain alluvium near the Tanana River and its tributaries, and alluvial-fan deposits on the north flanks of the Alaska Range that borders the river basin to the south. Locally, moraines deposited by glaciers in valleys of the Alaska Range interfinger with the alluvium and are considered to be slightly less permeable parts of the aquifer. Although the alluvial deposits locally comprise several aquifers separated by leaky confining units of silt and clay or by layers of permafrost, they are usually treated as a single aquifer whose permeability varies widely. The bedrock that underlies and surrounds the alluvial deposits consists primarily of folded, faulted metamorphic rocks, locally intruded by igneous rocks. The bedrock is generally dense, compact, and yields little water; locally, however, where it is fractured it will yield significant quantities of water to wells. For example, numerous wells completed in bedrock in the uplands north and northeast of Fairbanks yield sufficient water for domestic supplies.

The alluvial deposits consist of well-stratified layers and lenses of silt, sand, and gravel. Broad alluvial fans of the large rivers that enter the Tanana drainage basin from the Alaska Range coalesce to form a continuous alluvial apron of coarse, permeable sediments at the base of the range. Permeable flood-plain alluvium is also present as narrow to wide bands along the Tanana River and its larger tributaries. The alluvial deposits are very thick in some places: wells have penetrated more than 600 feet of alluvium near Fairbanks and about 550 feet near the junction of the Delta and Tanana Rivers. Where the alluvium is thick and permeable, it is reported to yield as much as 3,000 gallons per minute to large-capacity wells. Water in these widespread alluvial deposits is mostly unconfined.

By contrast, water in the alluvial deposits north and east of the Tanana River occurs under unconfined and confined conditions. The sediments that compose the aquifer here are poorly sorted and, because the aquifer is in the zone of discontinuous permafrost, the permanently frozen ground, as well as beds and lenses of silt and clay, create confined conditions (**fig. 22**). The silt and clay deposits are more likely to be permanently frozen than beds of sand and gravel. Unfrozen alluvium is present beneath the permafrost, however, in most parts of the aquifer. The water is generally unconfined in the higher parts of the alluvial fans and in the alluvial plains near major streams. Artesian conditions are common on the lower slopes of the alluvial fans, and some wells completed in confined parts of the aquifer in these areas flow at the land surface.

The occurrence and movement of ground water in the Tanana Basin aquifer are directly related to stream levels and streamflow. Most recharge to the aquifer is from seepage through streambeds, rather than from precipitation that falls directly on the aquifer. Water levels in streams that emerge from the bedrock of the Alaska Range onto permeable parts of the alluvial fans at the base of the mountains are much higher than the water table. Much of the flow of the larger streams, and all the flow of some smaller ones, is lost as the water seeps downward to recharge the aquifer. Water in the alluvial fans moves regionally toward the Tanana River and then downstream, in the same direction of flow as the river (**fig. 23**). Water discharges locally from the aquifer to springs and the lower reaches of Tanana River tributaries and regionally to the Tanana River; a small amount of water discharges to wells.

Water levels in wells located near streams fluctuate in direct response to rises and falls in stream water levels. A hydrograph comparing the water level in the Chena River at Fairbanks with that in a nearby well (**fig. 24**) shows that rises in river level are soon followed by rises in ground-water levels, indicating that the river and the aquifer are hydraulically connected. Both stream and aquifer water levels rise in response to precipitation events and snow melt.

During most of the year, the water level in a reach of the Tanana River near Fairbanks is higher than that of a nearby reach of the Chena River, a tributary of the Tanana. When this condition occurs, the shallower parts of the Tanana Basin aquifer between the two rivers receive recharge from the Tanana River and discharge to the Chena River (**fig. 25**). Thus, the local direction of shallow ground-water movement varies from the regional direction, which closely corresponds to the direction of stream flow. Deep ground-water flow, however, is thought to move under the Tanana River and toward the Chena River at all times of the year.

The chemical quality of water in the Tanana Basin aquifer is generally suitable for most uses. The water is a calcium bicarbonate or calcium magnesium bicarbonate type, and locally contains concentrations of iron and manganese that are higher than those recommended for drinking water by the U.S. Environmental Protection Agency.

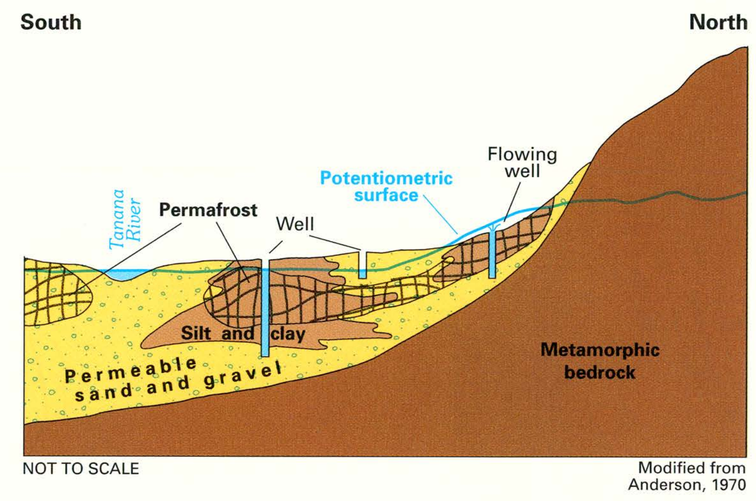
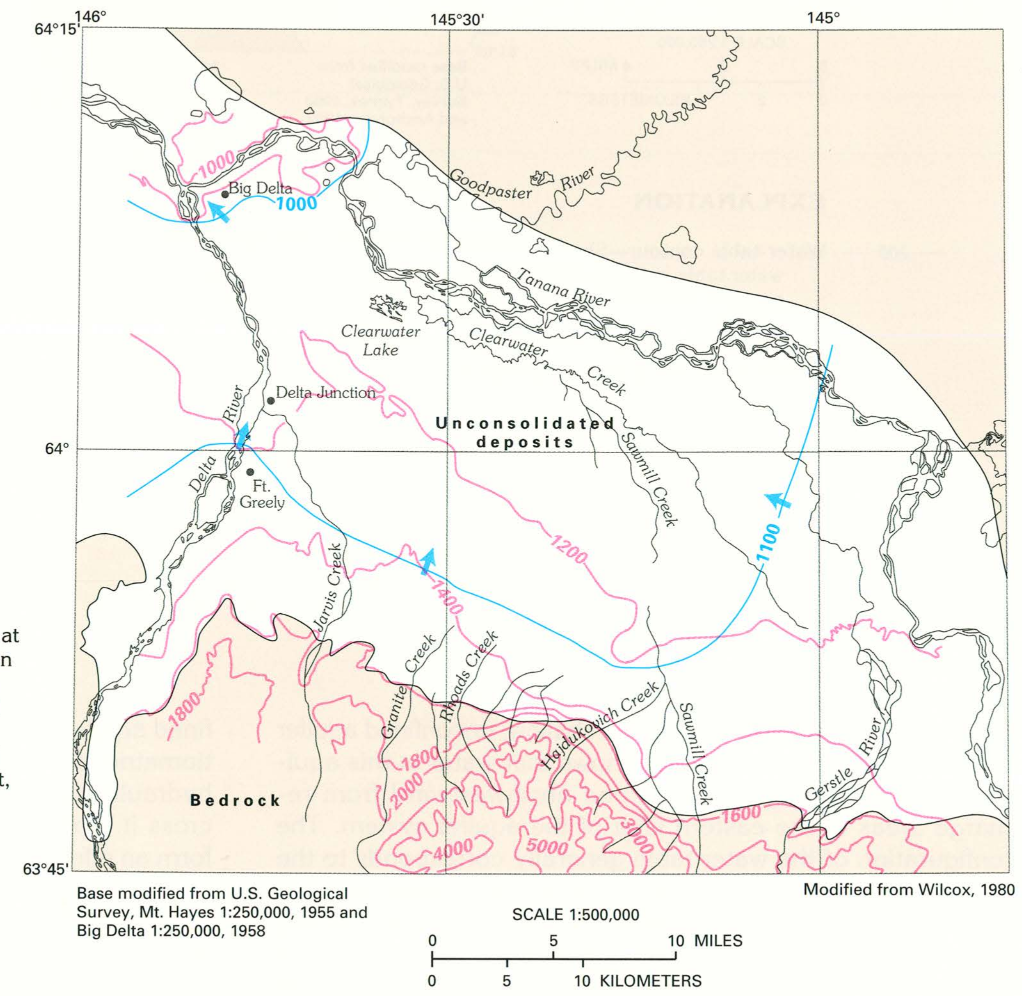


Figure 22. *Permafrost and beds of silt and clay in the upper part of the unconsolidated-deposit aquifer north of the Tanana River near Fairbanks confine water in the coarse grained sediments below. Where the potentiometric surface is sufficiently high, wells completed in the confined parts of the aquifer will flow.*

Figure 23. *Near the junction of the Delta and the Tanana Rivers, water in the unconsolidated deposits moves regionally from high altitudes near the apexes of alluvial fans toward the Tanana River. Near the river, the water moves northwestward, parallel to the flow of the river. Small streams such as Granite Creek and Rhoads Creek lose all their flow as seepage to the alluvial fan deposits. The water in Sawmill Creek vanishes into the alluvial fan and reemerges at a lower altitude.*



EXPLANATION

—1100— **Potentiometric contour**—Shows altitude at which water level would have stood in tightly cased wells in 1980. Contour interval 100 feet. Datum is sea level

—1200— **Topographic contour**—Shows altitude of land surface. Contour interval, in feet, is variable. Datum is sea level

→ **Direction of ground-water movement**

Figure 24. *Water levels in a well completed in the Tanana River aquifer near Fairbanks rise and fall soon after water levels in the nearby Chena River rise and fall. This indicates good hydraulic connection between the river and the aquifer.*

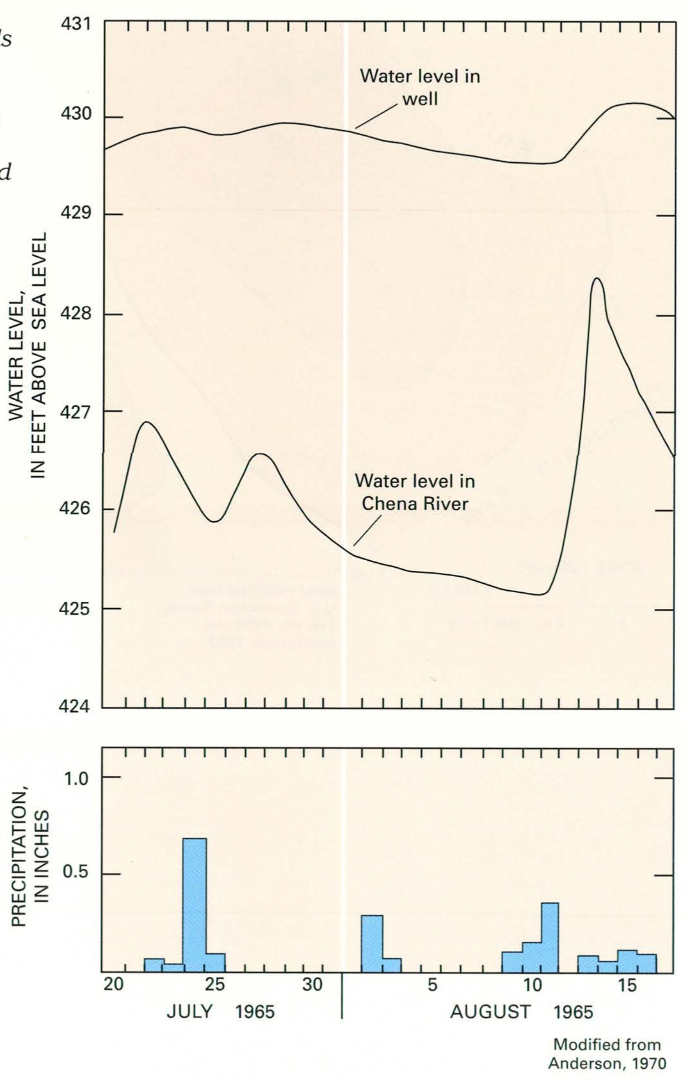
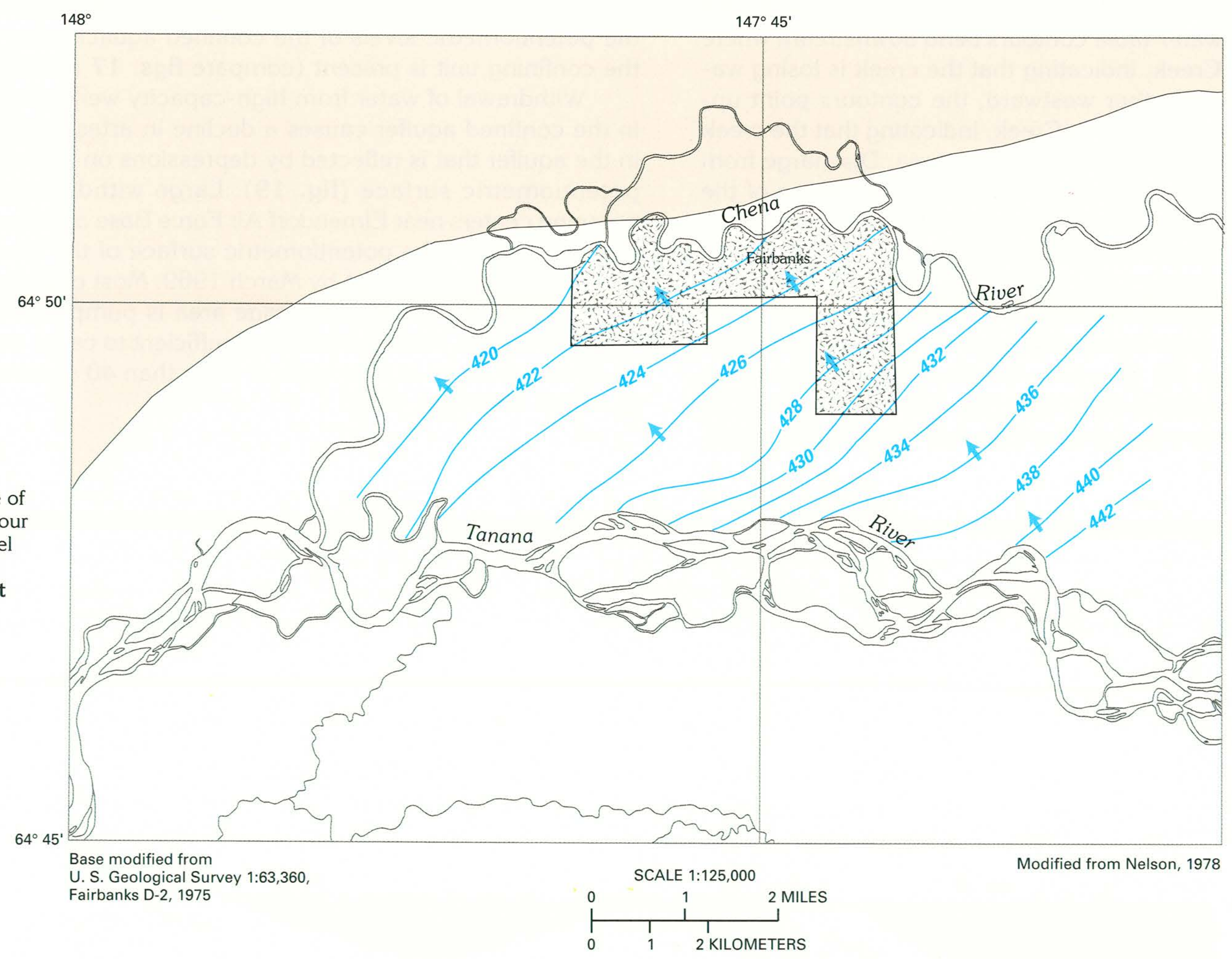


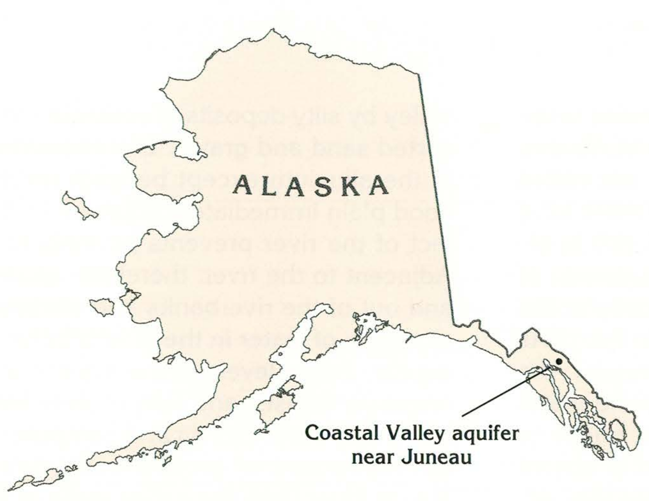
Figure 25. *Locally, near Fairbanks, the shallow part of the Tanana Basin aquifer is recharged by seepage from the Tanana River and discharges to the Chena River nearby. Flow in the deep parts of the aquifer, however, is under the Tanana River toward the Chena River. Movement of the shallow ground water shown here is different from the regional direction of movement, which is generally parallel to the direction of stream flow.*

EXPLANATION

—300— **Water-table contour**—Shows altitude of water table, summer 1978. Contour interval 2 feet. Datum is sea level

→ **Direction of ground-water movement**





EXPLANATION

Unconsolidated deposits

- Undifferentiated
- Mostly sand and gravel
- Mostly clay and silt
- Bedrock
- Glacier
- Saltwater
- Direction of ground-water movement

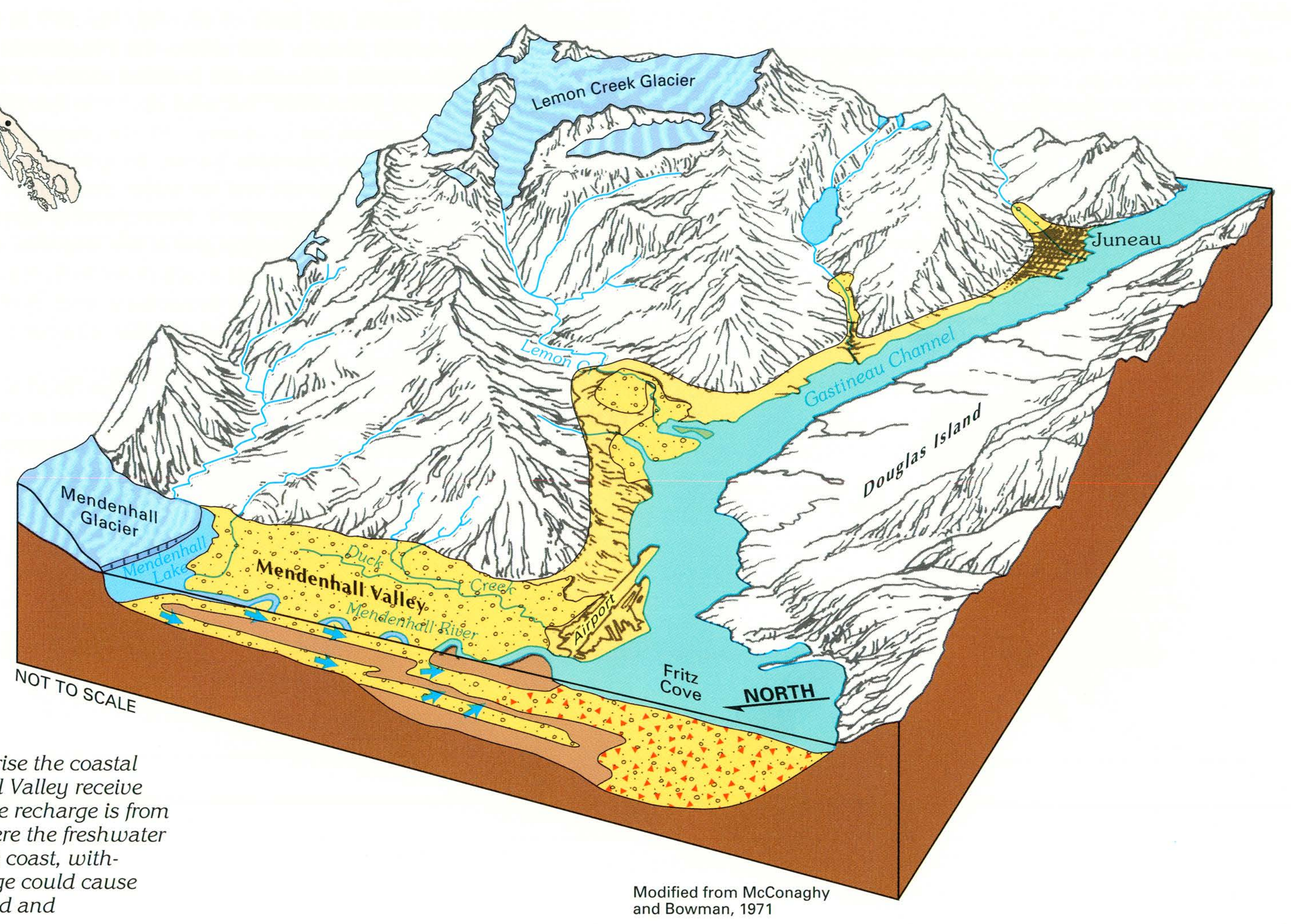


Figure 26. *Sand and gravel beds that comprise the coastal valley aquifer near Juneau and in the Mendenhall Valley receive recharge mostly from streambed seepage but some recharge is from precipitation that falls directly on the aquifer. Where the freshwater in the aquifer is in contact with saltwater near the coast, withdrawals of fresh ground water in excess of recharge could cause the freshwater-saltwater interface to migrate inland and contaminate the aquifer.*

COASTAL VALLEY AQUIFERS

Unconsolidated deposits of silt, sand, and gravel are common along the lower reaches of streams in coastal valleys. The coastal valley deposits near Juneau and in the Mendenhall River Valley (**fig. 13**) comprise a water-yielding unit that is an example of this type of aquifer. The aquifer consists of alluvial and glacial deposits of Quaternary age and contains water under unconfined conditions in its upper parts. Beds of silt and clay that interfinger with the permeable sand and gravel beds create confined conditions in the lower parts of the aquifer. The fine grained confining units are mostly discontinuous but are effective enough in some places to create artesian pressures sufficiently high so that early wells completed in permeable strata beneath them would flow at the land surface.

Water enters the aquifer primarily as seepage through the beds of streams such as the Mendenhall River where they flow across deposits of sand and gravel (**fig. 26**); a smaller amount of recharge to the aquifer is by precipitation that falls directly on permeable strata. Where permeable beds of the aquifer are exposed at the land surface, water levels in wells completed in these beds respond quickly to variations in precipitation (**fig. 27**). Some of the water stored in glaciers that cap low-permeability bedrock mountains to the north and east of Juneau and the Mendenhall Valley is released as meltwater during the summer months. The meltwater is channeled through bedrock valleys until it emerges onto the alluvial and glacial deposits that comprise the aquifer, where much of the streamflow seeps downward to enter the aquifer. The water subsequently moves coastward, where most of it discharges either to the lower reaches of the streams as base flow or directly into saltwater bodies; however, some of the water discharges by evapotranspiration and some discharges to wells.

Freshwater in some of the sand and gravel beds of the coastal valley aquifer near Juneau and in the Mendenhall Valley is hydraulically connected to saltwater bodies (**fig. 26**). Under natural conditions, saltwater in the parts of the aquifer beneath Fritz Cove and Gastineau Channel is in balance with freshwater in the inland parts of the aquifer, a condition known as hydraulic equilibrium. If the freshwater column inland is lowered as a result of withdrawal by wells, however, the saltwater can migrate inland, contaminate some of the freshwater in the aquifer, and render it unfit for use.

The hydraulic conditions that are likely to result in saltwater intrustion are summarized in **figure 28**. Under natural conditions, saltwater in the offshore parts of an unconsolidated-deposit aquifer is balanced by a thicker column of freshwater onshore (**fig. 28A**). Large withdrawals from wells completed in the freshwater parts of the aquifer cause the water table to decline and the thickness of the freshwater column to decrease (**fig. 28B**). The equilibrium between the saltwater and freshwater is, thus, imbalanced, and saltwater moves inland. Eventually, the saltwater might enter the pumping wells and contaminate the water to the extent that it is unsuitable for most uses.

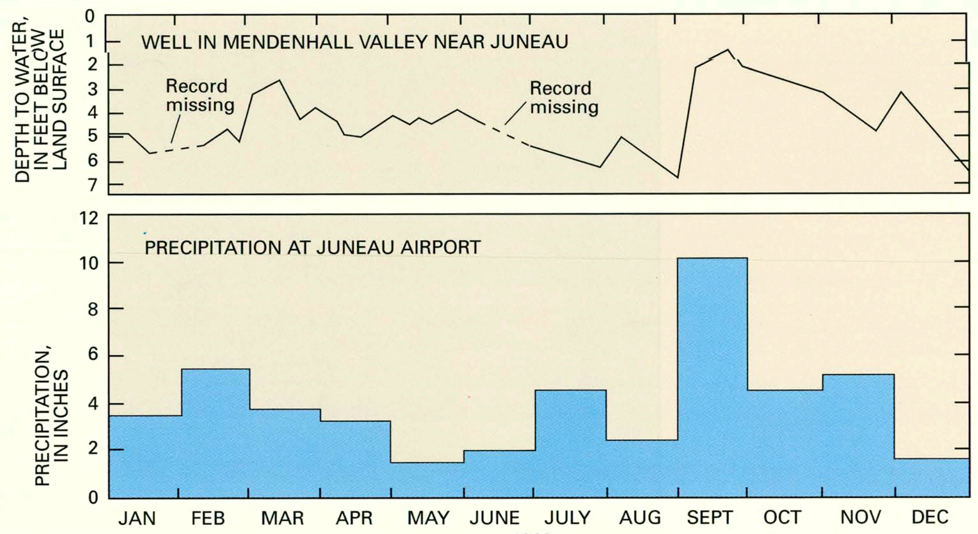


Figure 27. *Water levels in a well completed in the upper part of the aquifer rise in response to increases in precipitation and fall as precipitation amounts decline, indicating that this part of the aquifer is recharged in part by precipitation that falls directly on it.*

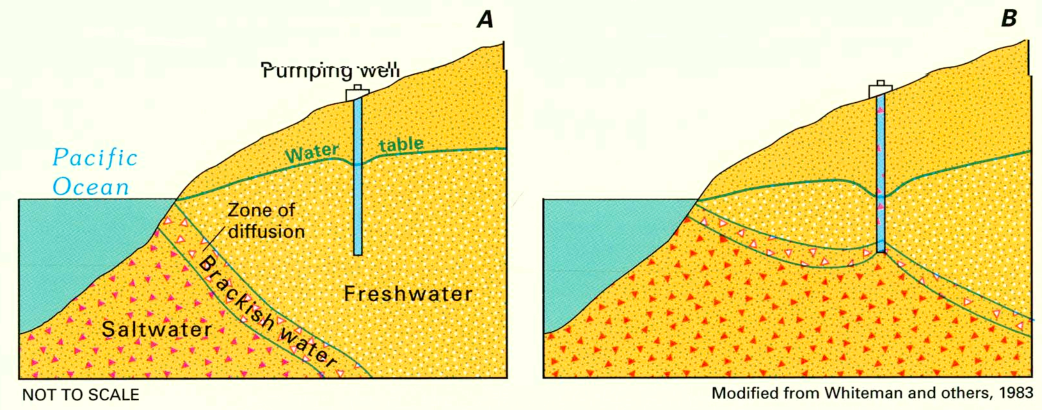


Figure 28. *Saltwater intrusion into unconsolidated-deposit aquifers in coastal areas of Alaska can result from large withdrawals by wells.* ***A****, diagram of a well under natural conditions (hydraulic equilibrium), where natural recharge balances natural discharge, and* ***B****, diagram of the same well showing saltwater intrusion under conditions of large ground-water withdrawals that exceed natural recharge.*

EXPLANATION

Unconsolidated-deposit aquifers

BEDROCK AQUIFERS

Consolidated rocks are exposed at the land surface over about 70 percent of Alaska, but are generally less permeable than the unconsolidated deposits discussed in the preceding section of this report. Accordingly, the consolidated rocks are used as a source of water supply only where the unconsolidated deposits are absent, thin, or poorly permeable. Information about the water-yielding characteristics of the consolidated rocks, which are called bedrock aquifers in this report, is scarce. The locations of known bedrock aquifers and the aquifer rock type are shown in **figure 29**.

Sedimentary bedrock that underlies the southwestern part of the Kenai Peninsula (**fig. 29**) provides water to numerous domestic wells and supplies some small communities. Poorly consolidated sandstone that is part of the Kenai Group of Tertiary age yields most of the water, but some water is also obtained from coal beds and seams within the group. Interbedded siltstone and claystone yield no water. Although most wells completed in strata of the Kenai Group yield less than 20 gallons per minute, yields of as much as 80 gallons per minute are reported locally. Several springs and seeps near Homer on the Kenai Peninsula discharge from beds of the Kenai Group. Sparse data from the Capps coal field, north of Cook Inlet across from the Kenai Peninsula, indicate that Tertiary beds of coal and poorly consolidated sandstone and conglomerate yield as much as 60 gallons per minute to wells. Water withdrawn from the Kenai Group and the strata in the Capps coal field locally contains objectionable concentrations of iron and hydrogen sulfide, both probably derived from the coal beds. Locally, methane gas that has been reported in water from some wells near Homer is also probably derived from the coal units.

Carbonate rocks comprise known or potential aquifers in some parts of Alaska. In the eastern part of the Brooks Range, at least 25 springs are known to discharge from carbonate rocks; the discharge of one of these springs is as much as 16,000 gallons per minute. The springs are thought to discharge from a network of solution cavities and conduits that have developed by partial dissolution of the carbonate rocks. Carbonate rocks on Admiralty Island in southeast Alaska locally yield large quantities of ground water, probably from a system of caves and solution conduits.

Metamorphic rocks yield water in substantial quantities only where they have been fractured. Perhaps the most important area underlain by a metamorphic-rock aquifer is north and northeast of Fairbanks, where wells completed in fractured schist supply approximately one-half of the population. Fractured slate and metagreywacke in the upland areas near Anchorage supply water to numerous domestic wells. Fractured slate and metamorphosed volcanic rocks on Kodiak Island generally yield less than 15 gallons per minute to wells, but locally yield as much as 100 gallons per minute.

Little is known about the water-yielding potential of the widespread volcanic rocks in Alaska, but they are permeable at least locally, where hot springs issue from them. The permeability in these rocks may be a combination of fractures produced when the rocks cooled and weathered and vesicular layers that developed on the tops of individual basalt flows. Basaltic rocks in the Pribilof Islands yield sufficient water to supply small communities.

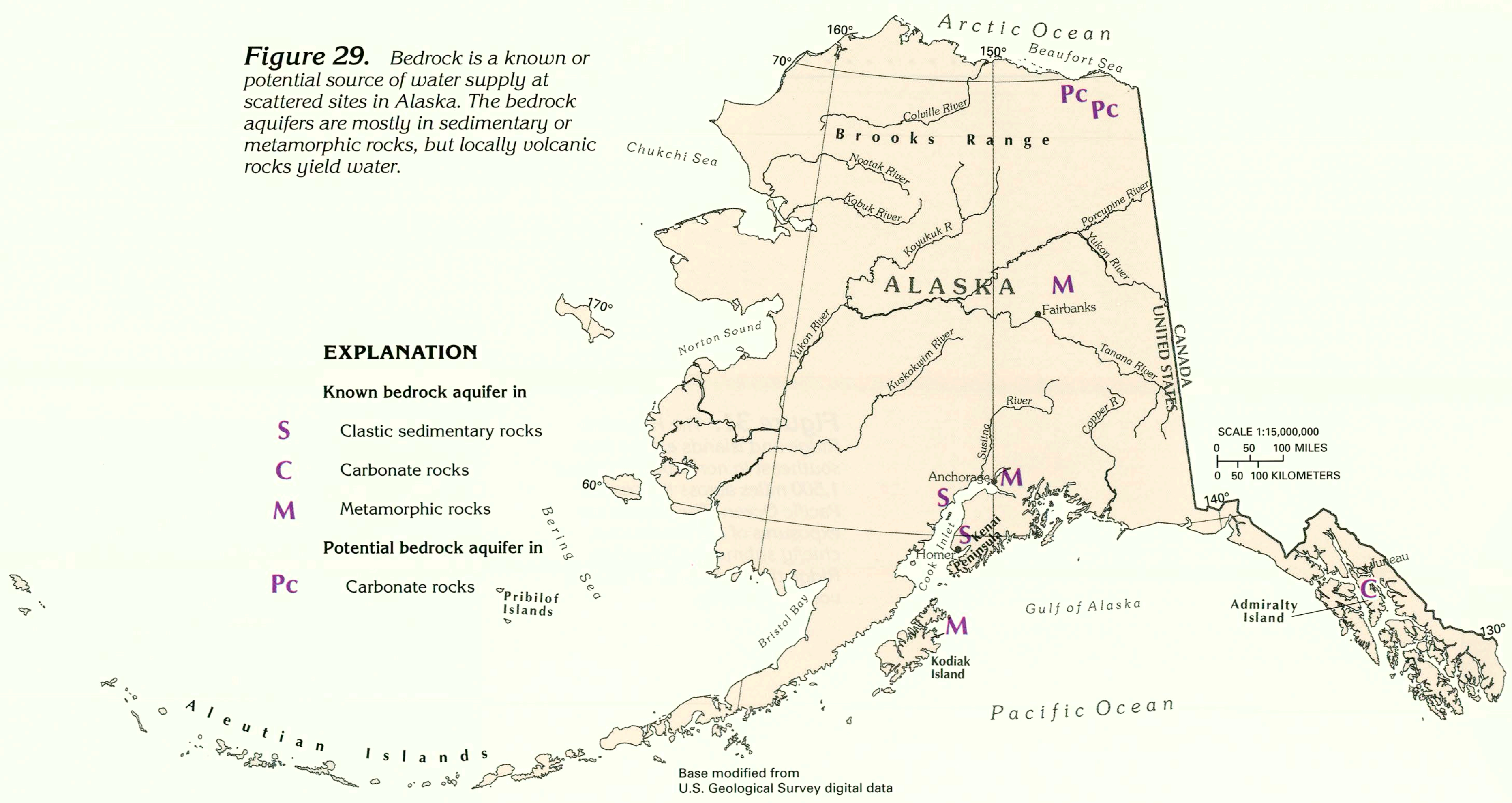


Figure 29. *Bedrock is a known or potential source of water supply at scattered sites in Alaska. The bedrock aquifers are mostly in sedimentary or metamorphic rocks, but locally volcanic rocks yield water.*

GEOTHERMAL WATER

Numerous springs in Alaska discharge geothermal water, or water with a temperature appreciably warmer than the local average annual air temperature. The location of known geothermal springs is shown in **figure 30**. The temperatures for the mapped springs are those where the water emerges at the land surface; temperatures within the geothermal reservoir that houses the water at depth are greater than those mapped.

Most of the geothermal springs in Alaska issue from consolidated bedrock. The springs are most common in two areas - a belt across central Alaska that is underlain largely by intrusive igneous rocks and an arcuate area in the mountain ranges in the southern part of the State which is underlain largely by volcanic rocks. Many of the springs issue from faults and fractures at the contacts of granitic plutons.

One theory of the origin of geothermal water is that precipitation falling in upland areas circulates to great depths in the consolidated rocks, mainly along faults. At some depth, the water is warmed by the natural increase in temperature with depth in the Earth's crust (the average increase is about 1 degree Fahrenheit for each 60 to 100 feet of depth) until it becomes lighter than the overlying water. The warm water then moves upward along faults and fractures and discharges to springs.

Geothermal water is a potential source of energy but has been developed only locally in Alaska. Some of the geothermal springs on Baranof Island in southeast Alaska are used to heat buildings and to supply water for a bathhouse. Other springs in scattered mainland areas are used for similar purposes.

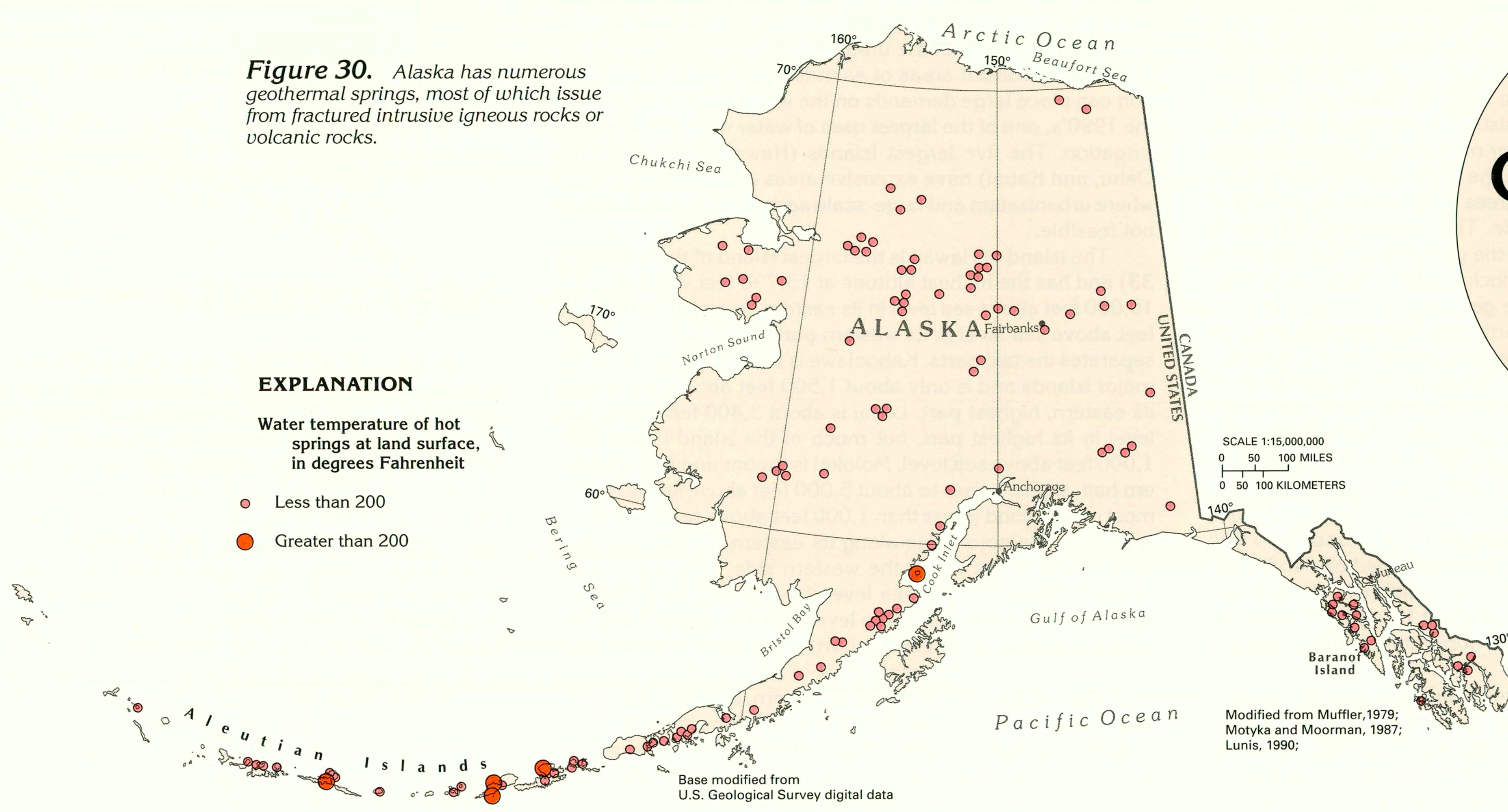
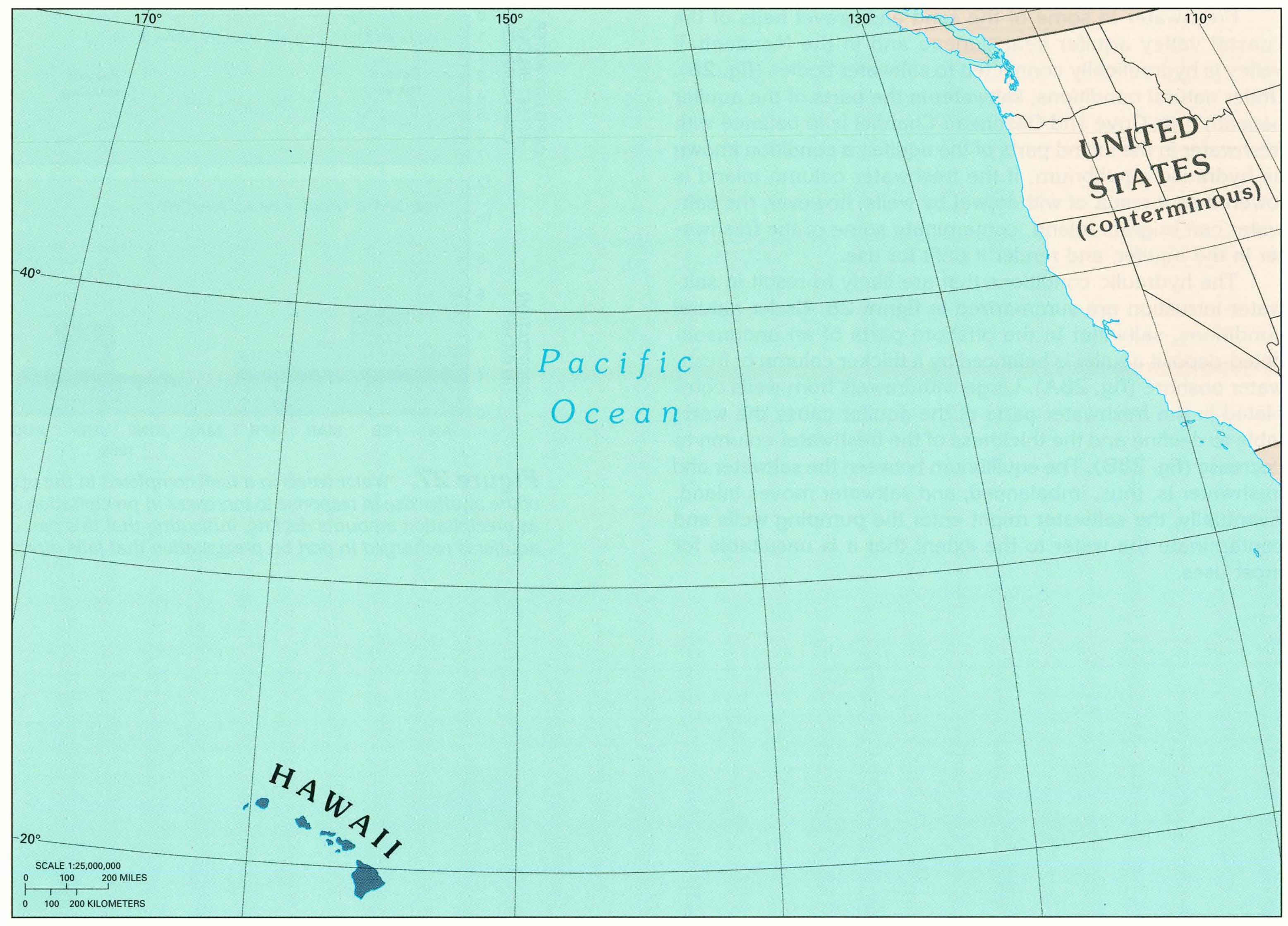


Figure 30. *Alaska has numerous geothermal springs, most of which issue from fractured intrusive igneous rocks or volcanic rocks.*



Hawaii

by Delwyn S. Oki, Stephen B. Gingerich, and R. L. Whitehead

CONTENTS

Regional Summary

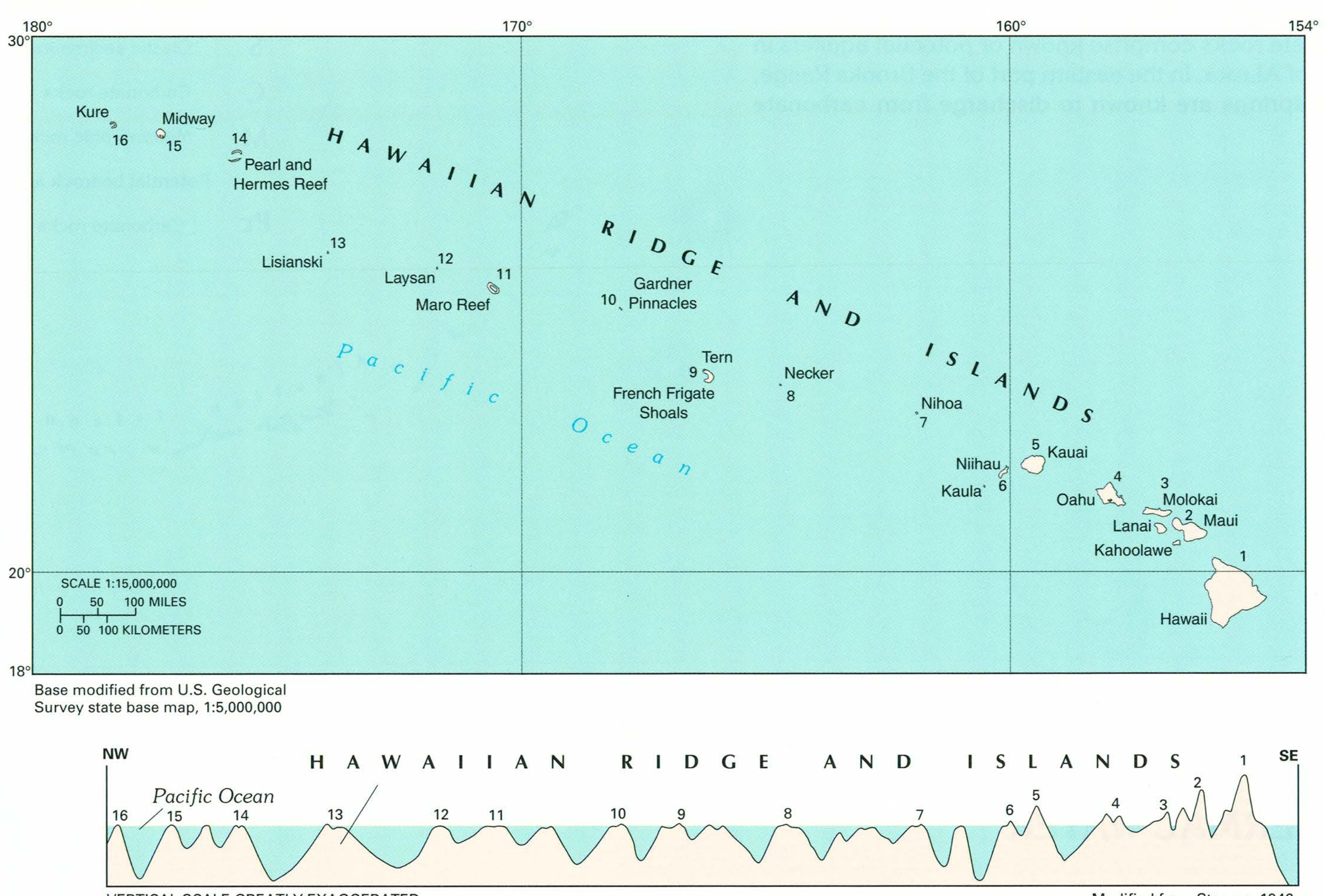


Figure 31. The Hawaiian Ridge and Islands extend from southeast to northwest for about 1,500 miles across the central Pacific Ocean. The islands are exposures of the continuous, chiefly submarine Hawaiian Ridge that formed as a result of volcanic activity.

INTRODUCTION

The Hawaiian islands are the exposed parts of the Hawaiian Ridge, which is a large volcanic mountain range on the sea floor. Most of the Hawaiian Ridge is below sea level (**fig. 31**). The State of Hawaii consists of a group of 132 islands, reefs, and shoals that extend for more than 1,500 miles from southeast to northwest across the central Pacific Ocean between about 155 and 179 degrees west longitude and about 19 to 28 degrees north latitude. The main inhabited islands are at the southeastern end of the group (**fig. 31**); not all the small islands, reefs, and shoals included in the State are shown.

The Hawaiian islands are geologically youngest in the southeast and oldest in the northwest. This report discusses only the eight largest islands near the southeastern end of the group; these eight main islands account for practically all of the 6,426-square-mile land area of the State. The eight islands and their approximate size, in square miles, from southeast to northwest are Hawaii, 4,021; Maui, 728; Kahoolawe, 45; Lanai, 141; Molokai, 259; Oahu, 603; Kauai, 553; and Niihau, 71. The total resident population in 1995 was 1,179,198, of which about 75 percent were on the island of Oahu. Honolulu, which is on Oahu, is the largest and most developed city and had a population of 369,485 in 1995. In addition to the resident population, a visitor population of about 150,000 has typically been present at any given time during the 1990's. Many of these visitors stay in Honolulu.

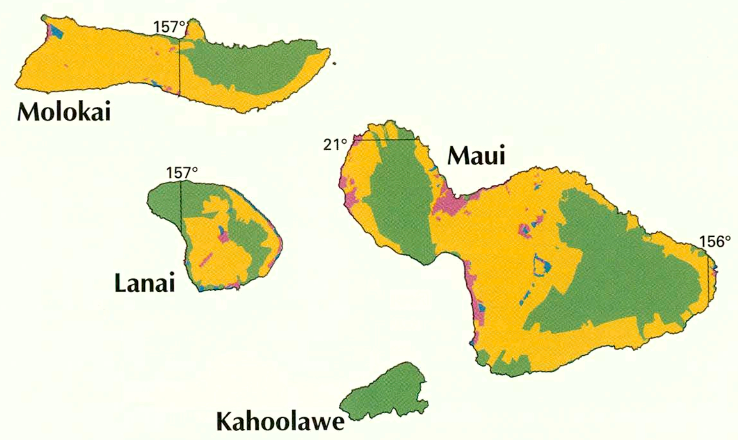
The State Land Use Commission is responsible for classifying the lands of the State into one of four categories called districts: conservation, agricultural, urban, or rural (**fig. 32**). In 1995, conservation, agricultural, urban, and rural districts accounted for about 48, 47, 5, and 0.2 percent of the land area in the State, respectively. Conservation districts include areas necessary for protecting the State's watersheds and water resources and are typically located in high-altitude, high-rainfall areas. Much of the urban development in Hawaii is in the lowland coastal areas of each island. Agricultural irrigation can place large demands on the water resources; prior to the 1990's, one of the largest uses of water was for sugarcane irrigation. The five largest islands (Hawaii, Maui, Molokai, Oahu, and Kauai) have extensive areas of mountainous land where urbanization and large-scale agricultural operations are not feasible.

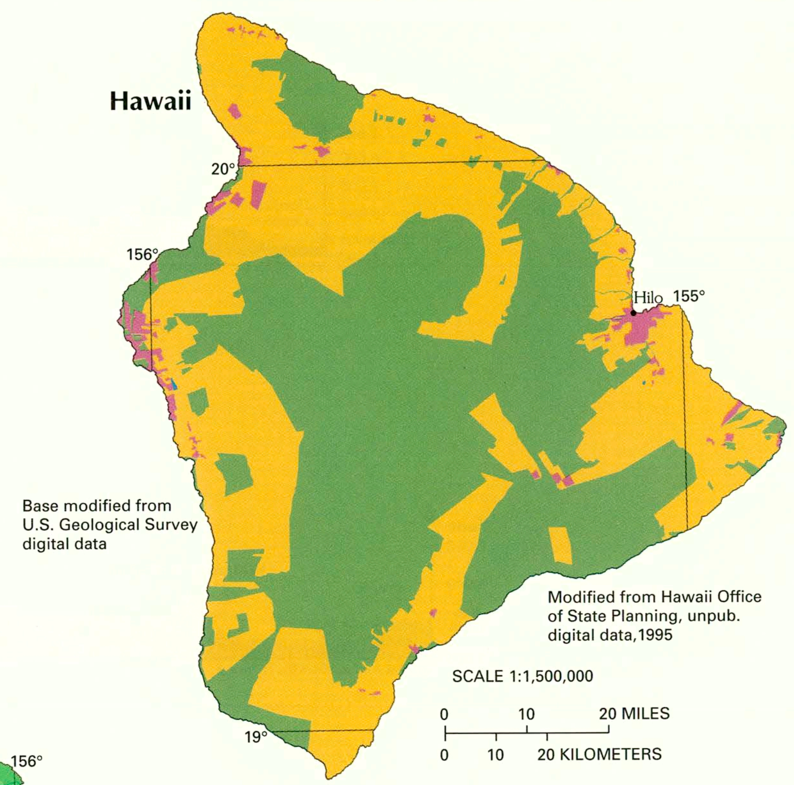
The island of Hawaii is the largest island of the State (**fig. 33**) and has the highest altitude at 13,796 feet. Maui is about 10,000 feet above sea level in its eastern part and about 5,800 feet above sea level in its western part; a broad lowland area separates the two parts. Kahoolawe is the smallest of the eight major islands and is only about 1,500 feet above sea level in its eastern, highest part. Lanai is about 3,400 feet above sea level in its highest part, but much of the island is less than 1,000 feet above sea level. Molokai is mountainous in its eastern half, where it rises to about 5,000 feet above sea level, but most of the island is less than 1,000 feet above sea level. Oahu has a mountainous ridge along its eastern side and another mountainous area along the western side, where it rises to about 4,000 feet above sea level; however, most of Oahu is less than 1,000 feet above sea level. Kauai is about 5,200 feet above sea level in its central part, but from the base of the mountains shoreward, large areas of the island are less than 1,000 feet above sea level in the southern, eastern, and northern parts. Niihau is mostly less than 1,000 feet above sea level, except for a narrow ridge about 1,300 feet above sea level along its northeastern side. The topography of each island has a profound effect on development and climate.

CLIMATIC EFFECTS

The Hawaiian islands are near the northern margin of the tropics, and because of the prevailing northeast tradewinds and the buffering effect of the surrounding ocean, air temperature at a given location in Hawaii is generally equable. At the Honolulu International Airport, for example, the warmest month of the year is August, which has a mean temperature of 80.5 degrees Fahrenheit, and the coolest month is February, which has a mean temperature of 72.0 degrees Fahrenheit. Air temperature can vary greatly from one location to another in Hawaii. The air temperature in the eight-island group can range from about 95 degrees Fahrenheit at sea level to below freezing at the top of some peaks on the island of Hawaii. In the geologic past, these peaks have been glaciated.

Northeasterly tradewinds are present about 85 to 95 percent of the time during the summer months (May through September), and 50 to 80 percent of the time during the winter months (October through April). The tradewinds are occasionally interrupted by large-scale storm systems which pass near the islands. The southwestern parts of some islands receive most of their rainfall from these severe storms, which produce a relatively uniform spatial distribution of precipitation. In general, the northeastern, or windward sides of the islands are wettest (**fig. 34**). This pattern is controlled by the orographic lifting of moisture-laden northeasterly tradewinds along the windward slopes of the islands. The winds blow across open ocean before arriving at the islands; when the moisture-laden air mass rises over the mountains, the moisture condenses as precipitation. Maximum rainfall occurs between altitudes of 2,000 and 6,000 feet above sea level, but exact amounts vary depending on the form, location, and topography of each island. Above 6,000 feet, precipitation decreases and the highest altitudes are semiarid. High mountain areas are dry because the upslope flow of moist air is prevented from penetrating above altitudes of about 6,000 to 8,000 feet by a temperature inversion. Areas that are leeward (southwest) of mountain barriers are generally dry because air is desiccated during its ascent over an upwind orographic barrier. This is known as the rain-shadow effect.





EXPLANATION

- Conservation
- Agricultural
- Urban
- Rural

Figure 32. During 1995, lands in the State were classified mainly as conservation and agricultural land-use districts.

On the island of **Hawaii**, 51 percent of the land was classified as conservation and 47 percent as agricultural land-use districts. Most of the remaining land was classified for urban use.

On the island of **Maui**, 53 percent of the land was classified as agricultural and 42 percent as conservation districts.

The entire island of **Kahoolawe** was classified as a conservation district.

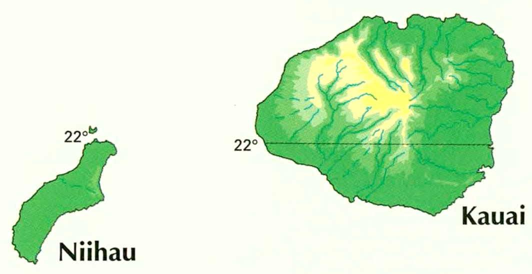
On the island of **Lanai**, 52 percent of the land was classified as agricultural and 42 percent as conservation districts.

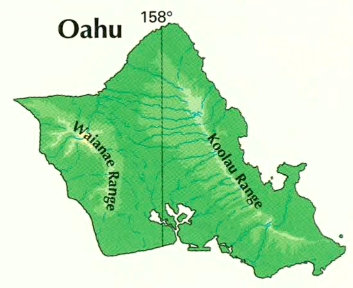
On the island of **Molokai**, 67 percent of the land was classified as agricultural and 30 percent as conservation districts.

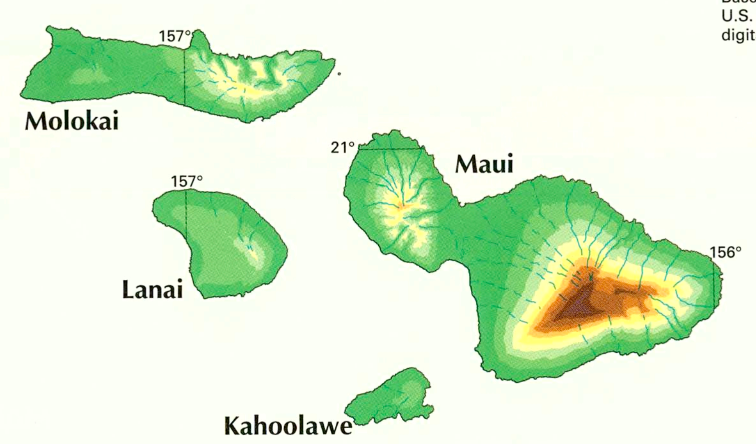
On the island of **Oahu**, 41 percent of the land was classified as conservation and 34 percent as agricultural districts. About 25 percent of the land on Oahu was classified for urban use.

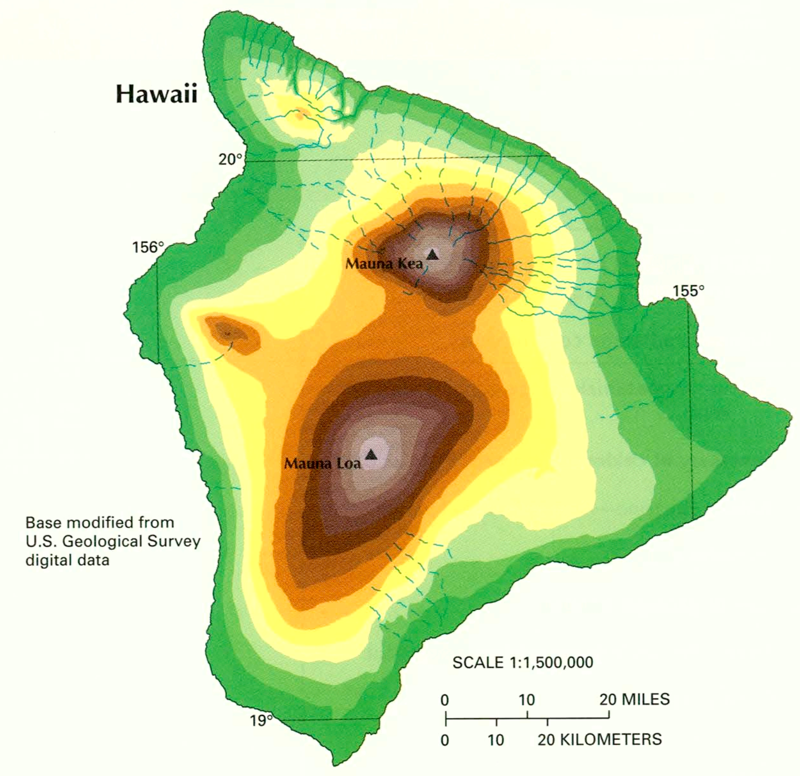
On the island of **Kauai**, 56 percent of the land was classified as conservation and 40 percent as agricultural districts.

The entire island of **Niihau** was classified for agricultural use.









EXPLANATION

Altitude, in feet above sea level

1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
11,000
12,000
13,000

Figure 33. The island of **Hawaii** is the largest island of the State and has the greatest variation in topography; Mauna Kea's summit is the highest point at 13,796 feet.

Maui is essentially two islands connected by a wide isthmus and is highest in the east-central part.

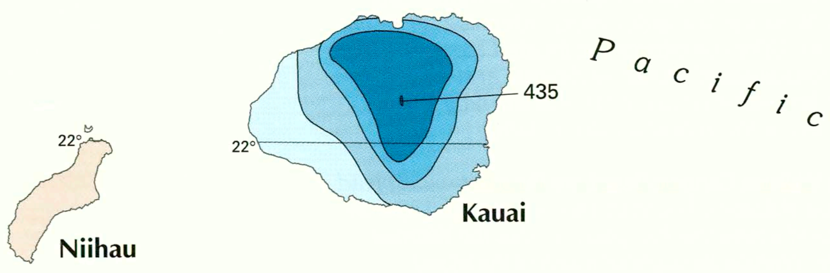
Kahoolawe, the smallest of the eight major islands of the State, is mostly less than 1,000 feet above sea level, as is most of **Lanai** except for the central part.

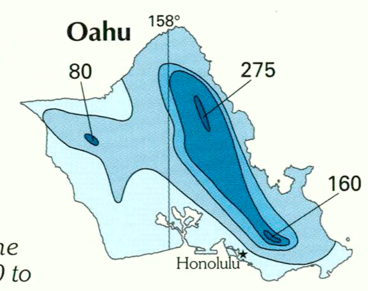
Most of **Molokai**'s mountainous eastern one-half is between 1,000 and 4,970 feet above sea level.

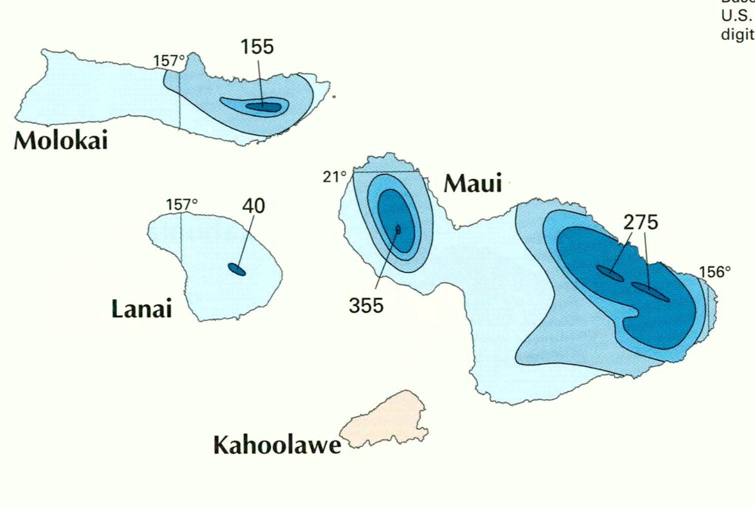
Oahu has two main mountain ranges, the Koolau and the Waianae, which trend northwestward.

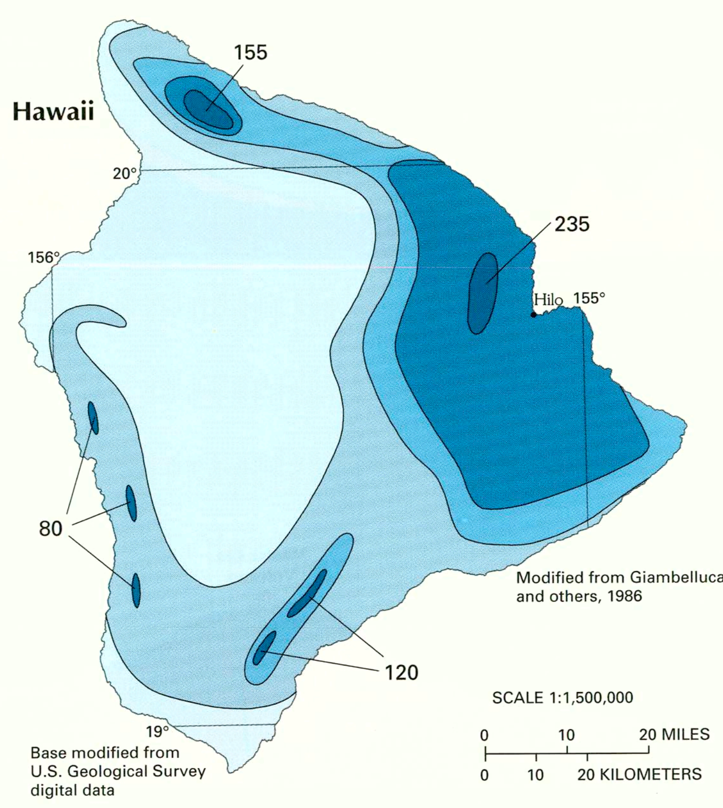
Kauai is mostly encircled by lowlands but has a large, west-central highland area that locally is as much as 5,243 feet above sea level.

Niihau, the second smallest of the eight major islands of the State, is mostly less than 1,000 feet above sea level.









EXPLANATION

Average annual precipitation (1931–83 for Molokai; 1916–83 for other islands), in inches

40
80
120

160 Area of greatest rainfall — Number is minimum average annual precipitation

Insufficient data

Figure 34. Average annual precipitation varies greatly among the islands and ranges from less than 10 to greater than 400 inches. Rainfall is generally greatest on the eastern, windward sides of the islands and in areas between 2,000 and 6,000 feet above sea level. Niihau, Lanai, and Kahoolawe receive little rainfall because they are in rain shadows that are formed by larger islands.

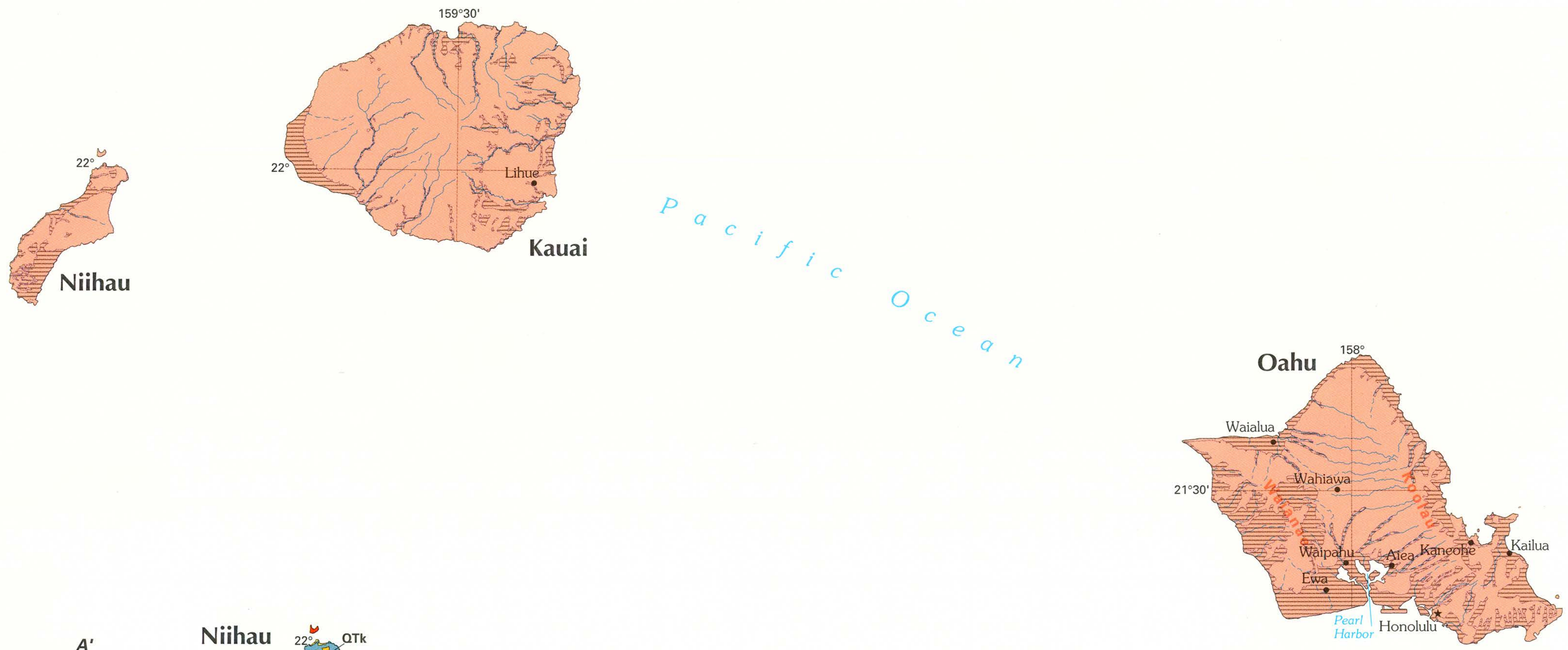
On Kauai, the island summit receives more than 435 inches of average annual rainfall (1916–83). West Maui has a small area where average annual rainfall is greater than 355 inches. Average annual rainfall is greater than 275 inches on the northeastern parts of Maui and Oahu, and greater than 235 inches on the northeastern part of the island of Hawaii. Because the island of Lanai is in the rain shadow of Maui and Molokai, it receives much less rain than the larger islands. Most of the southwestern coastal areas of all islands receive less than 40 inches of rain annually; the island of Hawaii has areas at high altitudes that receive less than 20 inches.

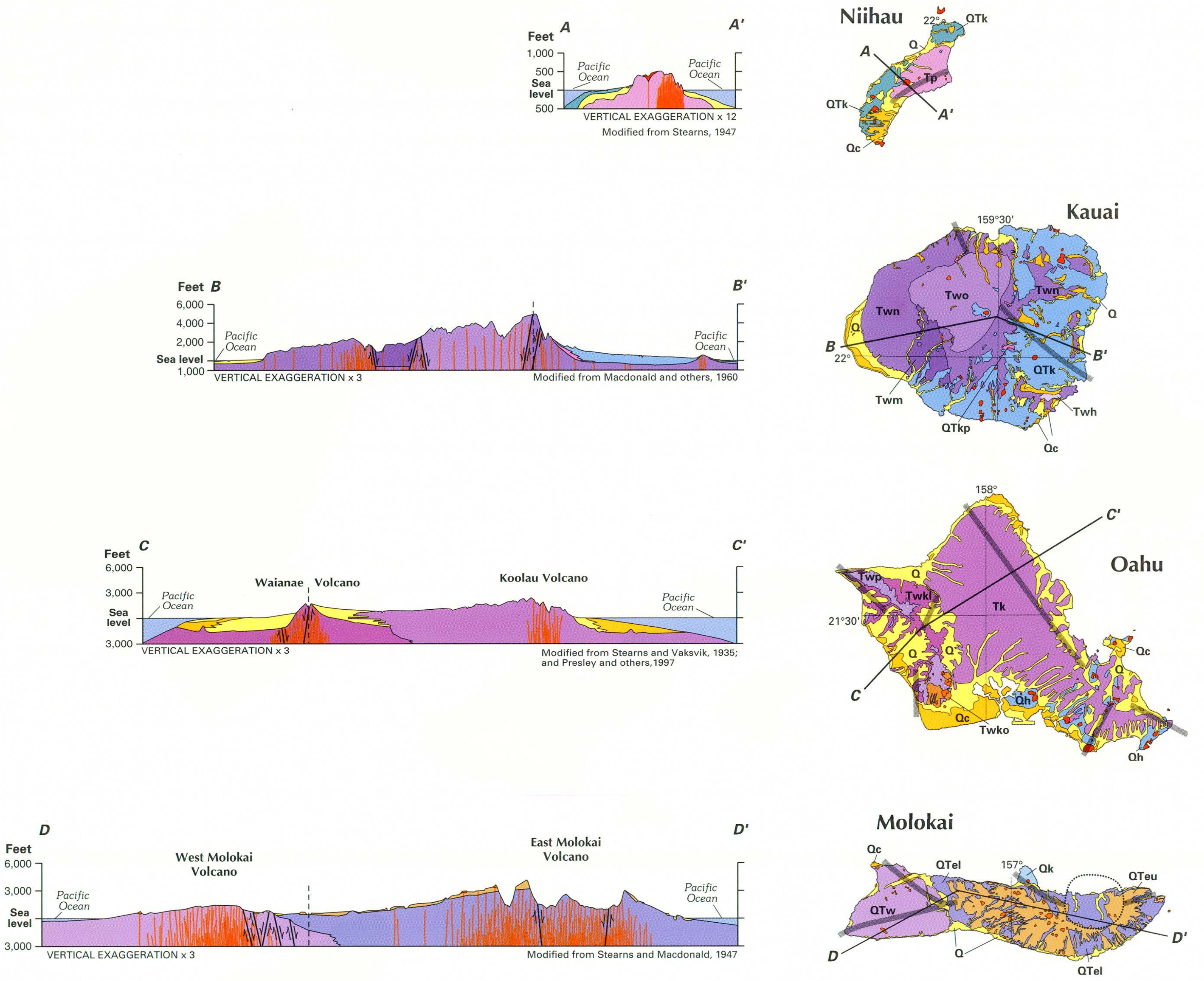
Two rainfall seasons are typical—a wet season during the winter months from October through April and a dry season during the summer months from May through September. An exception is the western side of the island of Hawaii, where summer months are wettest because of a thermally driven sea breeze.

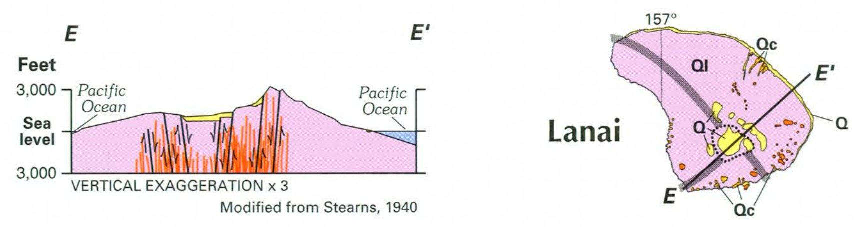
Evapotranspiration, which is the loss of water to the atmosphere by the combination of transpiration of plants and direct evaporation from land and water surfaces, is a major component of the hydrologic budget of the islands. In the Honolulu area of Oahu, for example, actual evapotranspiration was estimated to be about 40 percent of the total water (rainfall plus irrigation) falling on or applied to the ground surface during 1946–75. Pan evaporation is the main measurement used in Hawaii to assess the amount of water loss by evapotranspiration. Over the open ocean, the estimated annual pan-evaporation rate is 65 inches. As with precipitation, pan-evaporation rates in Hawaii are related to topography. At altitudes between 2,000 and 4,000 feet, where humidity is high and sunlight intensity is reduced because of clouds, pan-evaporation rates are reduced to as low as 25 percent of the open-ocean rate. In the leeward coastal areas, wind carrying dry, warm air increases annual pan-evaporation rates to as much as 100 inches. At the summits of Mauna Kea and Mauna Loa on the island of Hawaii, annual pan-evaporation rates exceed 70 inches because of clear skies and dry air.

The amount of recharge available to enter the aquifers on an annual basis is about equal to average annual precipitation minus water losses (average annual runoff and evapotranspiration). Runoff is directly related to rainfall, topography, soil type, and land use, and ranges from less than 5 to as much as 200 inches per year. Runoff typically averages about 10 to 40 percent of the average annual precipitation, but is greater than average where precipitation is high and slopes are steep and where precipitation falls on less-permeable land surfaces. Runoff is less than average where low amounts of precipitation fall on gentle slopes or where precipitation falls on highly permeable soils or rocks. Streams generally are small and have steep gradients, and many flow only immediately after periods of rainfall. Some streams, however, receive water from aquifers and have perennial flow.

Figure 35. Volcanic-rock aquifers extend throughout the eight major Hawaiian Islands and are the most important sources of potable ground water. Sedimentary deposits overlie the volcanic-rock aquifers in some areas. Because the island of **Hawaii** has not been extensively eroded, sedimentary deposits there are not widespread. The isthmus of **Maui** contains sedimentary deposits overlying the volcanic-rock aquifers. Sedimentary deposits exist in some coastal areas on the islands of **Kahoolawe**, **Lanai**, and **Molokai**. On **Oahu** and **Kauai**, sedimentary deposits act as caprock to the underlying volcanic-rock aquifers. Sedimentary deposits on **Niihau** occur mainly in the southeastern and northwestern parts of the island.







EXPLANATION of elements common to geology maps or sections

- Rejuvenated-stage cone or vent
- Shield- or postshield-stage cone, crater, or vent
- Boundary of caldera—Approximately located
- Axis of rift zone—Approximately located
- Intrusive body
- H——H' Line of geologic section
- Fault—Arrows indicate relative movement
- Bend in section

SCALE 1:500,000
0 5 MILES
0 5 KILOMETERS
Horizontal scale of sections

SCALE 1:1,000,000
0 5 10 15 MILES
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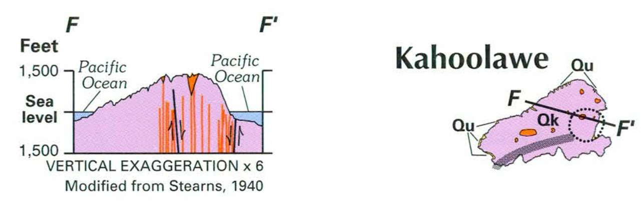
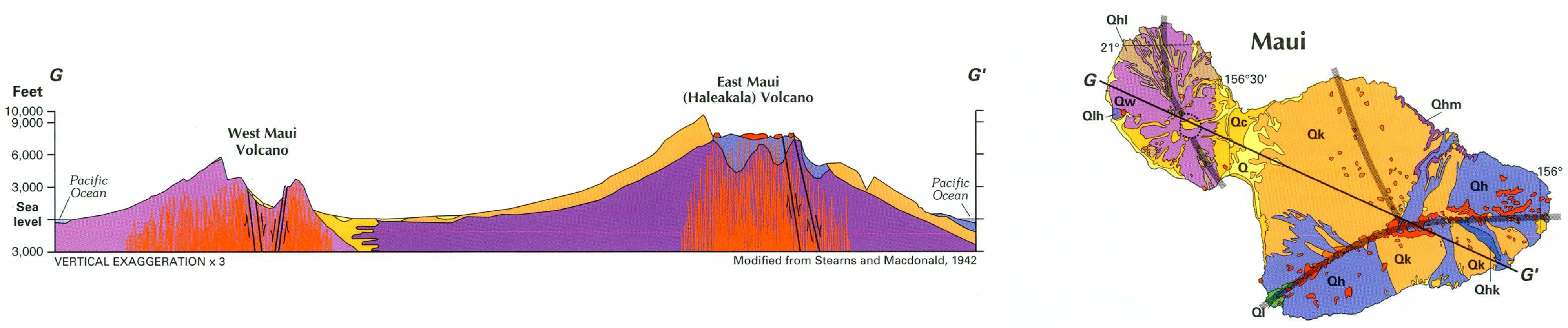
Scale of maps





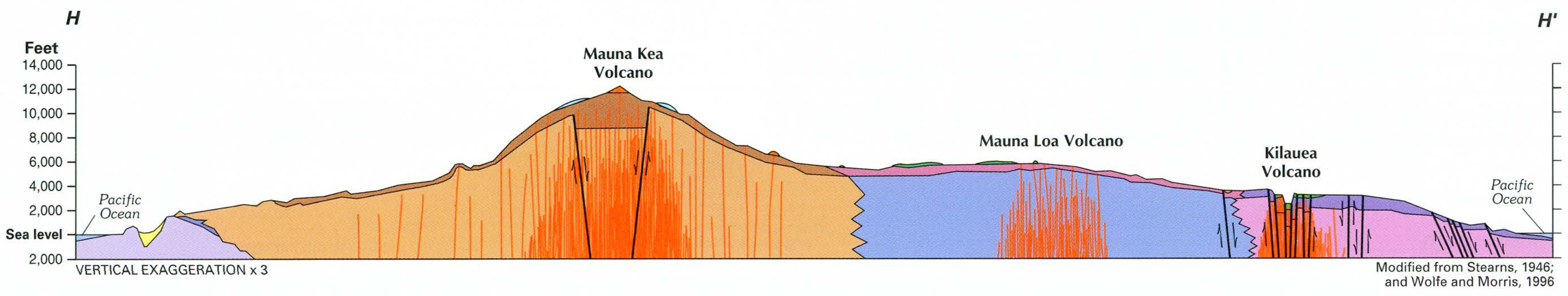


Figure 36. The island of **Hawaii** is formed by five volcanoes; Kohala, Mauna Kea, Hualalai, Mauna Loa, and Kilauea. Volcanic rocks that form the core of the island of Hawaii include the Ninole and Hilina Basalts, and the Pololu and Hamakua Volcanics. Extensive zones of vents and dikes exist on all of the volcanoes.

The island of **Maui** is formed by two volcanoes, the older West Maui Volcano and the East Maui Volcano. The East Maui Volcano, which forms the eastern two-thirds of the island, last erupted about 1790. The Honomanu Basalt overlies the Wailuku Basalt beneath the isthmus that separates west Maui from east Maui. The Kula Volcanics forms a veneer on the Honomanu Basalt. Dikes are found in the rift zones of the West and East Maui Volcanoes. Alluvium and coralline limestone cover the isthmus between the two volcanoes.

Kahoolawe consists of a single volcano. A single rock unit, the Kanapou Volcanics, forms most of Kahoolawe. The volcano contains a prominent rift zone in its southern half.

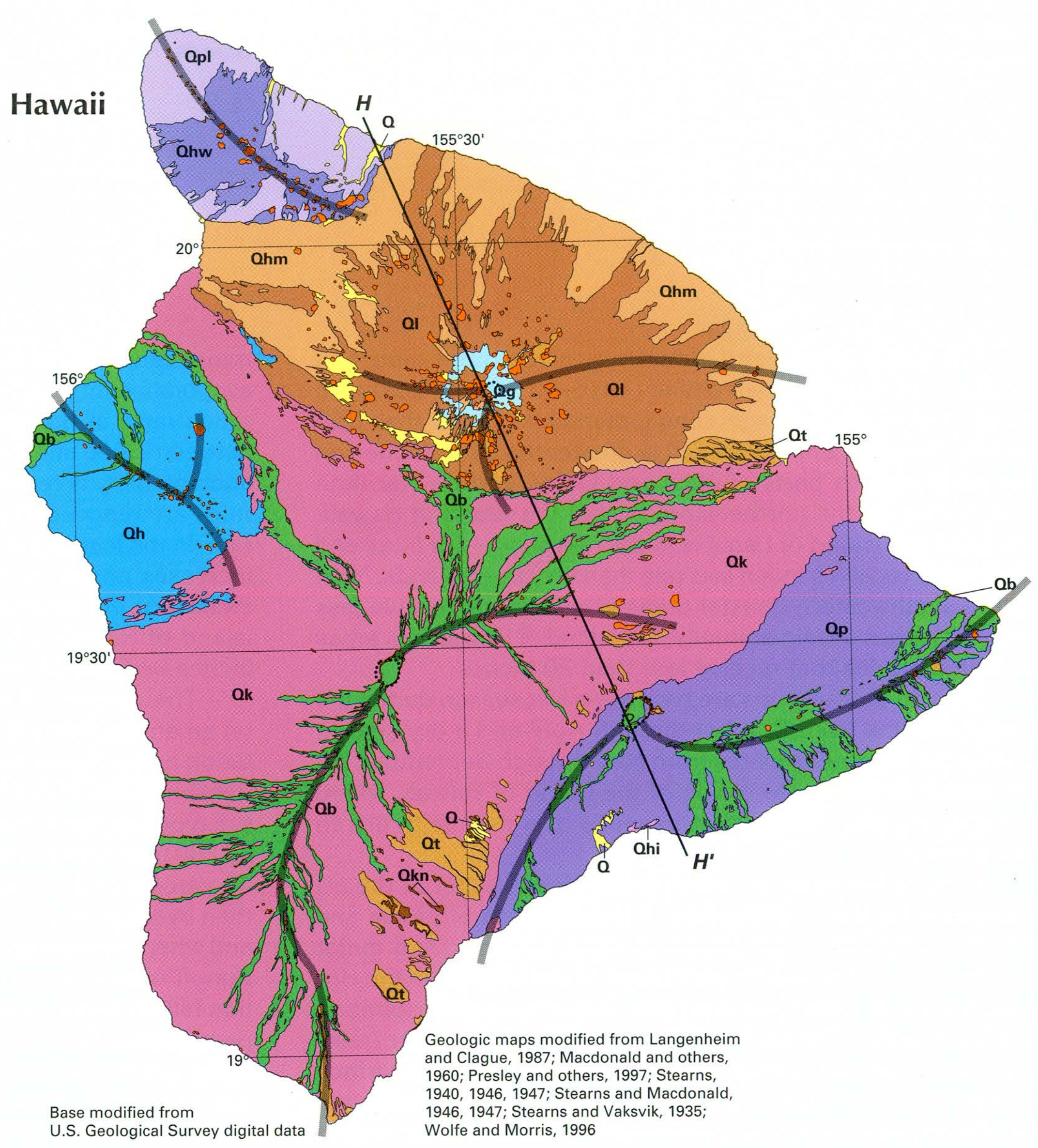
Lanai consists of a single volcano and the Lanai Basalt is the principal rock unit on the island. Sedimentary deposits fill several basins in the interior of the island.

The island of **Molokai** is formed by two volcanoes, the West Molokai Volcano and the East Molokai Volcano. The West Molokai Volcanics covers extensive areas on the island's western part, but the East Molokai Volcanics is overall the most widespread geologic formation on the island. The veneer that forms the upper member of the East Molokai Volcanics is thin in most places. A prominent dike complex is located in east Molokai. A plain covered with scattered deposits of alluvium separates the two volcanoes.

The Koolau Basalt is the most widespread geologic formation on **Oahu**, but rocks of the Waianae Volcanics cover extensive areas on the island's western part. Dike complexes are located along the axes of both volcanoes. Unconsolidated clastic sediments and consolidated, coralline limestone underlie large areas near the shoreline, particularly in southern and western Oahu.

The four members of the Waimea Canyon Basalt are the most widespread rocks on **Kauai**. The Koloa Volcanics, however, covers extensive areas on the eastern half of the island where this formation overlies the Waimea Canyon Basalt. Dikes are common throughout much of the island.

Niihau is formed by a single volcano consisting of the Paniau Basalt and the overlying younger Kiekie Basalt. Alluvial deposits, some of which are consolidated, are widespread on the island. Dikes are common in a rift zone along the eastern half of the island.



Geologic maps modified from Langenheim and Clague, 1987; Macdonald and others, 1960; Presley and others, 1997; Stearns, 1940, 1946, 1947; Stearns and Macdonald, 1946, 1947; Stearns and Vaksvik, 1935; Wolfe and Morris, 1996

Base modified from U.S. Geological Survey digital data

AREAL DISTRIBUTION OF AQUIFERS

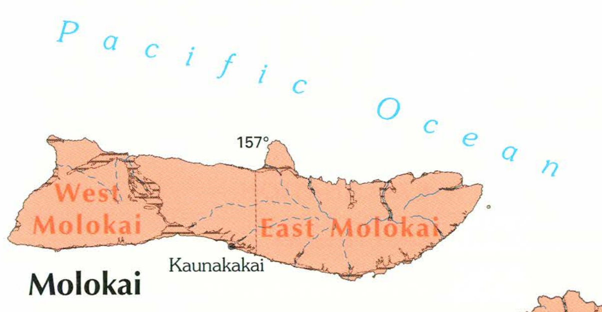
The rocks of the Hawaiian islands can be grouped into two general hydrogeologic categories. The principal aquifers occur in volcanic rocks ranging in age from Miocene to Holocene. Less-important aquifers occur in Quaternary-age sedimentary deposits of alluvium, coralline limestone, and cemented beach or dune sand. Volcanic-rock aquifers are found throughout the eight major islands (**fig. 35**) and are locally overlain by sedimentary deposits. The areas where sedimentary deposits are at the land surface on the eight major islands are shown in **figure 35**.

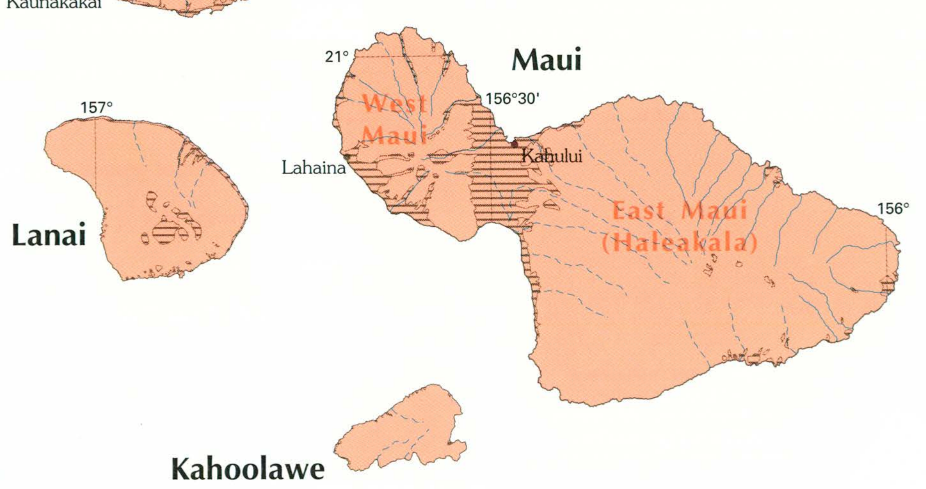
Volcanic-rock aquifers are by far the most extensive and productive aquifers in the Hawaiian islands. These aquifers are formed by layered sequences of permeable basalt. Less-productive volcanic-rock aquifers are formed by sequences of less-permeable, thick-bedded basalt. The basalt found in some areas, such as much of Kahoolawe, Niihau, and the western third of Molokai, may be permeable, but yields little potable water mainly because these areas receive little recharge.

Consolidated sedimentary deposits are found mostly in the coastal areas. The limestone is highly permeable in many places and usually yields brackish water or saltwater because of good hydraulic connection with the ocean and because of low recharge to the limestone. The brackish water is used for cooling and industrial purposes, particularly in southern Oahu. In addition, treated wastewater is injected into the limestone where it contains brackish water or saltwater. Coralline limestone overlies much of the isthmus area of Maui, but these rocks are not a significant source of potable water.

The unconsolidated sedimentary deposits consist of alluvium, beach and dune sand, and lagoonal mud and clayey sand. In some places, these deposits are interbedded with consolidated rocks. Sedimentary deposits, as well as weathered volcanic rocks are important to the ground-water hydrology of the islands in some areas. The combination of weathered volcanic rocks and overlying sedimentary material forms a low-permeability material called caprock in areas overlying high-permeability volcanic rocks. The caprock confines water in the volcanic rocks so that, in places such as the coastal plain of Oahu, freshwater exists in the volcanic rocks beneath brackish water or saltwater in the caprock.

The climate of the Hawaiian islands has a profound effect on weathering processes that affect the hydraulic properties of sedimentary deposits and volcanic rocks (especially ash and tuff). The permeability of the sediments and volcanic rocks can be greatly reduced by chemical weathering. During the weathering process, original pore spaces are closed by swelling of mineral particles as chemical changes cause the deposits and rocks to disintegrate. Weathering processes consist chiefly of oxidation, hydration, and carbonation (reaction with carbon dioxide) of various minerals in the rocks.

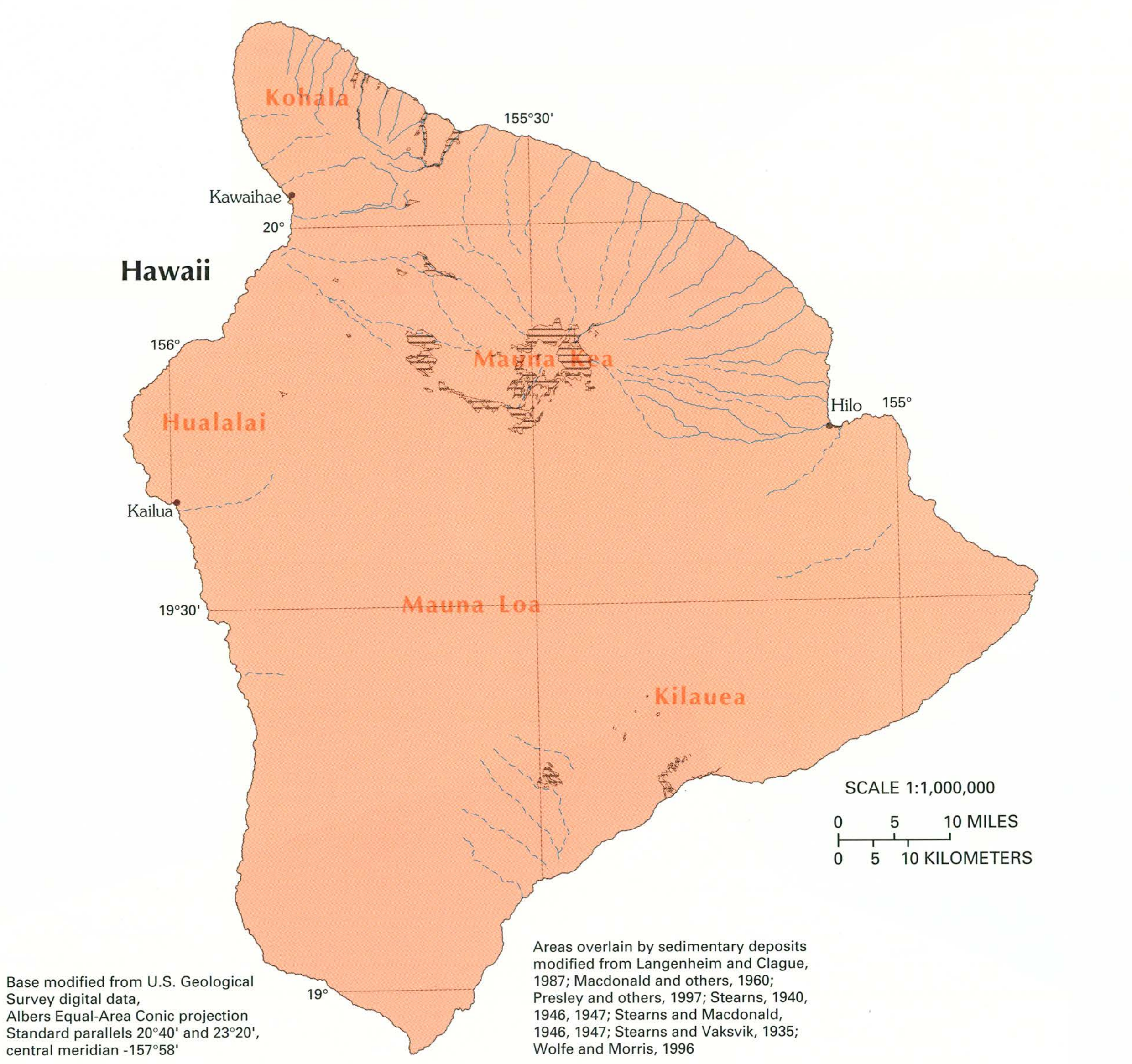




EXPLANATION

Volcanic-rock aquifer—Overlain by sedimentary deposits where patterned

Kilauea — Volcano name and location



Base modified from U.S. Geological Survey digital data, Albers Equal-Area Conic projection Standard parallels 20°40' and 23°20', central meridian -157°58'

Areas overlain by sedimentary deposits modified from Langenheim and Clague, 1987; Macdonald and others, 1960; Presley and others, 1997; Stearns, 1940, 1946, 1947; Stearns and Macdonald, 1946, 1947; Stearns and Vaksvik, 1935; Wolfe and Morris, 1996

GEOLOGY

A long chain of volcanoes known as the Hawaiian Ridge extends northwestward across the central Pacific Ocean. The volcanoes are youngest in the southeast and become progressively older to the northwest. The volcanoes of the Hawaiian Ridge have formed as a plate of the Earth's crust beneath the Pacific Ocean moves northward and westward relative to an area of anomalously high temperature, called a hot spot, in the Earth's mantle. As a volcano moves northwestward away from the hot spot, eruptions become less frequent, and a new volcano begins to form above the hot spot. Many of the younger volcanoes have grown above sea level, forming islands. As islands age, they erode and subside, eventually becoming atolls and then seamounts.

Some of the eight major Hawaiian islands, such as Kahoolawe, are composed of a single volcano, whereas Hawaii is formed by five volcanoes. Some of the older volcanoes have not erupted for millions of years, but as many as eight of the younger volcanoes may have erupted in the last 10,000 years. Historic eruptions have been recorded on five volcanoes: East Maui Volcano—on the island of Maui; Hualalai, Mauna Loa, and Kilauea—on the island of Hawaii; and Loihi—a submarine volcano currently (1998) forming to the southeast of Hawaii. Kilauea also is currently erupting. The volcanoes are called shield volcanoes because they are shaped like broad, flattened domes.

The evolution of Hawaiian volcanoes generally progresses through four distinct stages—preshield, shield, postshield, and rejuvenated. However, not all Hawaiian volcanoes have a postshield stage or a rejuvenated stage. The preshield stage is the earliest, submarine phase of activity, and is known primarily from studies of Loihi. Lava from the preshield stage consists predominantly of alkalic basalt (basalt that is low in silica and high in sodium and potassium). Lava from the principal stage of volcano building, called the shield stage, consists of fluid tholeiitic basalts (silica-saturated basalt) that characteristically form thin flows. This basalt forms during submarine, as well as subaerial, eruptions. A large central caldera, or craterlike depression, can form during the preshield or shield stages and might later be partly or completely filled during subsequent eruptions. Thousands of flows erupt from the central caldera and from two or three rift zones that radiate out from the caldera. Intrusive dikes fed by rising magma extend down the rift zones and may erupt if they reach the surface. The shield stage is the most voluminous phase of eruptive activity during which 95 to 98 percent of the volcano is formed. The postshield stage is marked by a change in lava chemistry and character. Postshield-stage lava includes alkalic basalt, and more viscous hawaiite, ankaramite, mugearite, and trachyte. Lava from the postshield stage may erupt from locations outside of the rift zones formed during the shield stage. Postshield-stage lava forms a veneer atop the shield-stage basalt. Eruptions of more viscous lava generally are explosive and may produce pyroclastic material (ash, cinder, spatter, and larger blocks), as well as thick, massive lava flows. After a period of quiescence, lava such as alkalic basalt, nephelinite, and basanite, might issue from isolated vents on the volcano during the rejuvenated stage. Pyroclastic material can be deposited during all of the subaerial stages of eruption.

Clastic sedimentary deposits, which primarily are alluvium derived from erosion of the volcanic rocks, have accumulated on the flanks of the islands. In some places, the clastic sediments are interbedded with coralline limestone that formed as reef deposits in shallow marine waters.

The island of **Hawaii** consists of five volcanoes, discussed here from oldest to youngest (**fig. 36**). All of the volcanic rocks range in age from Pleistocene to Holocene. Kohala Volcano, which forms the island's northwestern tip, consists mostly of the shield-stage, mainly tholeiitic Pololu Volcanics and is capped by flows of the postshield-stage Hawi Volcanics. Hualalai Volcano, which forms part of the island's west coast, is covered by the postshield-stage Hualalai Volcanics. Mauna Kea Volcano, which is southeast of Kohala Volcano, primarily consists of the shield- and postshield-stage Hamakua Volcanics, which is overlain by the postshield-stage Laupahoehoe Volcanics. In the central part of the island, the bottom unit of Mauna Loa Volcano is the Ninole Basalt; which is overlain by the Kahuku Basalt; which is in turn overlain by the Kau Basalt, the most widespread geologic unit on the island. All three units of Mauna Loa Volcano consist of shield-stage tholeiitic basalt. Kilauea Volcano, which forms the southeastern part of the island, contains shield-stage tholeiitic basalts, the Hilina Basalt and the younger Puna Basalt. Rift zones, marked by cones and fissures, contain numerous volcanic dikes, and are found on all the volcanoes. Small beaches composed of thin, unconsolidated sand, some created as lava enters the ocean (Hawaii's famous black sand beaches), fringe parts of the island's coastline.

Maui consists of two volcanoes—the older West Maui Volcano and the larger East Maui Volcano (Haleakala). The two volcanoes are separated by an isthmus that is covered with deposits of alluvium and coralline limestone that are as much as 5 miles wide. The Pleistocene-age rocks of West Maui Volcano consist of the mostly shield-stage Wailuku Basalt, which is overlain by the postshield-stage Honolua Volcanics and rejuvenated-stage Lahaina Volcanics. The Pleistocene- to Holocene-age rocks of East Maui Volcano consist of the tholeiitic, shield-stage Honomanu Basalt, which is overlain by the postshield-stage Kula Volcanics and the younger rejuvenated-stage Hana Volcanics. The Kula Volcanics and the Hana Volcanics are the most widespread geologic units exposed at the land surface on Maui. The East Maui Volcano has three rift zones and the West Maui Volcano has two.

Kahoolawe is a single, relatively small volcano. The Pleistocene-age Kanapou Volcanics forms most of the island and includes both shield-and postshield-stage lava. Rejuvenated-stage vents and small areas of alluvium are present at scattered places near the shoreline.

The island of **Lanai** is a single volcano, and all of the island's shield-stage tholeiitic rocks are mapped as the Pleistocene-age Lanai Basalt. Sedimentary deposits, predominantly alluvium but with small areas of consolidated conglomerate, fill many of the basins in the island's interior. Dikes are present in three rift zones radiating from the volcano's summit.

Molokai consists of two volcanoes, the older West Molokai Volcano and the larger East Molokai Volcano, joined by a plain. Both the West and East Molokai Volcanics consist of shield- and postshield-stage volcanic rocks ranging in age from Pliocene to Pleistocene. The widespread East Molokai Volcanics is separated into two informal members—the thick lower member that is mostly tholeiitic basalt and the thinner upper member that contains more alkalic basalt. The rejuvenated-stage Pleistocene-age Kalaupapa Volcanics forms a peninsula on Molokai's northern coast. Volcanic dikes are found in the rift zones of both volcanoes.

Oahu consists of two volcanoes—the older Waianae Volcano in the west and the larger Koolau Volcano in the east. The Pliocene-age Waianae Volcanics is divided into four members. The lower two members, the Lualualei (shield-stage) and the Kamaileunu (shield- and postshield-stage) Members, are combined on the map in this report, and the upper Palehua and Kolekole Members, which consist largely of alkalic basalt, are shown separately. The shield-stage tholeiitic rocks of the younger Koolau Volcano are named the Koolau Basalt. The Pliocene-age Koolau Basalt is the most widespread geologic unit exposed on Oahu. Rejuvenated-stage eruptions from about 50 vents scattered on the southeastern part of Koolau Volcano form the Honolulu Volcanics, which ranges in age from Pleistocene to Holocene. The largest rift zones in the Koolau and Waianae Volcanoes are on a nearly parallel northwest-southeast trend: other rift zones trend north and northeast. Oahu has larger areas of sedimentary deposits than any other island, and these deposits contain coralline limestone in coastal areas.

The geology of **Kauai** is complex and the island may consist of more than one volcano. Two geologic formations—the mainly shield-stage Waimea Canyon Basalt and the rejuvenated-stage Koloa Volcanics, have been identified. The Waimea Canyon Basalt, which ranges in age from Miocene to Pliocene, is divided into the Napali, the Haupu, the Olokele, and the Makaweli Members primarily on the basis of the bedding characteristics and structural relations of the rocks. The Pliocene- to Pleistocene-age Koloa Volcanics overlies the Waimea Canyon Basalt and is exposed at the land surface over most of the eastern half of Kauai. Clastic sedimentary deposits, which include lithified sand dunes, are scattered primarily around the periphery of the island.

Niihau consists of the deeply eroded remnants of a single volcano. The core of the island is the mainly shield-stage Miocene- to Pliocene-age Paniau Basalt, which is intruded by dikes and overlain by the rejuvenated-stage Pliocene- to Pleistocene-age Kiekie Basalt. Alluvial deposits are extensive on Niihau, and some of the alluvium is consolidated.

Holocene and Pleistocene

- Q — Unconsolidated sedimentary deposits
- Qc — Consolidated sedimentary deposits

NIIHAU EXPLANATION

Pleistocene and Pliocene

- QTk — Kiekie Basalt

Pliocene and Miocene

- Tp — Paniau Basalt

KAUAI EXPLANATION

Pleistocene and Pliocene

- QTk — Koloa Volcanics
- QTkp — Palikea Breccia Member

Pliocene and Miocene

Waimea Canyon Basalt

- Twm — Makaweli Member
- Two — Olokele Member
- Twh — Haupu Member
- Twn — Napali Member

OAHU EXPLANATION

Holocene and Pleistocene

- Qh — Honolulu Volcanics

Pliocene

- Tk — Koolau Basalt

Waianae Volcanics

- Twko — Kolekole Member
- Twp — Palehua Member
- Twkl — Kamaileunu and Lualualei Members

MOLOKAI EXPLANATION

Pleistocene

- Qk — Kalaupapa Volcanics

Pleistocene and Pliocene

- QTw — West Molokai Volcanics

East Molokai Volcanics

- QTeu — Upper member
- QTel — Lower member

LANAI EXPLANATION

Pleistocene

- Ql — Lanai Basalt

KAHOOLAWE EXPLANATION

Holocene

- Qu — Unconsolidated sedimentary deposits

Pleistocene

- Qk — Kanapou Volcanics

MAUI EXPLANATION

Holocene and Pleistocene

- Ql — Lava flow of 1790
- Qh — Hana Volcanics
- Qhk — Kipahulu Member

Pleistocene

West Maui Volcano

- Qlh — Lahaina Volcanics
- Qhl — Honolua Volcanics
- Qw — Wailuku Basalt

East Maui (Haleakala) Volcano

- Qk — Kula Volcanics
- Qhm — Honomanu Basalt

HAWAII EXPLANATION

Holocene and Pleistocene

- Qt — Ash and tephra deposits

Pleistocene

- Qg — Glacial deposits (Mauna Kea)

Holocene

- Qb — Historical basalt flow (Kilauea, Mauna Loa, Hualalai)
- Qp — Puna Basalt (Kilauea)

Holocene and Pleistocene

- Qk — Kau Basalt (Mauna Loa)
- Qh — Hualalai Volcanics (Hualalai)
- Ql — Laupahoehoe Volcanics (Mauna Kea)

Pleistocene

- Qhi — Hilina Basalt (Kilauea)
- Qkn — Kahuku Basalt or Ninole Basalt (Mauna Loa)
- Qhm — Hamakua Volcanics (Mauna Kea)
- Qhw — Hawi Volcanics (Kohala)
- Qpl — Pololu Volcanics (Kohala)

GROUND-WATER OCCURRENCE AND MOVEMENT

Certain geologic and hydrologic characteristics of the Hawaiian islands favor the occurrence and retention of freshwater. The larger islands have extremely productive freshwater aquifers. However, the geologic and hydrologic characteristics of the aquifers vary widely. The modes of emplacement of the volcanic rocks and sedimentary deposits and the subsequent weathering processes to which they have been subjected have resulted in a wide range of the hydraulic properties that control the storage and flow of water. Sedimentary deposits and some types of volcanic rocks (chiefly pyroclastic material) that typically are considered to be productive aquifers in much of the conterminous United States are commonly confining units or relatively poor aquifers in the Hawaiian islands. Basalt with thick lava-flow units, weathered ash and tuff beds, and unconsolidated coastal-plain and valley-fill sedimentary deposits generally are of low permeability, and impede the seaward and lateral movement of freshwater (defined in this report as water that contains less than 1,000 milligrams per liter dissolved solids).

The largest bodies of fresh ground water float on saltwater within the aquifers. This occurrence is known as a freshwater lens because of the lenticular shape of such bodies of water. The Ghyben–Herzberg principle is named after two scientists who independently described a freshwater–saltwater relation for conditions in which the two fluids do not mix and the freshwater is in static equilibrium with the ocean. In a static freshwater or Ghyben-Herzberg lens, the thickness of the freshwater lens below sea level is directly proportional to the height of the top of freshwater above sea level. In principle, at a place where the water table stands 1 foot above sea level, for example, 40 feet of freshwater will be below sea level, and the freshwater lens will thus be 41 feet thick. This relation exists because seawater is about one-fortieth more dense than freshwater. In most field situations, the lower limit of the freshwater is not a sharp boundary because mixing creates a zone of transition that separates freshwater from the saltwater body. The transition zone contains brackish water (water that contains between 1,000 and 35,000 milligrams per liter dissolved solids) and can be quite thick (several tens to hundreds of feet) depending on the extent of mixing. In many cases, the depth predicted by the Ghyben-Herzberg principle is about the depth where the brackish water in the transition zone has a dissolved-solids concentration about 50 percent of seawater.

On a small island that receives little precipitation or is made up of rocks that are highly permeable, the water level is just above sea level and the thickness of freshwater below sea level may be very thin. In some places where freshwater is significantly mixed with saltwater, brackish water may exist immediately below the water table (**fig. 37*A***). Where an aquifer receives more rainfall or is less permeable, the freshwater lens is thicker (**fig. 37*B***). The regional movement of fresh ground water is from interior areas toward the ocean, and all of the water discharges diffusely to the ocean or at springs near sea level.

In some coastal areas, such as southern Oahu, highly permeable volcanic-rock aquifers are overlain by a confining unit, called caprock, that consists of unconsolidated and consolidated sediments and weathered volcanic rock (**fig. 37*C***). The low overall permeability of the caprock impedes ground-water discharge to the ocean and results in a freshwater wedge inland that is thicker than it would be in the absence of the caprock. In places with a caprock, inland ground-water levels are at higher altitudes and the freshwater lens is significantly thicker than in places without a caprock.

For a given recharge rate, freshwater hydraulic heads will be lower in high-permeability rocks than in low-permeability rocks. In the most permeable volcanic rocks, the water table is generally no more than several tens of feet above sea level, indicative of a freshwater lens. In low-permeability volcanic rocks, ground-water flow is impeded to a greater extent, and higher water levels result. Water levels in these rocks are commonly greater than several tens of feet above sea level, and the rocks are fully saturated below the water table.

In some low-permeability volcanic-rock aquifers, such as in eastern Kauai (**fig. 38**), a vertically extensive freshwater-lens system develops with freshwater standing several hundreds or even thousands of feet above sea level. In such vertically extensive freshwater-lens systems, substantial vertical, freshwater hydraulic-head gradients exist in the aquifer and the Ghyben-Herzberg principle is not valid for predicting the depth at which saltwater lies beneath freshwater. Much of the fresh ground water in a vertically extensive freshwater-lens system discharges directly to stream valleys above sea level where the ground surface intersects the water table.

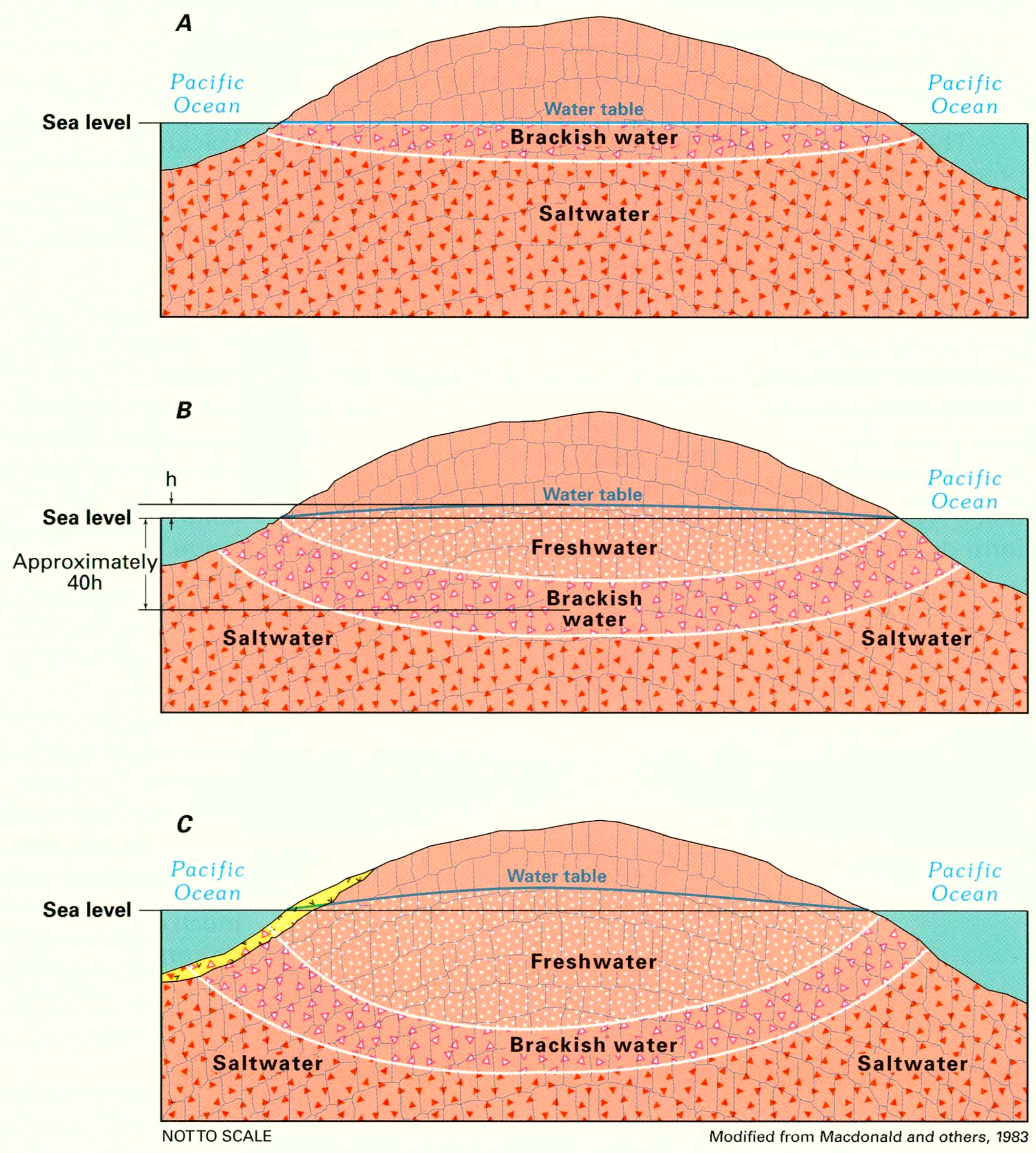


Figure 37. *On oceanic islands, such as the volcanoes of the Hawaiian Island group, freshwater commonly occurs as a body of water called a freshwater lens that floats on saltwater and is separated from the saltwater by a zone of transition that contains brackish water. On a small island that has minimal recharge from precipitation or that is composed of highly permeable rocks* ***(A)****, the water table near the center of the island may be only a few feet above sea level and the transition zone may be immediately below the water table. Where an island receives significant recharge or is composed of less permeable rocks, the water table is higher* ***(B)****, and a freshwater lens exists. The midpoint of the transition zone extends about 40 feet below sea level for each foot the water table stands above sea level. The transition zone varies in thickness depending on factors including withdrawals from wells and tides. Where caprock overlies and confines the freshwater lens* ***(C)****, the caprock tends to impede the seaward discharge of fresh ground water from the volcanic rocks, the freshwater lens builds up to a greater thickness, and potential for ground-water development is enhanced.*

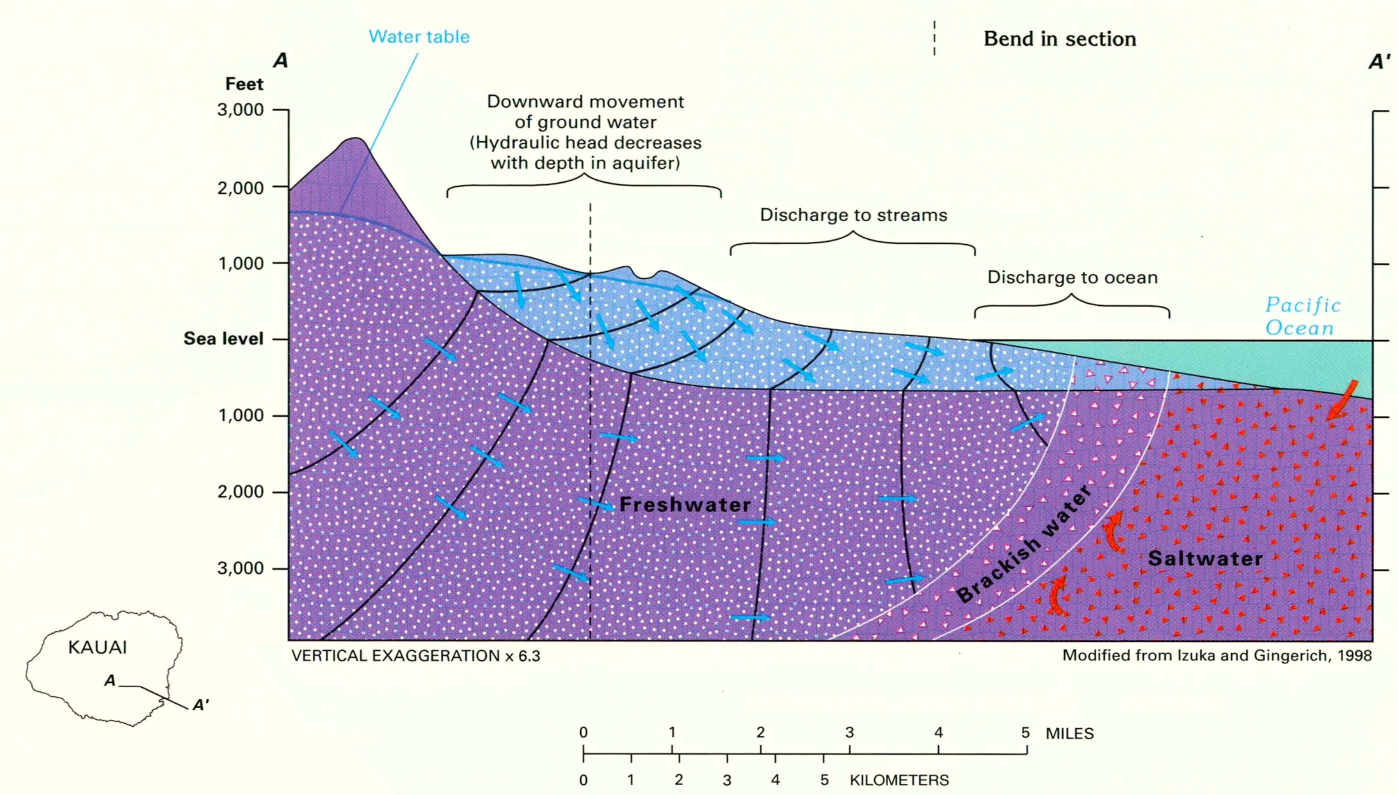


Figure 38. *A vertically extensive freshwater-lens system can exist where the volcanic rocks have low permeability, such as in eastern Kauai. In these systems, significant vertical hydraulic-head gradients exist, and the Ghyben-Herzberg relation does not accurately predict the depth to the midpoint of the transition zone.*

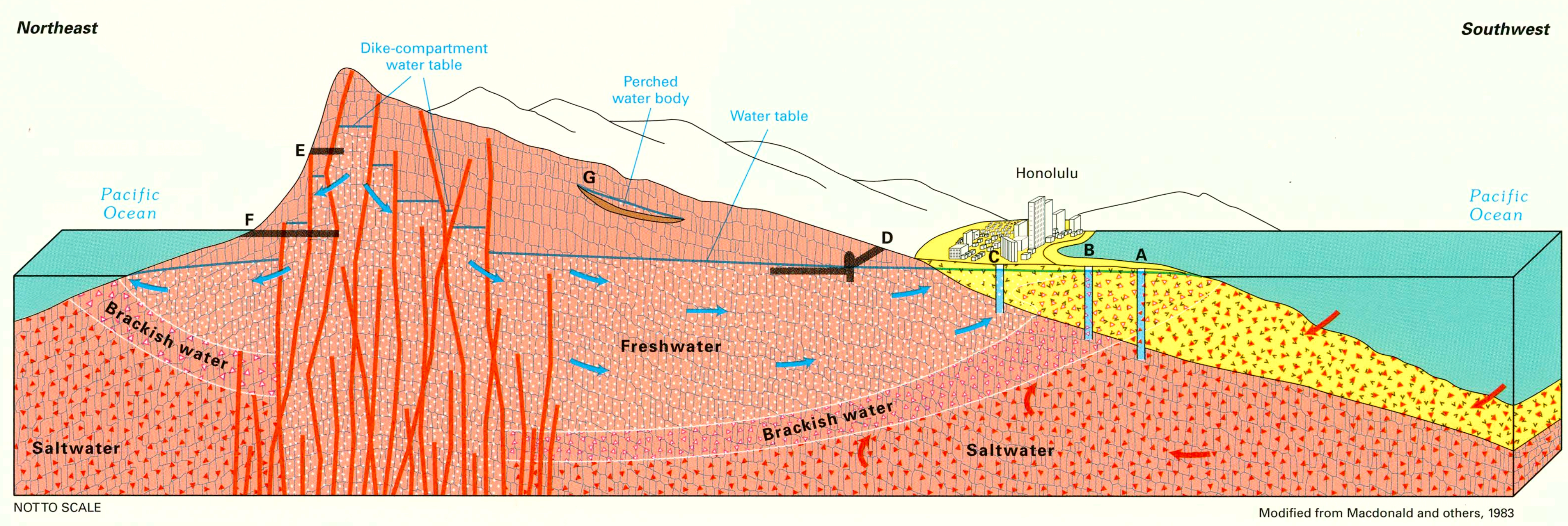


Figure 39. *On Oahu, freshwater is in a lens and dike-impounded water bodies and can be confined or unconfined. Wells A, B, and C are completed in a confined volcanic-rock aquifer. Well A produces only saltwater, well B produces brackish water, and well C produces freshwater. Shaft D produces large quantities of freshwater by skimming ground water just below the water table. Shafts E and F are constructed at different altitudes in dike-impounded water bodies; shaft F intercepts more dikes and likely will supply larger quantities of freshwater than shaft E. A bed of low-permeability ash creates a localized perched water body at site G.*

Dike-impounded water is an important source of low-salinity water on some of the islands. Sub-vertical dike systems tend to compartmentalize areas of permeable volcanic rocks, chiefly in the rift zones or caldera of a volcano. The dikes and rocks they intrude are known in Hawaii as dike complexes. Dikes impound water to great heights, as much as 3,300 feet above sea level on the islands of Maui and Hawaii and as much as 1,600 feet above sea level on Oahu. The depth to which freshwater extends below sea level within a dike complex is not known. Where dikes have been eroded or fractured, springs might issue from openings in the dikes. Shafts in dike complexes are particularly important sources of freshwater on the eastern side of Oahu, where much of the island's precipitation falls along the dike complex in the Koolau Range.

Perched water can occur in areas where low-permeability rocks impede the downward movement of ground water sufficiently to allow a saturated water body to develop over unsaturated rocks. These low-permeability rocks include massive, thick-bedded lava flows and extensive soil and weathered ash layers. Some perched water bodies supply usable quantities of water to wells.

The occurrence of ground water in the volcanic-rock aquifers of Oahu is summarized in **figure 39**. A freshwater lens underlies much of Oahu. Well A, which is nearest the coast, produces saltwater from below the transition zone, and well B produces brackish water from the transition zone. Well C is the inland-most well and produces freshwater. Horizontal shaft D (sometimes called a Maui shaft) has been dug into the volcanic rocks along and just below the water table and produces large volumes of freshwater by skimming water from near the top of the freshwater lens (**fig. 39**). Shafts E and F (sometimes called Lanai shafts) are dug horizontally into one or more of the dike-bounded compartments. Location G (**fig. 39**) indicates a perched water body containing minor amounts of water.

Fresh ground water generally moves from topographically high areas towards the ocean (**fig. 39**). Fresh ground-water flow is predominantly downward in the inland areas, upward in the coastal areas, and horizontal in between. Ground water from the dike compartments recharges downgradient freshwater lenses. A saltwater circulation system exists beneath the freshwater lens (**fig. 39**). Saltwater flows landward in the deeper parts of the aquifer, rises, then mixes with fresher water and discharges to the ocean.

The occurrence of fresh ground water in each of the Hawaiian islands can be depicted using water levels measured in wells, shafts, and springs as shown in **figure 40**. Water levels less than 50 feet above sea level were arbitrarily chosen to show occurrences of freshwater lenses for **figure 40**. Water levels greater than 50 feet above sea level were chosen to show areas where vertically extensive freshwater-lens systems or dike-impounded water exist. Non-dike-intruded areas containing wells that penetrate below sea level and that have high water levels are considered to have vertically extensive freshwater-lens systems. Where high water levels are found in wells that do not penetrate below sea level, the possibility of a perched-water system cannot be ruled out. Although many of the ground-water systems of the islands are well understood, exploration in others is only just beginning, and these areas are not fully understood.

The island of Hawaii contains high water levels (greater than 50 feet above sea level) in the rift zones of Kilauea and Kohala Volcanoes. High water levels, possibly associated with a buried rift zone of Hualalai Volcano or fault scarps draped with lava flows, also are present along the western coast. Areas of high water levels also are found along the northern flank and eastern flanks of Mauna Kea near Hilo and on the southeastern flank of Mauna Loa.

The central isthmus and most of the coastal areas of Maui (**fig. 40**) have low water levels (less than 50 feet above sea level) indicative of a freshwater lens. High water levels are found in the interior of West Maui Volcano where rocks are intruded by dikes. On East Maui Volcano, high water levels are found along the northern flanks of the volcano in the high rainfall areas. Both high and low water levels occur along the northern rift zone of the volcano, indicating that a perched-water system exists above a freshwater lens. Further to the east outside of any known rift zone, high water levels occur in wells drilled below sea level indicating that a vertically extensive freshwater-lens system is present.

Few wells exist on Kahoolawe but because rainfall is low, the freshwater lens is probably thin. Lanai has high water levels in the interior of the island within the rift zone and caldera complex. In the northern part of Molokai, areas of high water levels are found in association with the northwest rift zone of East Molokai Volcano.

A large number of wells on Oahu (**fig. 40**) in nearshore areas around most of the periphery of the island have low water levels. High water levels are found in rift zones near the eastern and western sides of the island and low-permeability features create high water levels in the central part. Some small areas of perched water in the southern part of Oahu are in alluvial deposits, but the perched water is not a significant source of supply.

Kauai has a large area with high water levels along the eastern side of the island (**fig. 40**). High water levels in wells that penetrate below sea level outside of any known rift zone indicate that a vertically extensive freshwater-lens system is present. Niihau receives little rain and data from existing wells indicate that a thin freshwater lens is present throughout much of the island.

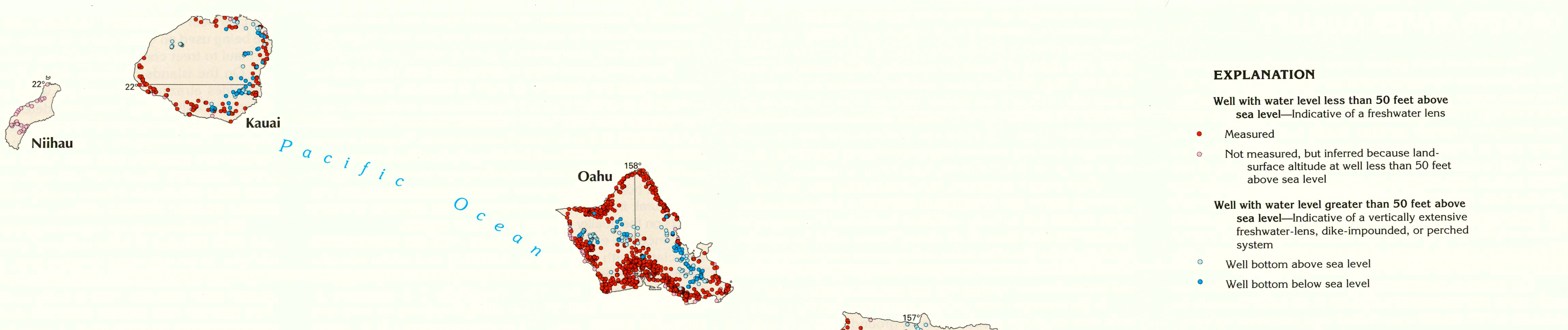
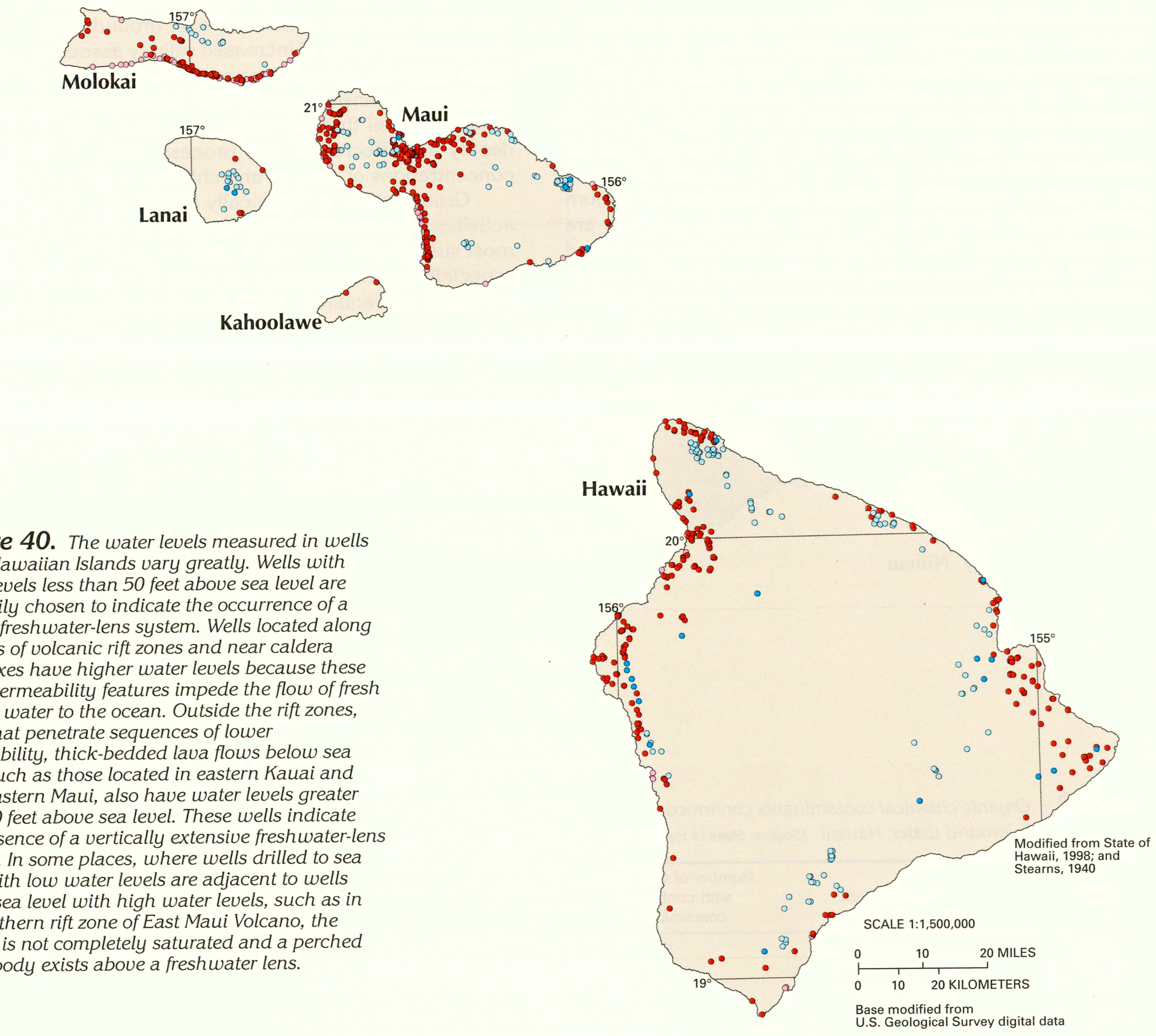



Figure 40. *The water levels measured in wells of the Hawaiian Islands vary greatly. Wells with water levels less than 50 feet above sea level are arbitrarily chosen to indicate the occurrence of a coastal freshwater-lens system. Wells located along the axes of volcanic rift zones and near caldera complexes have higher water levels because these lower-permeability features impede the flow of fresh ground water to the ocean. Outside the rift zones, wells that penetrate sequences of lower permeability, thick-bedded lava flows below sea level, such as those located in eastern Kauai and northeastern Maui, also have water levels greater than 50 feet above sea level. These wells indicate the presence of a vertically extensive freshwater-lens system. In some places, where wells drilled to sea level with low water levels are adjacent to wells above sea level with high water levels, such as in the northern rift zone of East Maui Volcano, the aquifer is not completely saturated and a perched water body exists above a freshwater lens.*

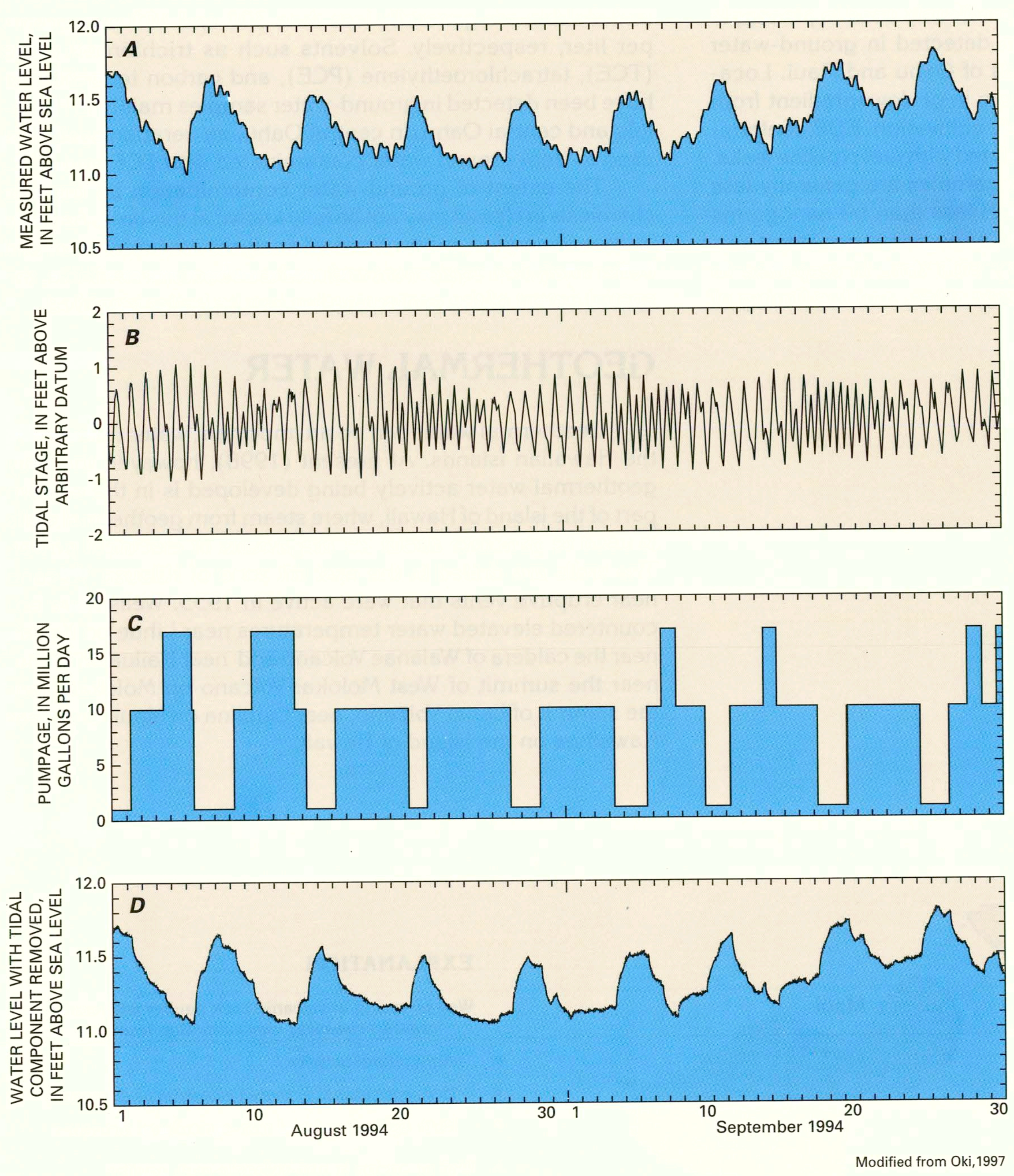
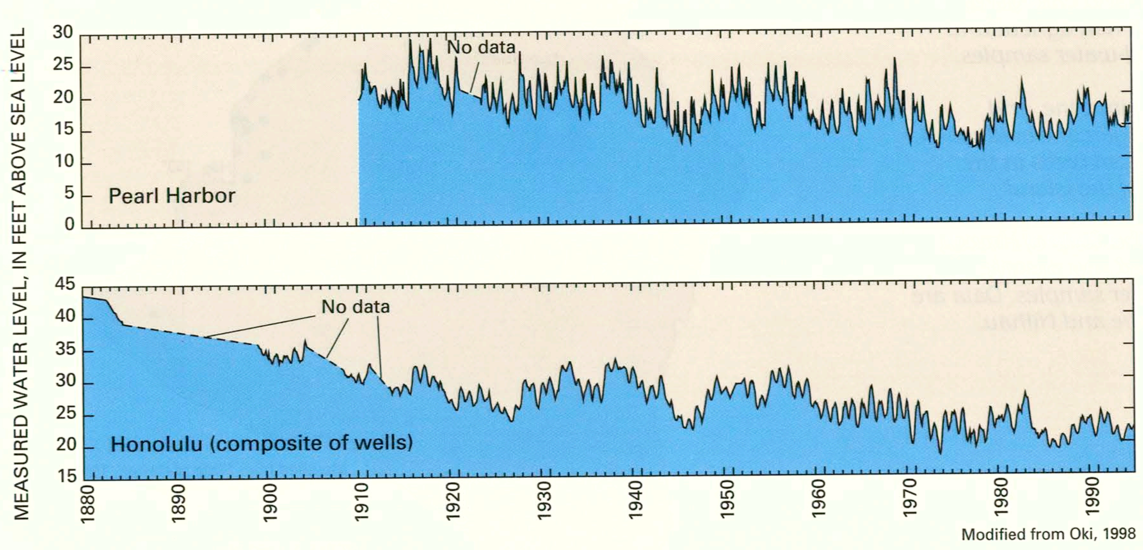


Figure 41. *Measured water levels* **(A)** *in a well in northern Oahu are affected by* **(B)** *ocean tides and* **(C)** *withdrawals from a nearby wellfield. The effects of withdrawals are more clearly seen in hydrograph* **D** *after the removal of the effects of ocean tides from the measured water levels.*



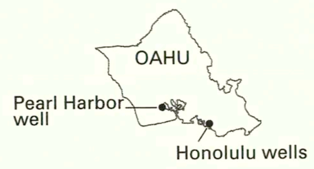


Figure 42. *Water levels in southern Oahu have declined over time in response to increased ground-water withdrawals. Seasonal fluctuations in water levels reflect increased demand for ground water during the dry summer months and reduced demand during the wetter winter months.*

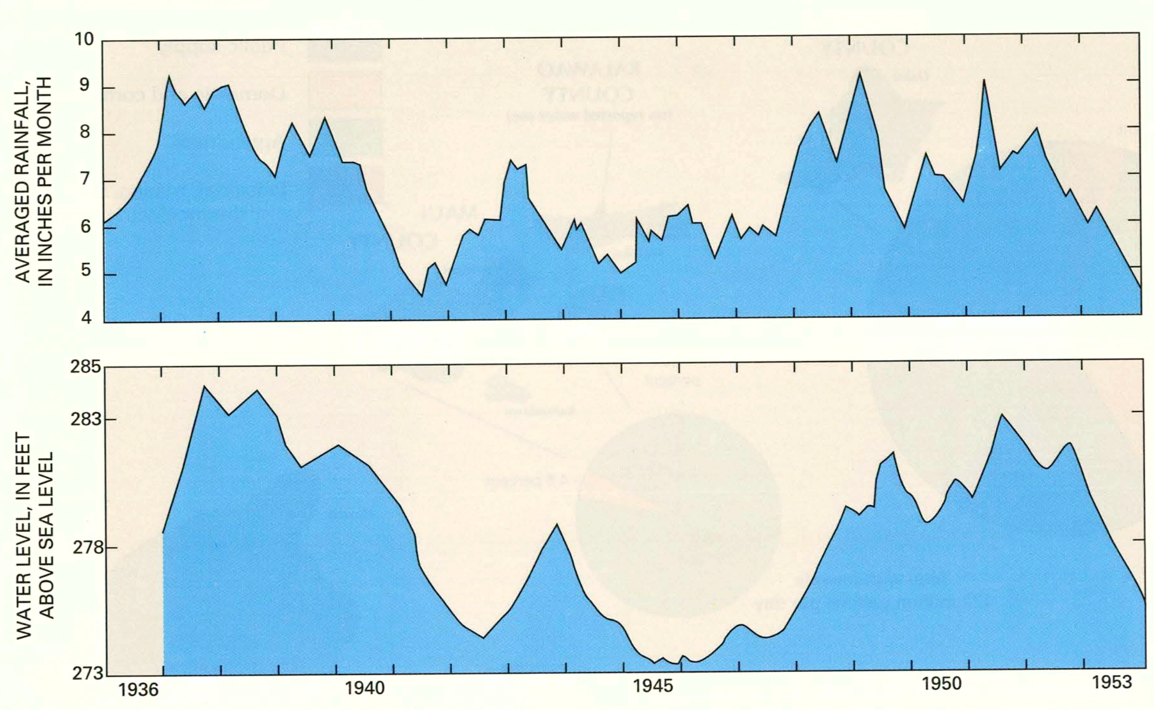


Figure 43. *Water levels in a well in central Oahu fluctuate in response to changes in rainfall. The wetter years, such as 1937–39, 1948, and 1951 are reflected by a corresponding rise in the water level. By contrast, during drier years, such as 1941 and 1944–46, the ground-water level declined.*

WATER-LEVEL FLUCTUATIONS

Water levels in wells fluctuate in response to both short- and long-term natural factors and human-induced stresses. Short-term (diurnal time scale or shorter) water-level fluctuations are caused by ocean tides, barometric pressure changes, evapotranspiration by phreatophytes, or earthquakes, and also by human-induced stress. Long-term fluctuations can be caused by pumping and changes in recharge.

Changes in ground-water storage caused by withdrawals of water from distant or nearby wells are reflected by water-level changes in wells. Data from an observation well in northern Oahu (**fig. 41**) show declines and recoveries of the water table caused by intermittent pumping from nearby wells. The magnitude of the water-level decline caused by pumping is dependent on the distance between the pumped well and the observation well, the rate at which water is withdrawn, and the hydraulic characteristics of the rocks. In addition, ocean tides can cause water-level variations that are superimposed on the water-level declines caused by pumping (**fig. 41**); ocean tides account for about 0.1 foot of water-level fluctuation at this well. The magnitude of the water-level fluctuation caused by ocean tides is dependent on the distance of the observation well from the coast and the hydraulic characteristics of the rocks. In addition to diurnal and semidiurnal ocean tides, longer term variations in ocean level also affect ground-water levels.

Ground-water levels are generally highest in the winter months because of greater rainfall and reduced demand for ground water, and decline during the summer months when demand for ground water is greatest. In the Pearl Harbor area, where ground-water demand for agriculture historically has been high, seasonal fluctuations in water level range from a few feet to as much as 10 feet (**fig. 42**). In the Honolulu area, seasonal fluctuations in water level are less pronounced. Long-term records indicate that water levels in parts of southern Oahu reflect an overall downward trend since the early 1900's because of increased ground-water withdrawals. In the extensively developed Honolulu area, water levels have declined from about 43 feet above sea level in 1880 to about 20 to 25 feet above sea level during the early 1990's. In the Pearl Harbor area, water levels have declined from about 20 to 25 feet above sea level in 1910 to about 15 to 20 feet above sea level during the early 1990's.

In the Schofield area of central Oahu, where ground-water withdrawals have generally been small relative to recharge, ground-water levels fluctuate mainly in response to changes in rainfall (**fig. 43**). The water-level response generally lags the averaged rainfall by several months to a year.

Spring discharge is related to aquifer water levels. The discharge of springs that issue from the volcanic-rock aquifer in the Pearl Harbor area of Oahu (**fig. 44**) varies directly with changes in the water level (hydraulic head) in the aquifer. When the water level in the aquifer is highest, spring discharge is greatest, and, conversely, when the water level is lowered, spring discharge decreases.

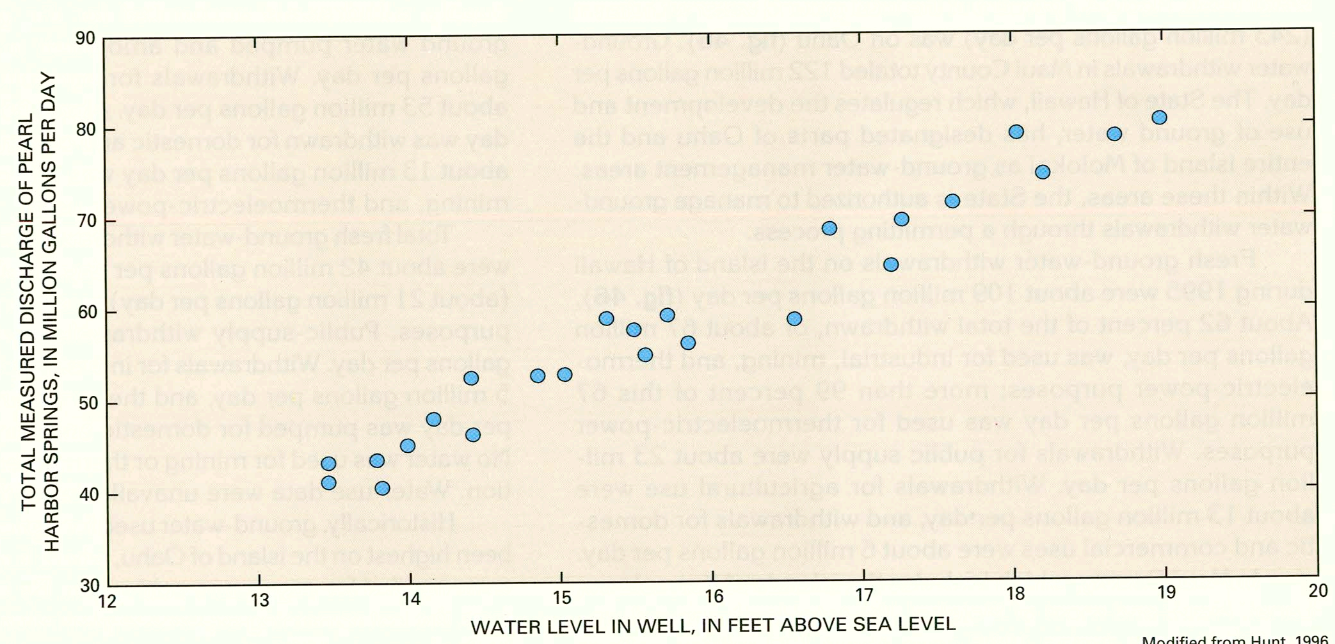


Figure 44. *Discharge of springs that issue from the volcanic-rock aquifer in the Pearl Harbor area of Oahu varies directly with changes in water levels in the aquifer.*

GROUND-WATER QUALITY

The source of fresh ground water in Hawaii is precipitation that originates as water evaporated from the surrounding ocean. The water vapor condenses on salt nuclei in the atmosphere, which are also commonly of oceanic origin. Accordingly, the rain that falls on the islands contains diluted concentrations of the same ions as those in seawater; the rainfall is particularly enriched with sodium and chloride, the major components of seawater. Even on days when no rainfall occurs, small concentrations of ocean salts accumulate on the land surface because the salts are transported as aerosols carried ashore by prevailing winds. These conditions account for the fact that most ground water in the Hawaiian islands, even in high-altitude recharge areas, contains sodium and chloride as the dominant ions.

The rainfall is altered naturally when it partly dissolves volcanic rocks and sedimentary deposits as the water moves in the subsurface from interior areas to discharge areas near the ocean. The water acquires calcium, magnesium, sodium, silica, and iron from volcanic rocks and alluvium. The water acquires bicarbonate and calcium as it infiltrates the consolidated sedimentary deposits especially where these deposits are calcareous.

In general, salinity of ground water in the Hawaiian islands decreases with distance inland from the coast and increases with depth in the aquifer. Elevated concentrations of sodium and chloride in ground water in nearshore rocks generally are the result of mixing of fresh ground water with saltwater derived from the ocean. These mixing effects are most pronounced in aquifers with highly permeable rocks exposed at the ocean floor because saltwater can readily flow into such aquifers. In addition, elevated concentrations of sodium and chloride in ground water may reflect a low recharge rate. In some of the western parts of the island of Hawaii, for example, a freshwater lens does not exist: only brackish water overlies saltwater in the highly permeable volcanic-rock aquifer because of both low recharge and lack of a coastal caprock. Water in coralline limestone along the southern coast of Oahu is also generally brackish because recharge is low and because highly permeable limestone crops out at the ocean floor, allowing easy inflow of saltwater.

When water is withdrawn from a freshwater lens, the freshwater lens shrinks and saltwater will encroach or intrude into parts of the aquifer that formerly contained freshwater. The degree of saltwater intrusion depends on several factors, which include the hydraulic properties of the rocks, recharge rate, and pumping rate. The effect of intrusion on a particular well depends on the vertical and lateral distance between the well and the transition zone.

In the Honolulu area of Oahu, some free-flowing artesian wells that originally produced fresh ground water were later abandoned because of increased salinity associated with saltwater intrusion. Pumping from a well can cause the freshwater-saltwater transition zone to rise into the pumped well. Many wells in Hawaii that are pumped at high rates or drilled too deeply are affected by this process, resulting in increased concentrations of sodium and chloride in pumped water.

Ground water is chemically altered as a result of human activities in developed areas. Shallow, unconfined aquifers are most susceptible to contamination through the land surface, especially where infiltration of water from the surface rapidly recharges the aquifers. Even deeply buried aquifers are not immune to contamination. In general, areas that receive large amounts of rainfall or irrigation water and that have highly permeable soils are susceptible to ground-water contamination.

Sources of ground-water contamination that result from human activities are classified as point or nonpoint. Point sources are specific local sites from which pollutants are discharged. Common types of point sources are cesspools, disposal wells, landfills, industrial sites, and underground storage tanks. Nonpoint sources extend over broad areas and include agricultural fields treated with pesticides or fertilizers and residential areas where chemicals are used near homes and on lawns. Human activities associated with agricultural, industrial, and residential areas can have profound effects on the quality of water in affected aquifers.

Since the early 1980's, organic-chemical contaminants associated with agricultural, industrial, and urban activities have been detected in water samples from wells in the State (**fig. 45**; **table 2**). The chemicals 1,2-dibromo-3-chloropropane (DBCP), 1,2-dibromoethane or ethylene dibromide (EDB), and 1,2,3-trichloropropane (TCP), which are associated with nematicides previously used in pineapple cultivation in Hawaii, have been detected in ground-water samples from wells on the islands of Oahu and Maui. Locations of contaminated well sites are in or downgradient from areas of past and present pineapple cultivation. EDB contamination on Oahu also may be associated with fuel pipeline leaks. Concentrations of DBCP in water samples are generally less than 200 nanograms per liter, EDB less than 50 nanograms per liter, and TCP less than 3,000 nanograms per liter. Concentrations of contaminants vary with time in response to changes in pumping rates, recharge rates, and the timing of the chemical applications. Granular activated carbon filters are being used on Oahu and an aeration system is being used on Maui to treat contaminated water before distribution.

On the islands of Hawaii, Maui, Oahu, and Kauai, the herbicides atrazine and ametryn, which are associated with sugarcane cultivation, have been detected in wells within or downgradient from areas of past and present sugarcane cultivation. Concentrations of atrazine and ametryn in water samples are generally less than 1,000 nanograms per liter. Other chemicals associated with agricultural activities that have been detected to a lesser spatial extent include the herbicides alachlor, simazine, diuron, and hexazinone.

Chemicals associated with non-agricultural activities have also been detected in water samples, primarily on the island of Oahu. In the urbanized Honolulu area, for example, pesticides such as chlordane and dieldrin have been detected in ground-water samples. Prior to being banned in 1988, chlordane was the most popular pesticide used in Hawaii for termite treatments around homes. Concentrations of chlordane and dieldrin are generally less than 300 and 100 nanograms per liter, respectively. Solvents such as trichloroethylene (TCE), tetrachloroethylene (PCE), and carbon tetrachloride have been detected in water samples mainly in Honolulu and central Oahu. In central Oahu, an aeration system is used to treat ground water contaminated with TCE and PCE.

The extent of ground-water contamination by organic chemicals in Hawaii may not be fully known at this time. As more wells are sampled, more chemical analyses are performed, and better analytical equipment and methods become available, the spatial extent of the contamination can be better identified.

GEOTHERMAL WATER

Geothermal water can be an important water resource in the Hawaiian islands. At present (1998), however, the only geothermal water actively being developed is in the eastern part of the island of Hawaii, where steam from geothermal wells is used to generate about 25 megawatts of electrical power. The wells are drilled in the east rift zone of Kilauea Volcano near eruptive vents that were active in 1955. Wells have encountered elevated water temperatures near Lihue on Kauai, near the caldera of Waianae Volcano and near Kailua on Oahu, near the summit of West Molokai Volcano on Molokai, near the summit of Lanai Volcano, near Lahaina on Maui, and near Kawaihae on the island of Hawaii.

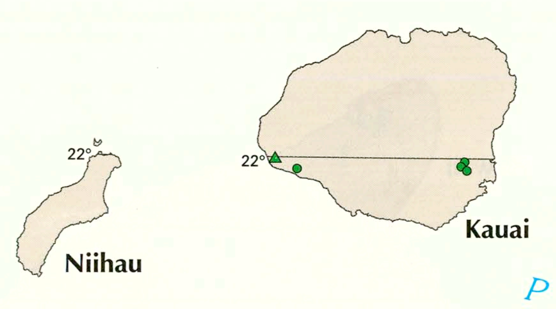


Table 2. *Organic chemical contaminants confirmed in ground water, Hawaii* [Source: State of Hawaii, 1997]

Island	Contaminant	Number of well fields with confirmed contamination
Kauai	ametryn	1
	atrazine	5
	desethyl atrazine	1
	simazine	1
Oahu	alachlor	1
	ametryn	2
	atrazine	15
	desethyl atrazine	14
	despropyl atrazine	3
	diamino atrazine	3
	carbon tetrachloride	3
	chlordane	4
	dieldrin	10
	lindane	1
	1,2-dibromo-3-chloropropane	13
	1,2-dichloropropane	4
	ethylene dibromide	4
	tetrachloroethylene (PCE)	8
	trichloroethylene (TCE)	7
	1,2,3-trichloropropane	19
Maui	ametryn	3
	atrazine	10
	desethyl atrazine	5
	despropyl atrazine	1
	diamino atrazine	3
	1,2-dibromo-3-chloropropane	7
	ethylene dibromide	4
	simazine	1
	1,2,3-trichloropropane	6
Hawaii	ametryn	1
	atrazine	24
	desethyl atrazine	13
	despropyl atrazine	4
	diamino atrazine	5
	diuron	3
	hexazinone	9
	tetrachloroethylene (PCE)	1
	simazine	1

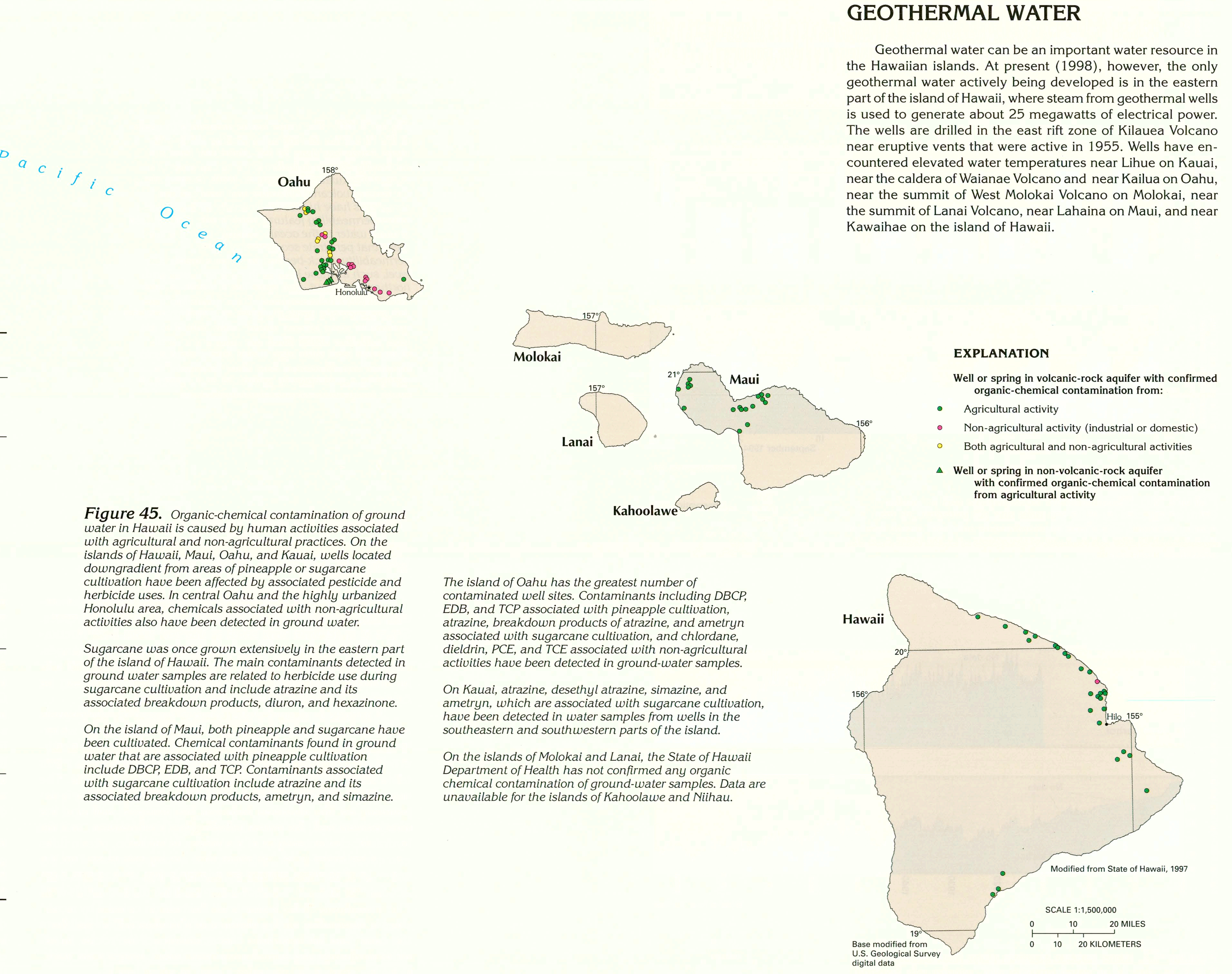


Figure 45. *Organic-chemical contamination of ground water in Hawaii is caused by human activities associated with agricultural and non-agricultural practices. On the islands of Hawaii, Maui, Oahu, and Kauai, wells located downgradient from areas of pineapple or sugarcane cultivation have been affected by associated pesticide and herbicide uses. In central Oahu and the highly urbanized Honolulu area, chemicals associated with non-agricultural activities also have been detected in ground water.*

Sugarcane was once grown extensively in the eastern part of the island of Hawaii. The main contaminants detected in ground water samples are related to herbicide use during sugarcane cultivation and include atrazine and its associated breakdown products, diuron, and hexazinone.

On the island of Maui, both pineapple and sugarcane have been cultivated. Chemical contaminants found in ground water that are associated with pineapple cultivation include DBCP, EDB, and TCP. Contaminants associated with sugarcane cultivation include atrazine and its associated breakdown products, ametryn, and simazine.

The island of Oahu has the greatest number of contaminated well sites. Contaminants including DBCP, EDB, and TCP associated with pineapple cultivation, atrazine, breakdown products of atrazine, and ametryn associated with sugarcane cultivation, and chlordane, dieldrin, PCE, and TCE associated with non-agricultural activities have been detected in ground-water samples.

On Kauai, atrazine, desethyl atrazine, simazine, and ametryn, which are associated with sugarcane cultivation, have been detected in water samples from wells in the southeastern and southwestern parts of the island.

On the islands of Molokai and Lanai, the State of Hawaii Department of Health has not confirmed any organic chemical contamination of ground-water samples. Data are unavailable for the islands of Kahoolawe and Niihau.

FRESH GROUND-WATER WITHDRAWALS

Ground water is an important resource in the State of Hawaii. During 1995, ground water supplied about 51 percent, or about 516 million gallons per day, of the estimated total freshwater used. About 47 percent of the total ground water withdrawn (243 million gallons per day) was on Oahu (**fig. 46**). Groundwater withdrawals in Maui County totaled 122 million gallons per day. The State of Hawaii, which regulates the development and use of ground water, has designated parts of Oahu and the entire island of Molokai as ground-water management areas. Within these areas, the State is authorized to manage groundwater withdrawals through a permitting process.

Fresh ground-water withdrawals on the island of Hawaii during 1995 were about 109 million gallons per day (**fig. 46**). About 62 percent of the total withdrawn, or about 67 million gallons per day, was used for industrial, mining, and thermoelectric-power purposes; more than 99 percent of this 67 million gallons per day was used for thermoelectric-power purposes. Withdrawals for public supply were about 23 million gallons per day. Withdrawals for agricultural use were about 13 million gallons per day, and withdrawals for domestic and commercial uses were about 6 million gallons per day.

In Maui County, which includes the islands of Kahoolawe, Lanai, Maui, and most of Molokai, the total fresh ground-water withdrawals during 1995 were about 122 million gallons per day. About 93 percent of the 122 million gallons per day was withdrawn on the island of Maui. For Maui County during 1995, the largest withdrawals, about 77 percent (94 million gallons per day), were for agricultural irrigation. Withdrawals for domestic and commercial uses amounted to about 5 million gallons per day, and public-supply withdrawals were about 22 million gallons per day. Industrial, mining, and thermoelectric-power withdrawals were about 1 million gallons per day.

The total fresh ground-water withdrawal on Oahu during 1995 was about 243 million gallons per day, which nearly equaled the total withdrawn on all the other islands. Public-supply withdrawals accounted for the greatest amount of ground water pumped and amounted to about 142 million gallons per day. Withdrawals for agricultural purposes were about 53 million gallons per day. About 35 million gallons per day was withdrawn for domestic and commercial supplies, and about 13 million gallons per day was withdrawn for industrial, mining, and thermoelectric-power uses.

Total fresh ground-water withdrawals on Kauai during 1995 were about 42 million gallons per day, about one-half of which (about 21 million gallons per day) was pumped for agricultural purposes. Public-supply withdrawals were about 14 million gallons per day. Withdrawals for industrial purposes were about 5 million gallons per day, and the remaining 2 million gallons per day was pumped for domestic and commercial purposes. No water was used for mining or thermoelectric-power generation. Water-use data were unavailable for the island of Niihau.

Historically, ground-water used for agricultural irrigation has been highest on the island of Oahu, where large amounts of water were needed for sugarcane cultivation. By October 1996, however, the last remaining sugarcane plantation on Oahu harvested its final crop. In 1995, the amount of ground water withdrawn for agricultural use on Oahu was about 53 million gallons per day, and in Maui County, where sugarcane is extensively grown in areas that receive little rainfall, ground-water withdrawn for agricultural irrigation was about 94 million gallons per day.

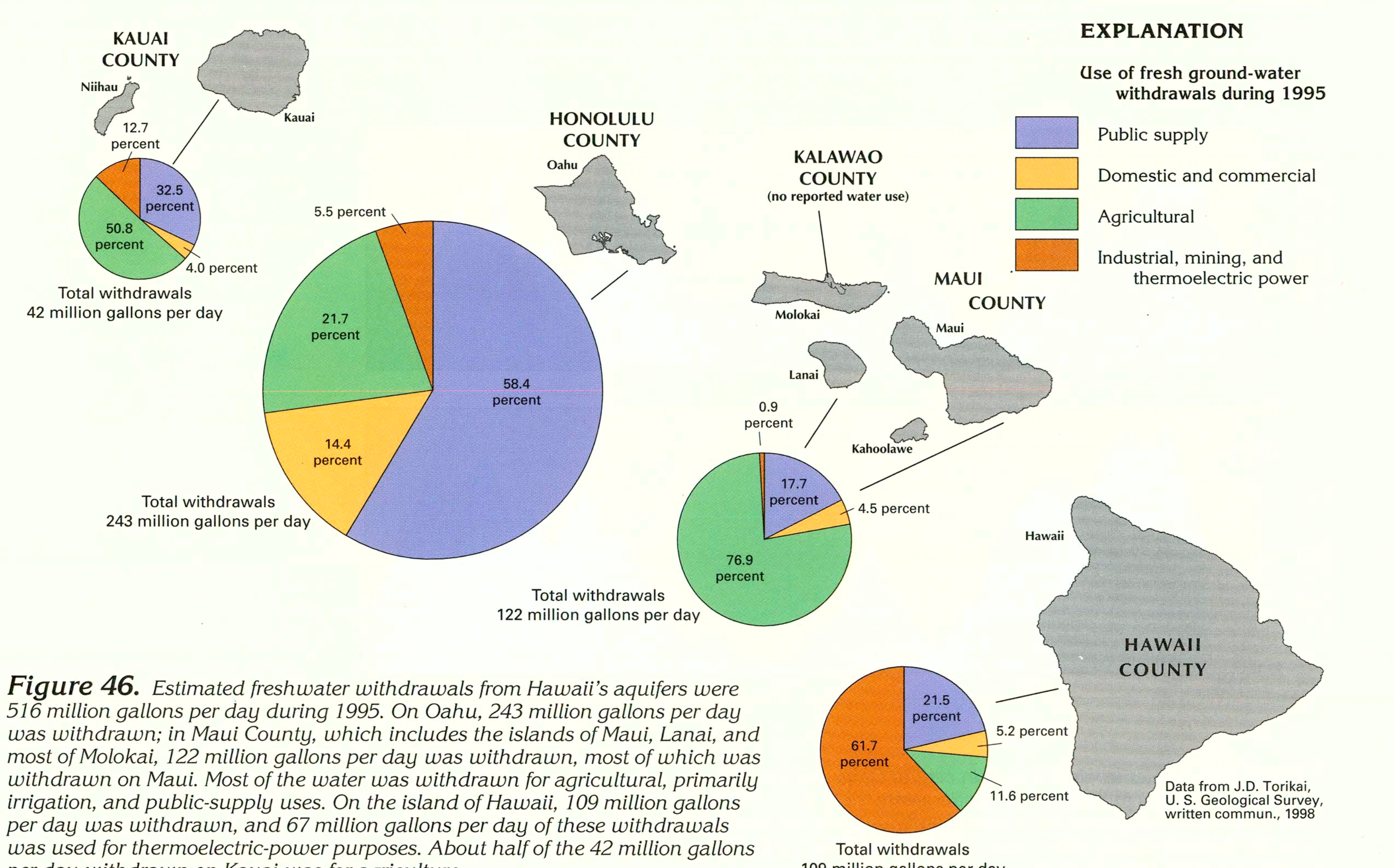


Figure 46. *Estimated freshwater withdrawals from Hawaii's aquifers were 516 million gallons per day during 1995. On Oahu, 243 million gallons per day was withdrawn; in Maui County, which includes the islands of Maui, Lanai, and most of Molokai, 122 million gallons per day was withdrawn, most of which was withdrawn on Maui. Most of the water was withdrawn for agricultural, primarily irrigation, and public-supply uses. On the island of Hawaii, 109 million gallons per day was withdrawn, and 67 million gallons per day of these withdrawals was used for thermoelectric-power purposes. About half of the 42 million gallons per day withdrawn on Kauai was for agriculture.*

Volcanic-rock aquifers

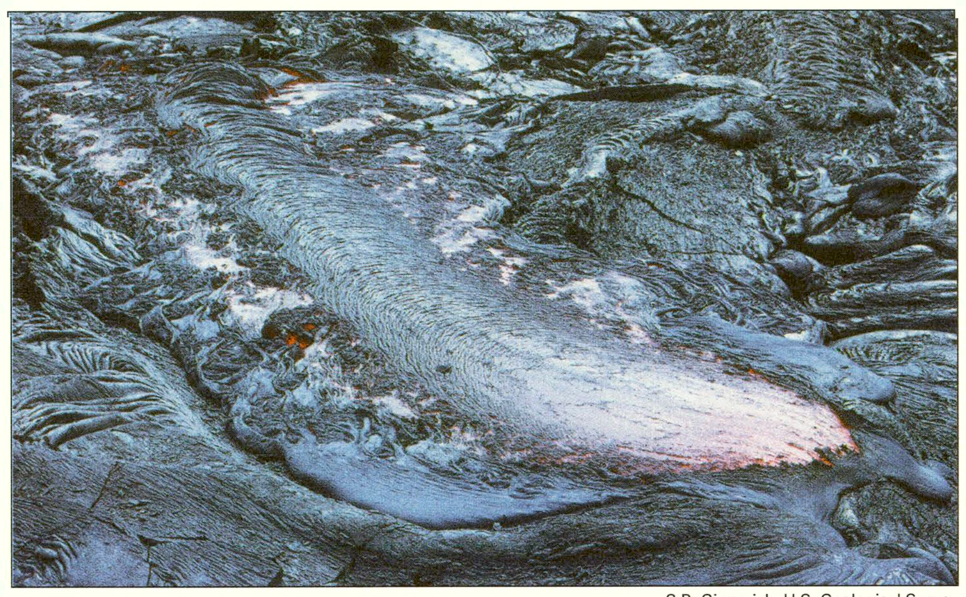


Figure 47. *Pahoehoe lava is thin and fluid with a characteristic ropy appearance. Pahoehoe flows are usually more common near an eruptive vent. The active flow shown is about 30 feet long.*

Figure 48. *As flowing aa lava cools, degases, and becomes more viscous, the hardened crust on the flow surface breaks up into rubble and gives the flow a rough, clinkery appearance. The flow shown is about 8 feet high.*

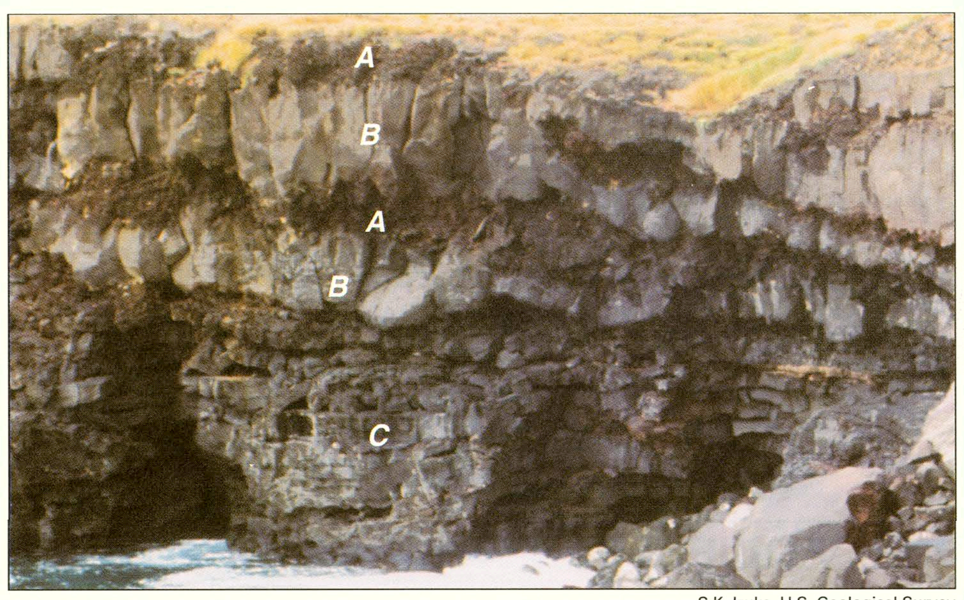
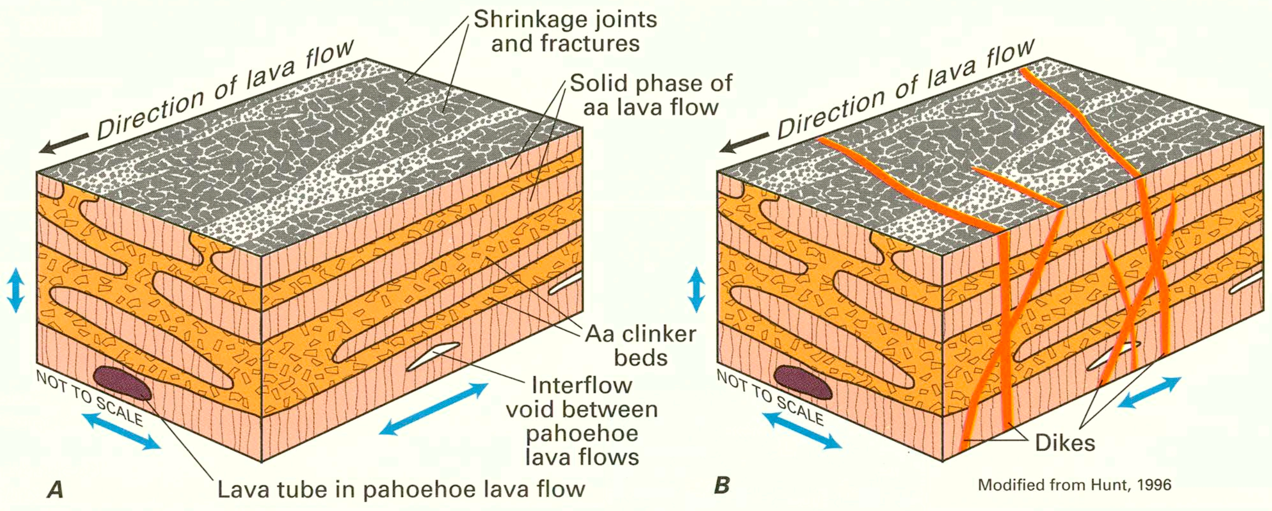


Figure 49. *A typical sequence of lava flows contains aa clinker zones **(A)** of relatively high permeability that occur above and below the massive central cores of aa flows **(B)**, and many thin pahoehoe **(C)** flows. The sequence shown is about 40 feet thick.*



EXPLANATION

Arrow length denotes relative magnitude of permeability in direction of arrows

Figure 50. *Stratified sequences of lava flows form the most productive aquifers in Hawaii. The high permeability is due to the presence of the many types of void spaces caused during flow emplacement. Hydraulic conductivity is greatest parallel to the direction of flow **(A)** and lower across flows. Dikes **(B)** can impede the movement of ground water and channel the flow of water parallel to the dikes.*

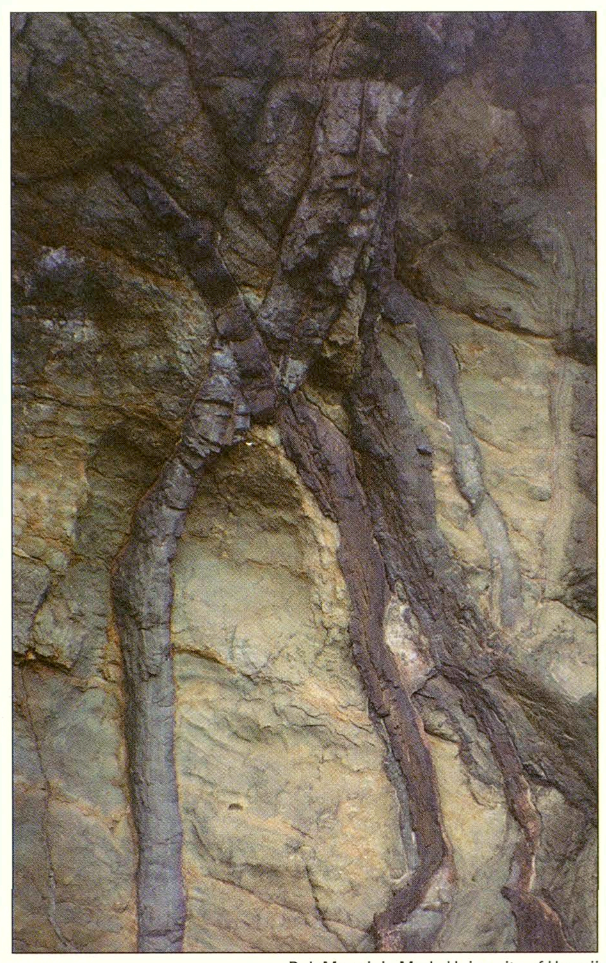
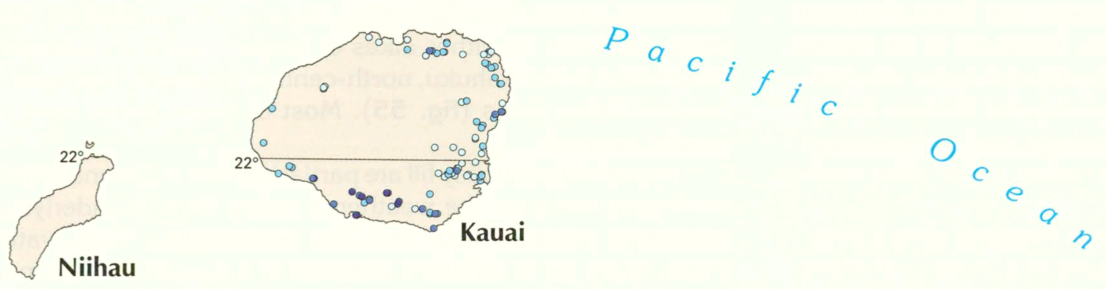
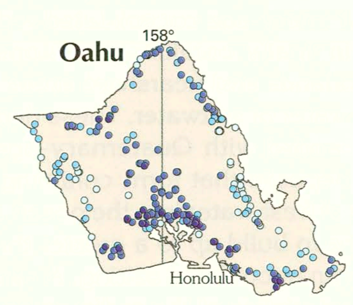
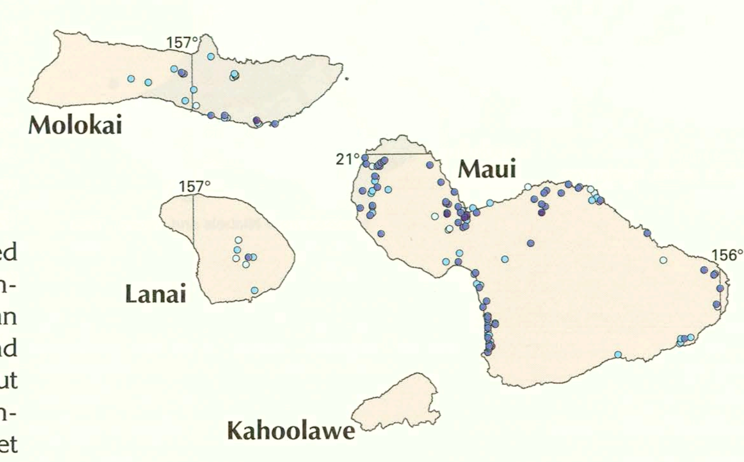


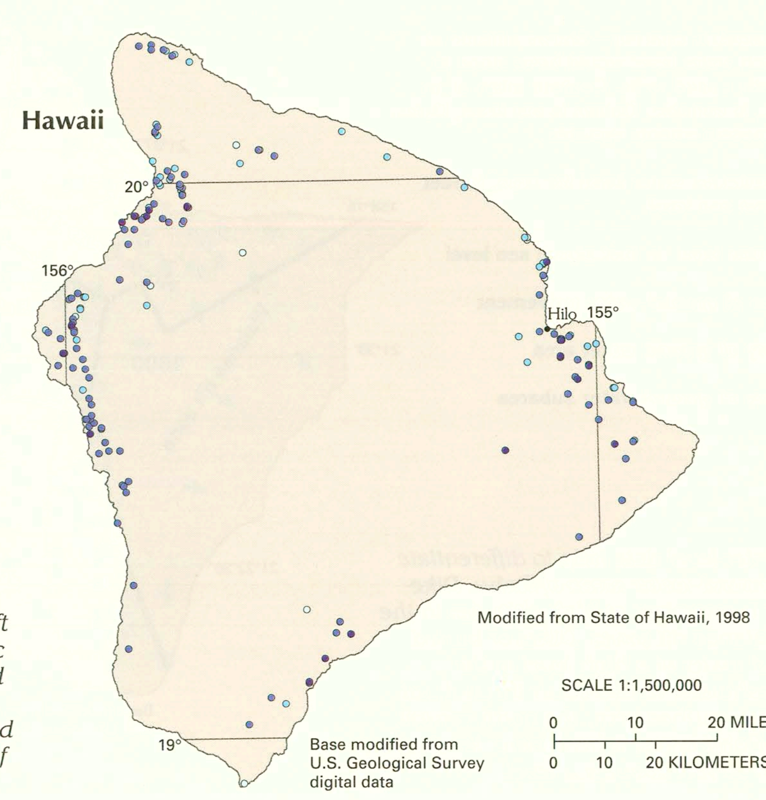
Figure 51. *Near-vertical dikes impede the movement of ground water. Dikes cut through existing volcanic rocks, including other dikes. The dikes shown are about 1 foot thick.*

Figure 52. *The humid, subtropical climate of Hawaii fosters intense weathering of rock into saprolite that retains the textural features of the original rock. Saprolite can be as much as 300 feet thick in areas that receive the highest rainfall. The sequence of saprolite shown is about 15 feet thick.*









EXPLANATION

Measured specific capacity of well, in gallons per minute per foot of drawdown

- Less than or equal to 10
- Greater than 10 and less than or equal to 100
- Greater than 100 and less than or equal to 1,000
- Greater than 1,000

Figure 53. *The specific capacities of wells in the volcanic-rock aquifers of the Hawaiian Islands vary greatly. Wells with the highest specific capacities are located in the most permeable shield-building-stage lava flows. Wells located along the axes of volcanic rift zones and near caldera complexes have lower specific capacities because they penetrate lava flows intruded by low-permeability volcanic dikes. Wells that penetrate sequences of low-permeability, thick-bedded lava flows, such as those located in the eastern half of Kauai, also have low specific capacities.*

INTRODUCTION

Volcanic rocks that range in age from Miocene to Holocene are the primary rocks in the islands and are the most productive aquifers in the State of Hawaii. The rocks vary widely in origin, chemical composition, and texture and in their ability to transmit water. Volcanic-rock aquifers are found on all the islands and in some places are overlain with sedimentary deposits.

GROUND-WATER OCCURRENCE AND MOVEMENT

The permeability of volcanic rocks is variable and depends mainly on the mode of emplacement of the rocks. Three main groups of volcanic rocks exist: lava flows, dikes, and pyroclastic deposits. Weathering reduces the permeability of all three types of volcanic rocks. Lava flows are mainly pahoehoe (**fig. 47**), which has a smooth, undulating surface with a ropy appearance and aa (**fig. 48**), which has a surface of coarse rubble (clinker) and an interior of massive rock. A typical sequence of lava flows (**fig. 49**) contains both aa and pahoehoe flows. Aa clinker zones are found above and below the massive central core of the aa flow. Pahoehoe flows commonly occur in a sequence of numerous thin flows. Void spaces in a layered sequence of lava flows (**fig. 50**) include vesicular (gas bubbles), fracture (joints and cracks), interflow (separations between flows), intergranular (fragmental rock), and conduit (lava tubes) porosity. Pahoehoe flows are fluid, flow rapidly, and tend to spread out. The void spaces in a sequence of pahoehoe flows imparts high intrinsic permeability. Pahoehoe lava commonly grades into aa lava with increasing distance from the eruptive vent. The layers of clinker at the top and bottom of aa flows commonly form productive aquifers with permeability similar to that of coarse-grained gravel. However, the lava in the core of an aa flow typically cools as a massive body of rock with much lower permeability. The most productive and most widespread aquifers consist of thick sequences of numerous thin lava flows.

The hydraulic conductivity of an aquifer is a measure of how easily water will move through the aquifer; the higher the hydraulic conductivity, the more permeable the aquifer. In volcanic-rock aquifers composed mainly of flat-lying lava flows, the hydraulic conductivity is greatest parallel to the direction of the flows (**fig. 50*A***), and is least perpendicular to the layered sequence of flows. On Oahu, the vertical hydraulic conductivity has been estimated to be hundreds of times less than the horizontal hydraulic conductivity. Lava tubes are extremely permeable features that can vary from less than 1 foot to more than 50 feet in diameter and can be several miles long. They form as molten lava drains out from under a solidified crust. The hydraulic conductivity of clinker zones ranges from several hundred to several thousand feet per day, which is similar to that of coarse, well-sorted gravel.

Dikes are thin, near-vertical sheets of massive, low-permeability rock that intrude existing rocks, commonly the permeable lava flows of the Hawaiian islands. Dikes (**fig. 51**) can extend vertically and laterally for long distances and impede the flow of ground water. Within a dike complex, dikes intersect at various angles and compartmentalize the more permeable rock in which ground water can be impounded (**fig. 50B**). The dikes lower overall rock porosity and permeability; the hydraulic conductivity of a dike complex can be as low as 0.01 feet per day. Dikes tend to channel ground-water flow parallel to the general trend of the dikes. In some areas, the level of dike-impounded water is much higher than that of the regional, freshwater lens.

Pyroclastic rocks include ash, cinder, spatter, and larger blocks. These deposits have hydraulic conductivity between 1 and 1,000 feet per day. Compaction and weathering can reduce the permeability; weathered ash beds commonly act as thin confining units within lava sequences.

Saprolite is a soft, clay-rich, thoroughly weathered rock that has retained textural features of the parent rock (**fig. 52**). Exposed weathered profiles include inches to several tens of feet of saprolite. In areas of high precipitation, saprolite may be from 100 feet to as much as 300 feet thick. Rocks with a high proportion of pore space and surface area, such as ash, cinder, and aa clinker, weather preferentially; weathering of massive rock proceeds more slowly. The hydraulic conductivity of saprolite is generally less than 1 foot per day and can be as low as 0.001 foot per day.

AQUIFER EXTENT AND CHARACTERISTICS

Volcanic-rock aquifers are found on all the major islands of Hawaii. In some areas, sedimentary or pyroclastic deposits mapped at the ground surface overlie the volcanic-rock aquifers. The areal distribution of aquifer permeability can be depicted on a map showing the values of specific capacity determined from short-term (less than 7 days) aquifer tests using wells that penetrate the volcanic-rock aquifers (**fig. 53**). The specific capacity of a well is the rate of discharge of water from the well divided by the depth that the water level in the well is lowered as the water is withdrawn. A well with a higher specific capacity can produce more water per foot of water-level decline, generally indicating that the permeability of the aquifer that the well penetrates is higher. In the Hawaiian islands, wells with the highest specific capacities are commonly located in volcanic-rock aquifers composed of high-permeability, dike-free, shield-building-stage lava flows. Many of these wells are along the southern coast of Kauai, in the Pearl Harbor area and northern coast of Oahu, and in most of the coastal areas of Maui and the island of Hawaii. Areas where the lava flows are intruded with dikes are less permeable and usually contain wells with lower specific capacities. The locations of these wells coincide with the rift zones and caldera complexes of many of the volcanoes. In much of the eastern half of Kauai, wells with low specific capacities are located in the low-permeability, thick-bedded lava flows of the Koloa Volcanics. No specific capacity values are available from wells on Niihau or Kahoolawe.

Oahu regional aquifer system

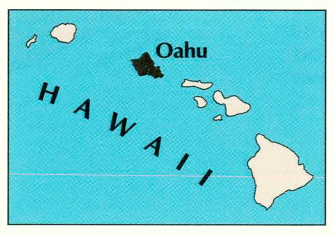


Table 3. *Hydrologic characteristics of the rocks and deposits of Oahu and mode of occurrence of ground water*

[—, not known. Source: Hunt, 1996]

Geologic material	Horizontal permeability	Horizontal hydraulic conductivity (feet per day)	Ground-water occurrence: Principal	Ground-water occurrence: Secondary
VOLCANIC ROCKS				
Waianae Volcanics:				
Lava flows:				
Dike complex	Low to moderate	1 – 500	Dike impounded	Perched
Marginal dike zone	Moderate to high	100 – 1,000	Dike impounded	Freshwater lens
Dike free	Moderate to very high	500 – 5,000	Freshwater lens	—
Breccia	Low	1 – 100	Perched	—
Saprolite	Very low	Less than 1	Perched	—
Koolau Basalt:				
Lava flows				
Dike complex	Low to moderate	1 – 500	Dike impounded	Perched
Marginal dike zone	Moderate to high	100 – 1,000	Dike impounded	Freshwater lens
Dike free	Moderate to very high	500 – 5,000	Freshwater lens	—
Breccia	Low	1 – 100	Perched	—
Saprolite	Very low	Less than 1	Perched	—
Honolulu Volcanics:				
Lava flows	Low to moderate	1 – 500	Perched	—
Cinders	Low to moderate	1 – 500	Perched	—
Tuff	Low	1 – 100	Perched	—
Saprolite	Very low	Less than 1	Perched	—
SEDIMENTARY DEPOSITS				
Coral:				
In situ reef limestone	Moderate to very high	100 – 20,000	Freshwater lens	Perched
Reworked coral rubble	Moderate to very high	100 – 10,000	Freshwater lens	Perched
Dunes:				
Consolidated	Low	1 – 100	Perched	Freshwater lens
Unconsolidated	Low to moderate	1 – 500	Freshwater lens	Perched
Sand:				
Consolidated	Low to moderate	1 – 500	Freshwater lens	—
Unconsolidated	Moderate to high	100 – 1,000	Freshwater lens	—
Lagoonal deposits:				
Sand	Low to moderate	1 – 500	Freshwater lens	—
Mud	Very low	Less than 1	Freshwater lens	Perched
Alluvium:				
Younger	Low to moderate	1 – 500	Perched	Perched
Older:				
Consolidated	Very low	Less than 1	Perched	—
Unconsolidated	Low	1 – 100	Perched	Freshwater lens

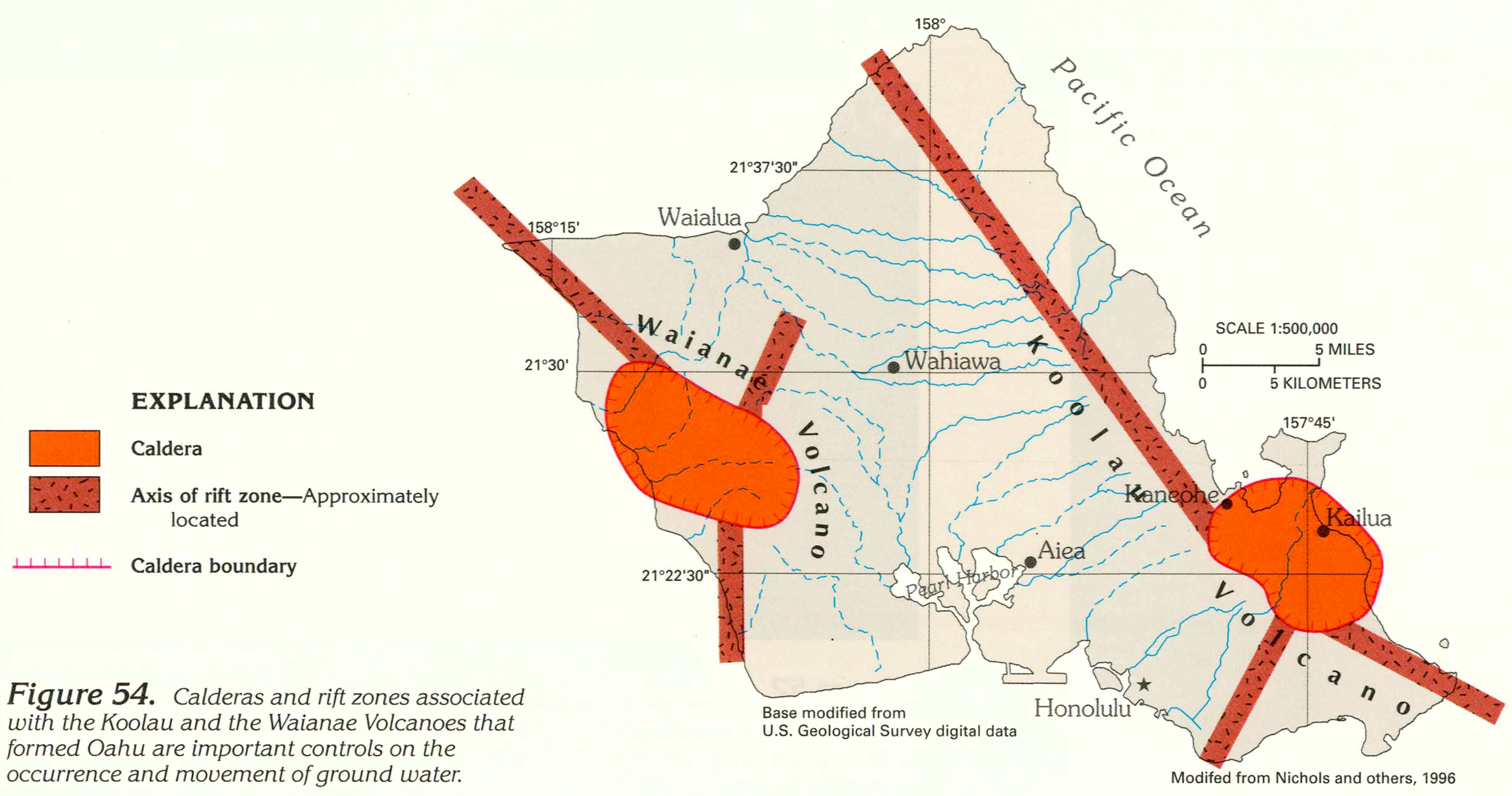


Figure 54. *Calderas and rift zones associated with the Koolau and the Waianae Volcanoes that formed Oahu are important controls on the occurrence and movement of ground water.*

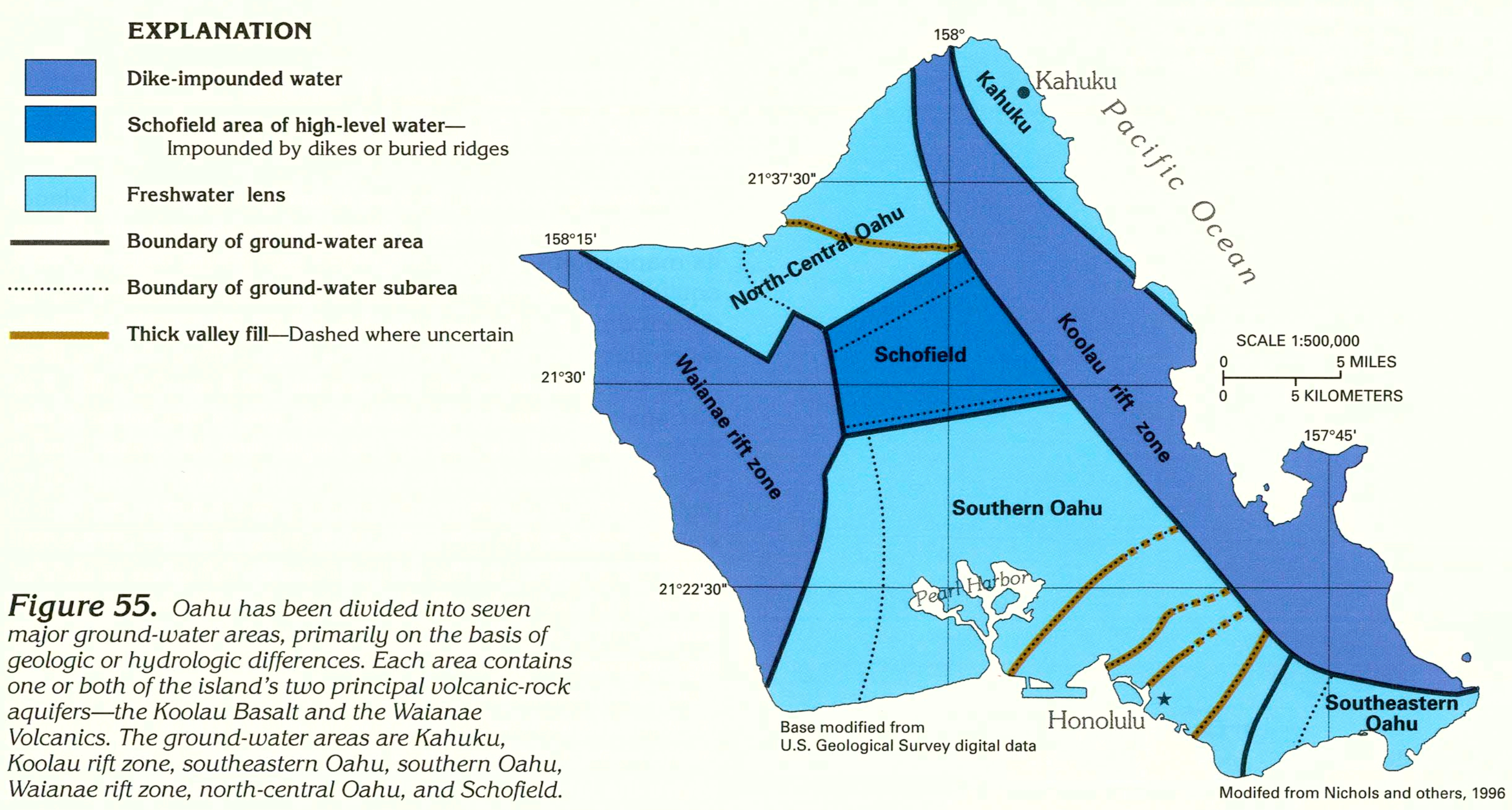


Figure 55. *Oahu has been divided into seven major ground-water areas, primarily on the basis of geologic or hydrologic differences. Each area contains one or both of the island's two principal volcanic-rock aquifers—the Koolau Basalt and the Waianae Volcanics. The ground-water areas are Kahuku, Koolau rift zone, southeastern Oahu, southern Oahu, Waianae rift zone, north-central Oahu, and Schofield.*

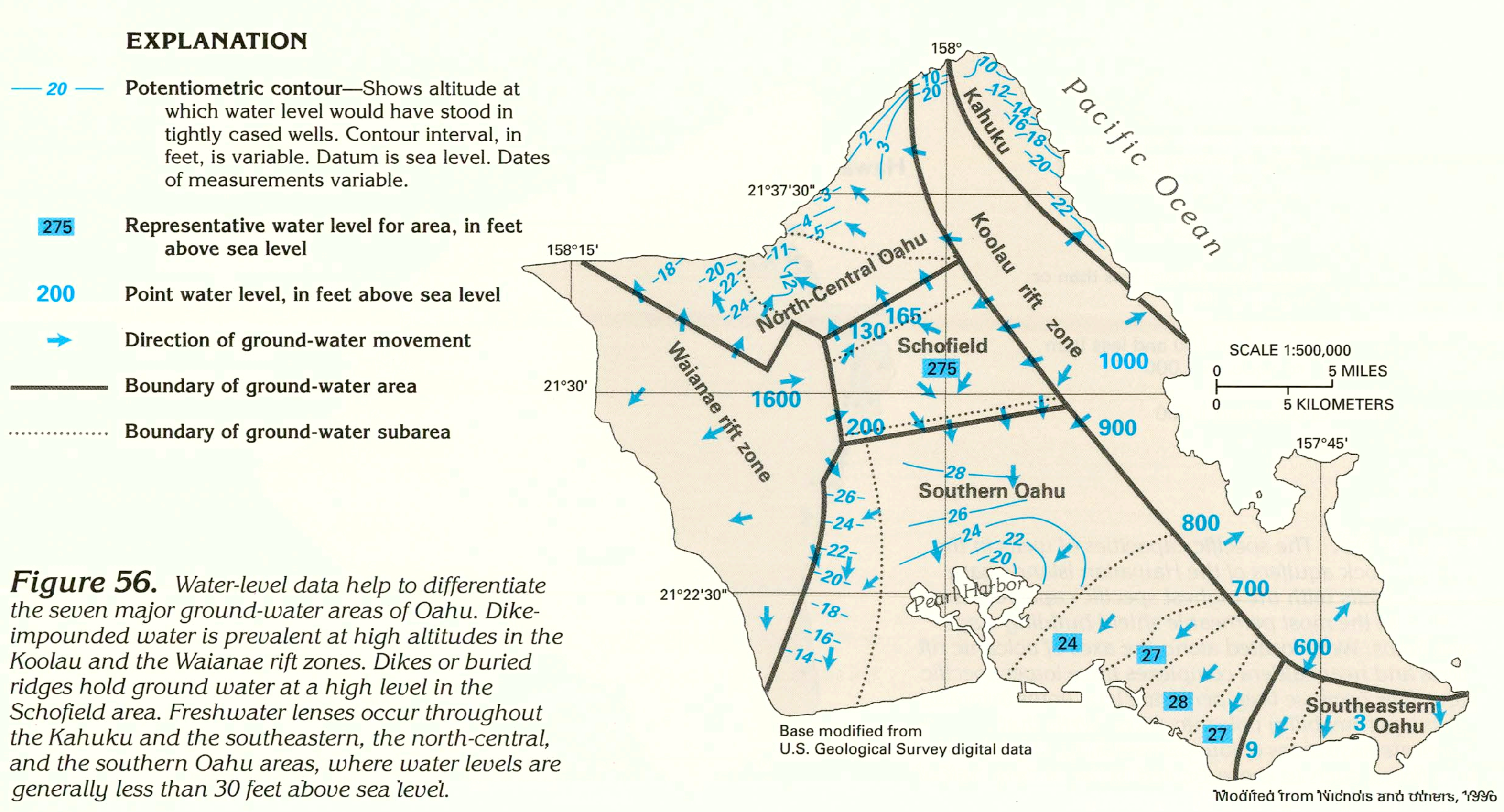


Figure 56. *Water-level data help to differentiate the seven major ground-water areas of Oahu. Dike-impounded water is prevalent at high altitudes in the Koolau and the Waianae rift zones. Dikes or buried ridges hold ground water at a high level in the Schofield area. Freshwater lenses occur throughout the Kahuku and the southeastern, the north-central, and the southern Oahu areas, where water levels are generally less than 30 feet above sea level.*

OAHU REGIONAL AQUIFER SYSTEM

Oahu is the most developed island in the State of Hawaii and contains the largest population. Because of its varied geohydrologic framework and intense ground-water development, Oahu was chosen for a Regional Aquifer-System Analysis (RASA) study. Analysis of the hydrologic and geohydrologic characteristics of Oahu has transfer value to the other main islands of Hawaii.

Volcanic rocks ranging in age from Pliocene to Holocene, make up most of Oahu and compose the most important aquifers. Quaternary-age consolidated sedimentary deposits, which are principally coralline limestone, form productive aquifers in lowlands and nearshore areas but generally contain brackish water or saltwater. These deposits are underlain by and interbedded with Quaternary-age low-permeability sedimentary deposits that form confining units that impede the discharge of freshwater into the ocean and, thus, allow the freshwater lens to build up to a greater thickness than would be possible in an unconfined setting. A synopsis of the water-yielding characteristics of the sedimentary deposits and volcanic rocks of Oahu is shown in **table 3**.

Sedimentary deposits (**table 3**) include coralline limestone, dunes, sand, lagoonal deposits, and alluvium. Permeability of the deposits ranges from very low to very high. Where the coralline limestone has been partially dissolved, it contains large secondary openings and can have a hydraulic conductivity of 20,000 feet per day, which is the highest known for any aquifer in the Hawaiian islands. The limestone mostly contains saltwater or brackish water except where locally recharged by irrigation water or by upward-flowing freshwater from the underlying volcanic-rock aquifer. Consolidated dunes and sand have low permeability, and unconsolidated dunes and sand have low to moderate permeability. The dunes and sand mostly contain brackish water or saltwater. The lagoonal deposits range from mud with very low permeability to sand with low to moderate permeability. The lagoonal deposits are near the shore and mostly contain brackish water or saltwater. The unconsolidated younger alluvium generally is in stream valleys and is unsaturated. The older alluvium generally is highly weathered and has low permeability.

Oahu is formed by two volcanoes—Waianae on the west and Koolau on the east (**fig. 54**). Major rift zones in these volcanoes intersect near the center of each volcano. The caldera complex near the center of each volcano occupies a large area and is underlain by rocks that commonly have low permeability.

The Waianae Volcanics forms the most important aquifer in western Oahu and the Koolau Basalt is overall the most important aquifer on Oahu. Permeability ranges from low in the dike complexes to very high in dike-free lava flows (**table 3**). The level of ground water in the dike complexes generally is much higher than the level of the regional water table in the freshwater lenses. The Honolulu Volcanics in eastern Oahu generally has low to moderate permeability and does not form significant aquifers. Saprolite that develops from weathering of Waianae Volcanics, Koolau Basalt, and Honolulu Volcanics has very low permeability.

The principal occurrences of ground water on Oahu are shown in **figure 55**. Areas of dike-impounded water coincide with the main rift zones in the Koolau Basalt and the Waianae Volcanics. In the Schofield area, water is impounded to high levels probably by either dikes or buried ridges. Freshwater lenses exist in the Kahuku, north-central, southern, and southeastern Oahu areas (**fig. 55**). Most of these areas have a coastal caprock.

Areas of thick valley fill are partial barriers to ground-water movement because the weathered valley fill and underlying weathered volcanic rocks have low permeability. Thus, water levels might be at different altitudes in adjacent areas separated by thick valley fill. In the western parts of the north-central and the southern Oahu ground-water areas, Koolau Basalt may overlie older rocks of the Waianae Volcanics. The surface of the Waianae Volcanics consists of soil, saprolite, and pyroclastic material of low permeability that separates the two volcanic-rock aquifers and causes a discontinuity in ground-water levels between the aquifers.

Water-level data (**fig. 56**) emphasize the differences among the ground-water areas of Oahu. Ground water generally moves from inland areas toward the ocean. Water levels in rift zones are as much as 1,600 feet above sea level in the Waianae rift zone and 1,000 feet above sea level in the Koolau rift zone. Ground water in the rift zones is impounded in compartments between dikes where the volcanic rocks are saturated with thick columns of freshwater. The exact thickness of the freshwater in the rift zones is not known, but the freshwater is thought to extend far below sea level. Water levels in the Schofield ground-water area are about 275 feet above sea level. The Schofield area receives recharge from the adjacent Koolau and Waianae rift zones; the water then flows to the north or south across boundary zones with slightly lower water levels and recharges downgradient areas that have freshwater lenses.

Water levels in the freshwater lens of the southeastern Oahu area (**fig. 56**) generally are less than 10 feet above sea level near the western boundary and the levels decrease eastward.

Water levels in the southern Oahu ground-water area (**fig. 56**) generally range from about 25 to 30 feet above sea level inland to about 15 to 20 feet above sea level near the shore where the water is under artesian pressure because it is confined by caprock. The caprock impedes the seaward movement of fresh ground water. In the eastern part of the area, thick valley fill and underlying weathered rocks form partial barriers to ground-water flow. In the western part of the area, the weathered zone near the unconformity separating Koolau Basalt from underlying Waianae Volcanics impedes the flow of water between the two volcanic-rock aquifers.

In the north-central Oahu ground-water area (**fig. 56**), water levels in the freshwater lens range from more than 20 feet above sea level in the southwestern part where the caprock is thick, to less than 3 feet above sea level nearshore in the northern part where the caprock is thin. The weathered zone separating Koolau Basalt from underlying Waianae Volcanics and a thick sequence of valley fill form partial barriers to ground-water flow in the western and eastern parts of the area, respectively.

In the Kahuku ground-water area (**fig. 56**), water levels in the freshwater lens range from about 20 feet above sea level inland to less than 10 feet above sea level near the shore. The nearshore artesian pressure is the result of confinement by caprock.

Fresh ground water in the volcanic-rock aquifer moves seaward and discharges upward through the caprock (**fig. 57**). Such discharge can form springs near the inland margin of the caprock, as in the Pearl Harbor area. Springs also can form where valleys are eroded into dike-impounded water bodies or where perched water bodies emerge at cliff faces (**fig. 57**).

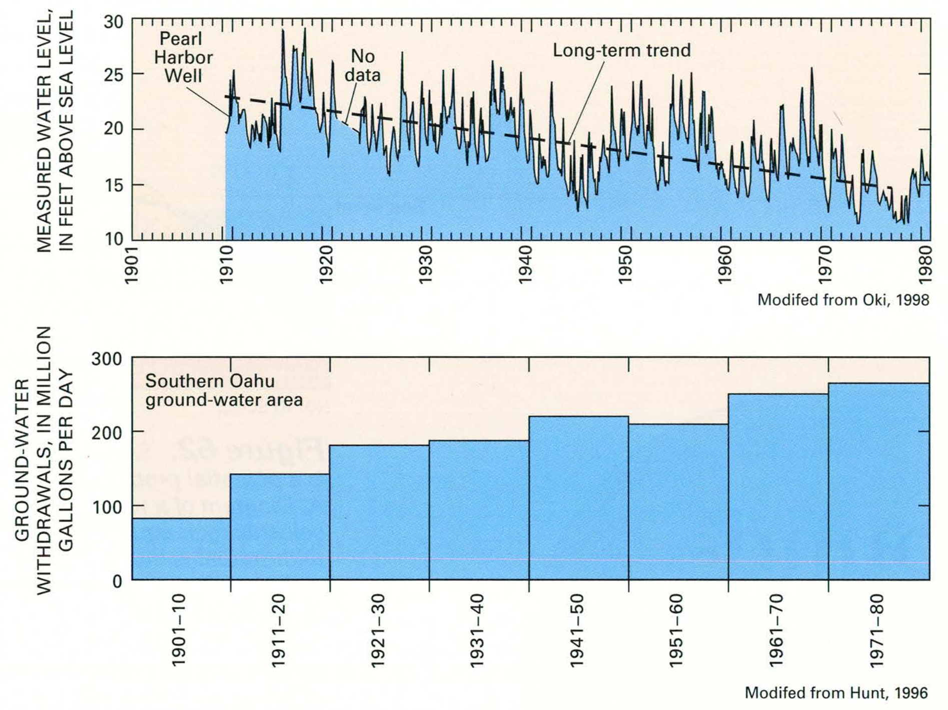
Barriers separate some of the ground-water areas or subareas, and accordingly, water levels are significantly different across such barriers. In southeastern Oahu (**fig. 58**), dikes in the Kaau rift zone separate the southern Oahu ground-water area from the southeastern Oahu ground-water area. Water levels in the southern Oahu area are about 10 to 20 feet higher than those in the southeastern Oahu area because of the barrier effect of the dikes. Likewise, northeast-trending dikes within the southeastern Oahu area create a barrier that causes water levels to be about 7 to 8 feet higher in the western part of the area than in the eastern part (**fig. 58**). In the eastern parts of the southern and north-central Oahu ground-water areas, low-permeability valley-fill deposits and underlying weathered volcanic rocks impede ground-water movement and also create differences in water levels in adjacent subareas.

Water levels in the Pearl Harbor area and other places are directly affected by large ground-water withdrawals (**fig. 59**). As ground-water withdrawals increased in the Pearl Harbor area from 1901 through 1980, water levels in observation wells decreased. During years when withdrawals decreased, water levels rose. The long-term trend, however, has been one of water-level decline.

Recharge to Oahu's aquifers is not evenly distributed. Annually, some areas receive a significant amount of recharge (greater than 150 inches), and in other areas, recharge is low (less than 10 inches). Water-conveyance structures are used to transport water from areas of excess to areas of deficiency. The amount of mean annual predevelopment recharge available to Oahu's aquifers was estimated for each of the seven major ground-water areas (**fig. 60**). Estimates of recharge for the areas range from less than 4 to about 369 million gallons per day and are greater for areas at higher altitudes and for larger areas in the eastern and central parts of the island.

Reported ground-water withdrawals by decade from 1901 to 1980 from wells and shafts were computed for each of the seven major ground-water areas on Oahu (**fig. 61**). Discharge from shafts in dike complexes was not included. The Waianae rift zone and the southeastern Oahu ground-water areas each had less than 5 million gallons per day of withdrawals. Between 1921 and 1980, withdrawals in the Koolau rift zone area increased to a maximum of about 13 million gallons per day during 1971–80. Withdrawals in the Schofield ground-water area increased over the decades to a maximum of about 15 million gallons per day during 1971–80. In the Kahuku ground-water area, maximum withdrawals of about 31 million gallons per day was during 1941–50, when sugarcane was cultivated in the area. Since 1940, withdrawals in the north-central Oahu ground-water area have ranged from about 40 to 60 million gallons per day. The southern Oahu ground-water area withdrawals were greatest, ranging from about 81 million gallons per day during 1901–10 to about 265 million gallons per day during 1971–80. Withdrawals in the north-central and southern Oahu ground-water areas have decreased in the 1990's because sugarcane is no longer cultivated on Oahu. In addition to the withdrawals, an unknown quantity of ground water is discharged naturally to the ocean by submarine springs and seeps.

Figure 59. *Large ground-water withdrawals from 1901 through 1980 in southern Oahu have caused water levels in the volcanic-rock aquifer in the Pearl Harbor area to decline.*



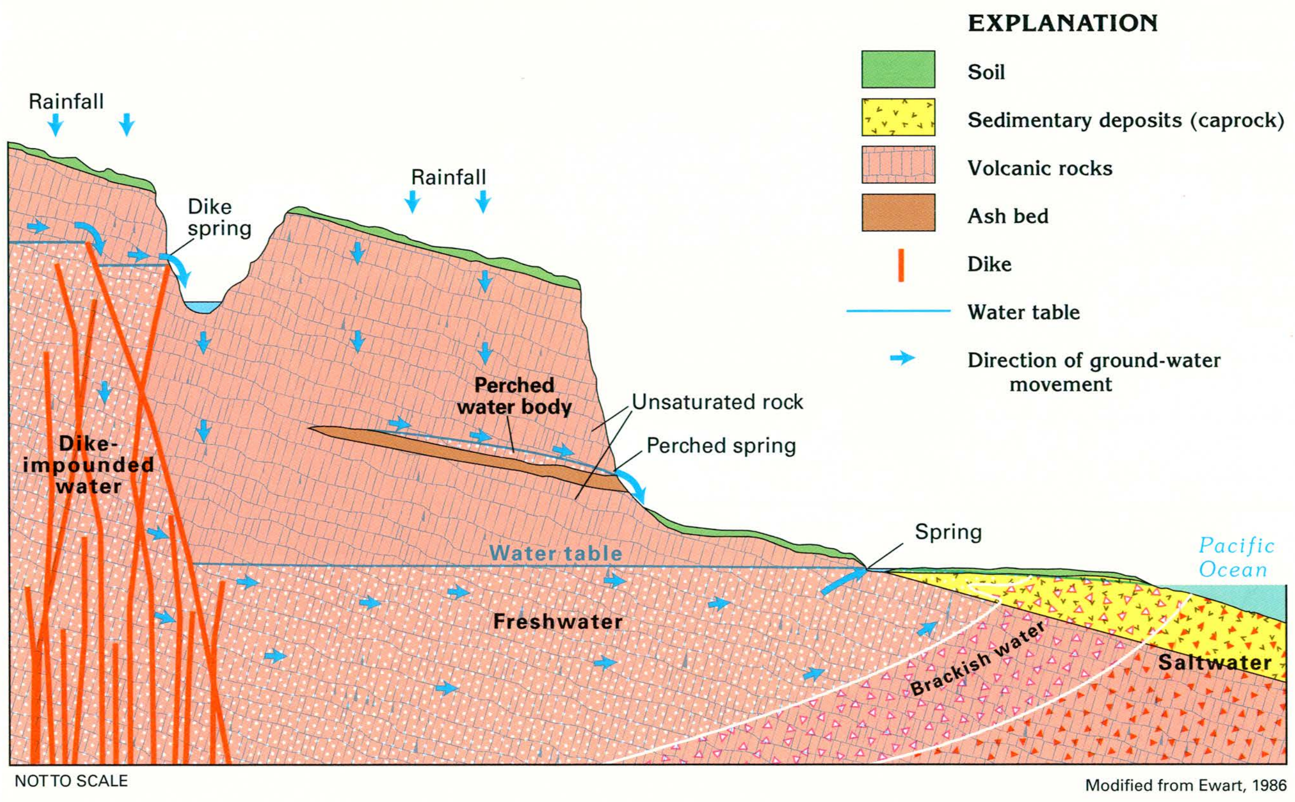
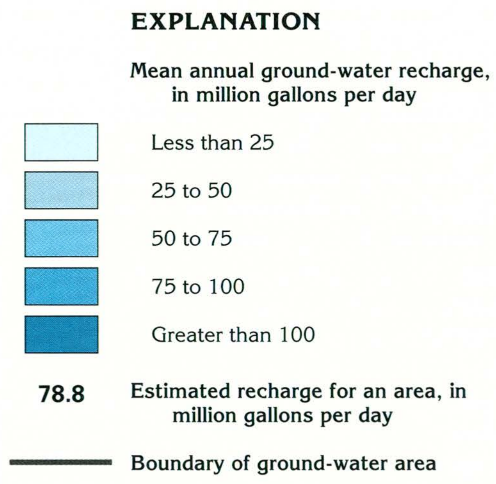


Figure 57. *Dike-impounded and perched ground water are at high altitudes, whereas water levels in the freshwater lens generally are much lower. Springs can form where erosional features intersect perched and dike-impounded water bodies and where the caprock near the shore is underlain by volcanic-rock aquifers that contain water under artesian pressure. The ground water generally becomes saltier towards the ocean and with depth.*



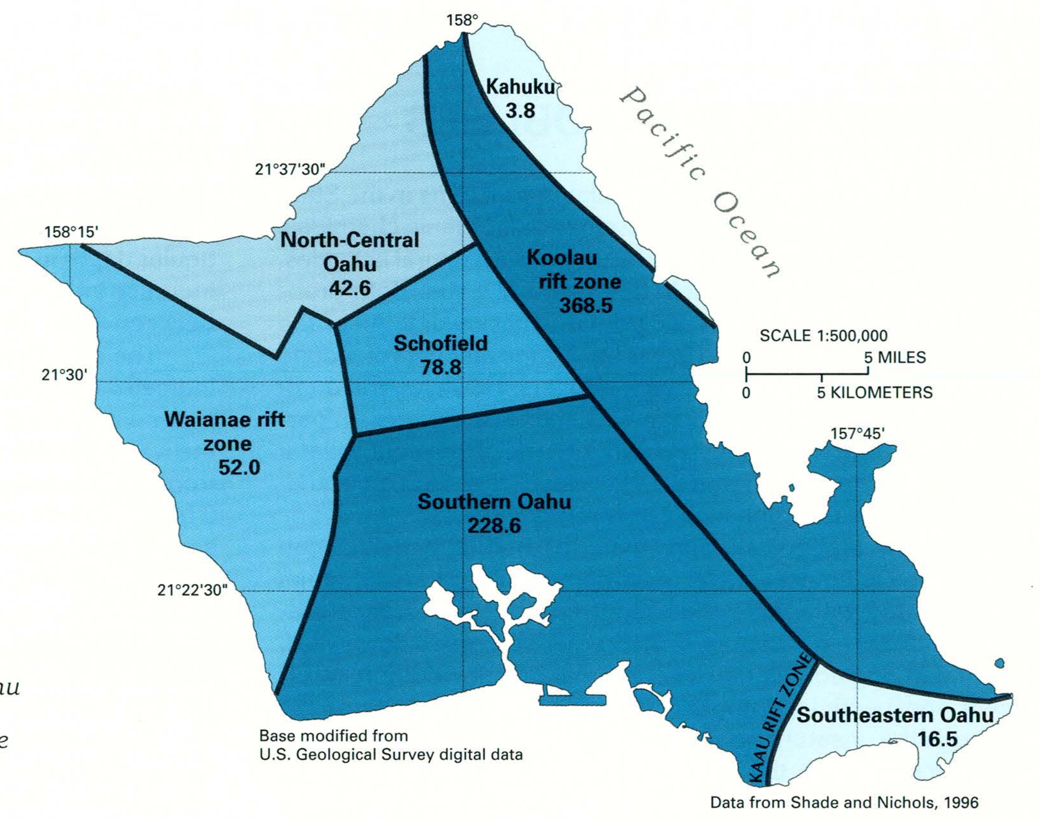
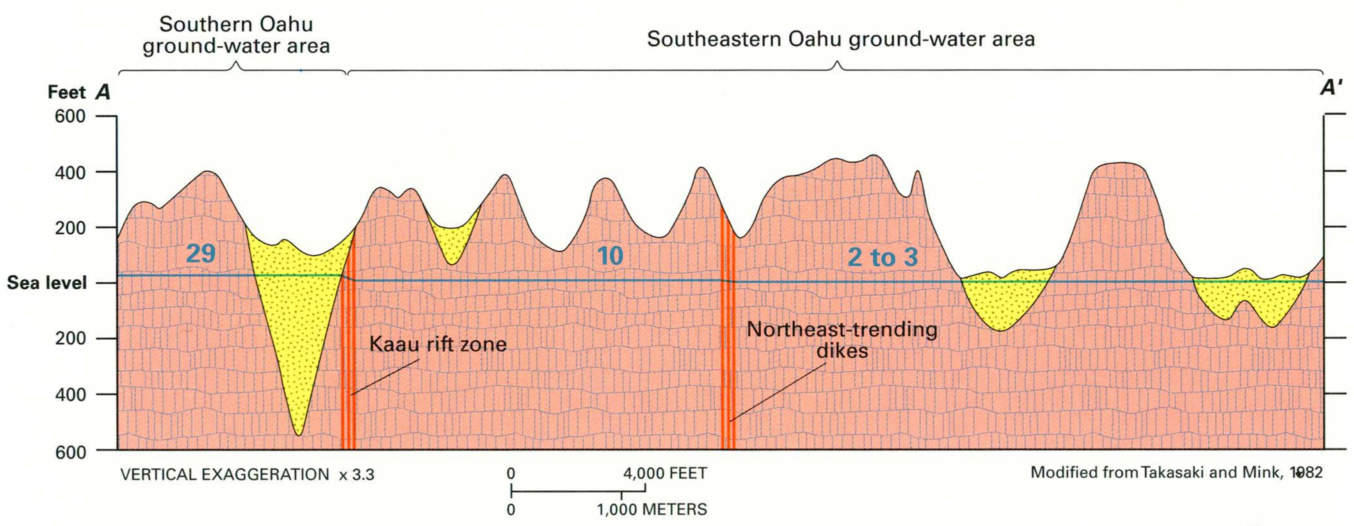


Figure 60. *Estimates of predevelopment recharge to the main ground-water areas on Oahu range from less than 4 to about 368 million gallons per day. The greatest recharge was in the Koolau rift zone ground-water area, whereas recharge was least in the smaller Kahuku and southeastern Oahu ground-water areas. Total mean annual recharge to Oahu's ground-water areas before development is estimated to have been about 791 million gallons per day.*



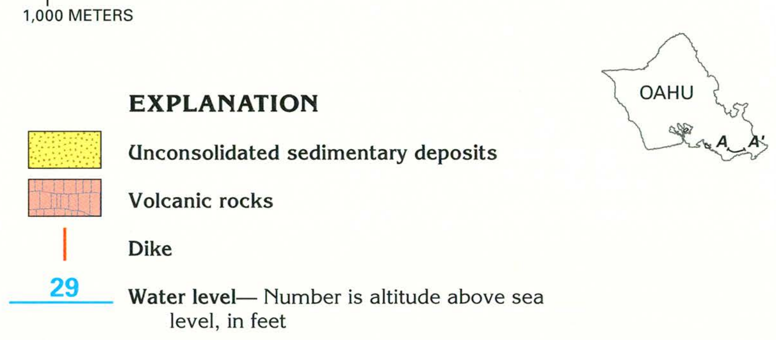
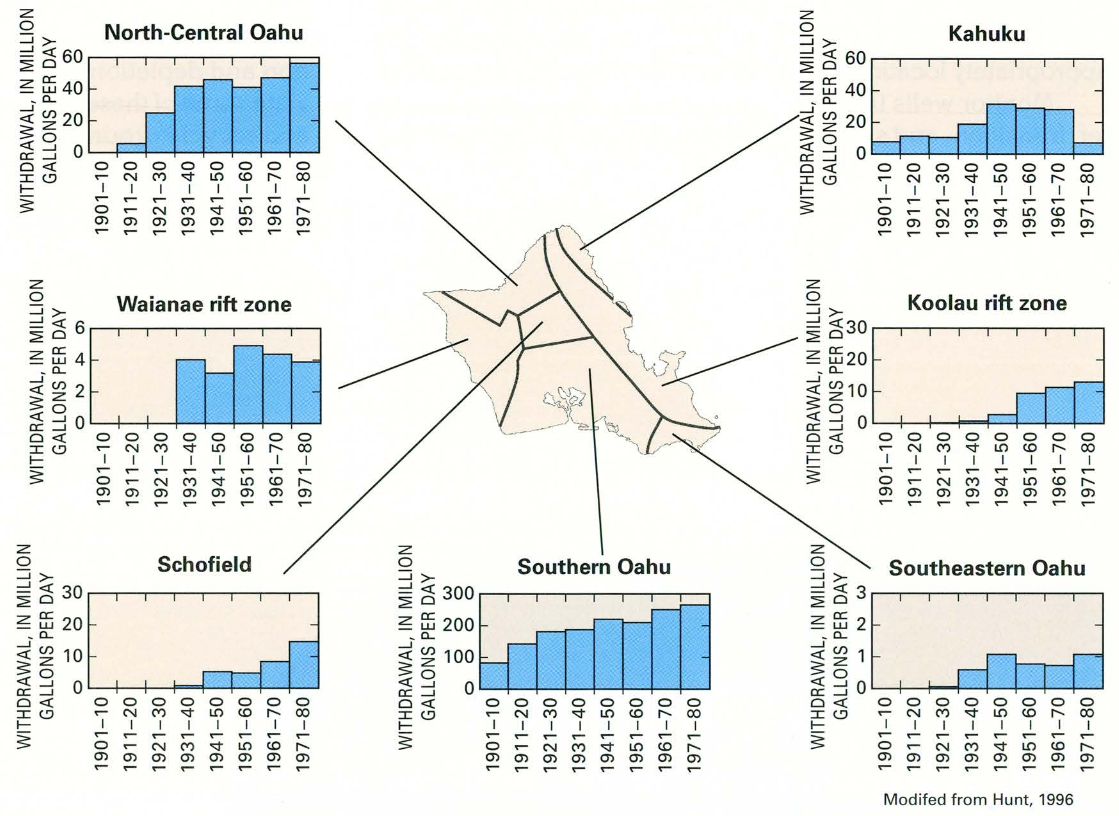


Figure 58. *Low-permeability dikes tend to impede the movement of ground water and can cause water levels in volcanic-rock aquifers in adjacent ground-water areas or subareas to be different by as much as about 20 feet.*

Figure 61. *Estimates of ground-water withdrawals for each ground-water area range from less than 5 million to more than 200 million gallons per day during the decades from 1901 to 1980. The greatest withdrawals were in the southern Oahu ground-water area; withdrawals were least in the southeastern Oahu and the Waianae rift zone ground-water areas.*



A synopsis of the ground-water areas of Oahu follows:

- **The Kahuku ground-water area** consists of dike-free volcanic rocks in the northern end of the Koolau Range and overlying unconsolidated and consolidated sedimentary deposits. Aquifers were heavily developed for agriculture before 1971 when sugarcane cultivation ceased; consequently, estimated water use declined after 1971. Most fresh ground water is found as a lens in the Koolau Basalt. Regional ground-water movement is northeastward from highlands of the Koolau Range towards the ocean. Mean annual predevelopment ground-water recharge from direct infiltration of rainfall was about 3.8 million gallons per day, but ground-water flow through the area is much greater than this because of ground-water inflow from the adjacent dike complex. Discharge is predominantly from the volcanic-rock aquifers into the overlying sedimentary deposits and from there to the ocean.
- **The Koolau rift zone ground-water area** in eastern Oahu consists mostly of dike-intruded Koolau Basalt but also includes extensive areas of unconsolidated sedimentary deposits and local areas of the Honolulu Volcanics and consolidated sedimentary deposits. Most of the area is mountainous and has been deeply dissected by erosion. Land in the coastal areas is used for agricultural, military, and urban purposes. The area is wet, exceptionally so in the mountains. The Koolau Basalt is the principal aquifer; sedimentary deposits are poorly permeable and yield little water. These deposits form a caprock that confines water in the Koolau Basalt inland and in the coastal plains. Regional ground-water movement is from the highlands to adjacent ground-water areas and directly to the ocean. Dike-impounded water is most important in this ground-water area, and some water levels are as much as 1,000 feet above sea level. Mean annual predevelopment recharge was about 368 million gallons per day and was entirely from rainfall. Discharge is to streams and by ground-water outflow to adjacent ground-water areas; withdrawals from wells, shafts, and springs; evapotranspiration; and outflow to the ocean.
- **The southeastern Oahu ground-water area** is in the dry southeastern tip of Oahu. The Koolau Basalt is the principal aquifer in the area. Unconsolidated and consolidated sedimentary deposits in valleys and the coastal plain are generally not developed for water supply; in the coastal plain, these deposits are confining units. The area is highly urbanized, and water is imported from adjacent ground-water areas to supplement the limited resource in this area. Regional ground-water movement is from the highlands southward to the ocean. Mean annual predevelopment recharge was about 17 million gallons per day from infiltration of rainfall. Discharge is by outflow to the ocean and withdrawals from wells.
- **The southern Oahu ground-water area** is the largest ground-water area on Oahu. The Koolau Basalt is the primary aquifer in the central and eastern parts of the area, whereas the Waianae Volcanics forms the main aquifer in the western part. Unconsolidated and consolidated sedimentary deposits form a thick confining unit near the coast. Coralline limestone within the sedimentary deposits is at shallow depths and is extremely permeable but commonly contains brackish water that is withdrawn for cooling and industrial purposes. The confining unit locally is more than 1,000 feet thick near the coast. Because of widespread development, the aquifers in the area have been studied more than those elsewhere. Regional ground-water movement is from adjacent highland rift zones and the Schofield ground-water area towards the ocean. Mean annual predevelopment recharge from direct infiltration of rainfall is estimated to have been about 229 million gallons per day. Discharge is primarily to wells and shafts and to springs in the Pearl Harbor area. Some ground water also flows out of the southern Oahu ground-water area to the adjacent southeastern Oahu ground-water area to the east.
- **The Waianae rift zone ground-water area** encompasses most of western Oahu. Except in the mountains, the area receives little rainfall. The Waianae Volcanics forms the principal aquifer in the area; locally, consolidated sedimentary deposits are minor aquifers, but, for the most part, these deposits have low permeability and confine water in the underlying volcanic-rock aquifer near the coast. The area is chiefly undeveloped, except for some agricultural and military development inland and residential development near the coast. Regional ground-water movement is from areas of dike-impounded water at high altitudes, as much as 1,600 feet above sea level, to downgradient ground-water areas or directly to the ocean. Mean annual predevelopment recharge to the area was about 52 million gallons per day from infiltration of rainfall. Discharge is primarily as ground-water outflow to downgradient ground-water areas and to the ocean.
- **The north-central Oahu ground-water area** composes the northwestern coastal area of Oahu. The principal aquifers are the Koolau Basalt in the east and the Waianae Volcanics in the west, which are overlain near the coast in most areas by a confining unit of sedimentary deposits. The area is little developed, except near Waialua. Regional ground-water movement is from adjacent areas of dike-impounded water and the Schofield ground-water area northward toward the ocean. The water in the north-central Oahu ground-water area occurs as a freshwater lens. Mean annual predevelopment recharge from direct infiltration of rainfall to the area was about 43 million gallons per day. Recharge also is by ground-water inflow from adjacent areas. Discharge is by outflow to springs and the ocean, and withdrawals from wells and shafts.
- **The Schofield ground-water area** is in the Schofield Plateau of central Oahu. Poorly known geologic structures of low permeability impound ground water at altitudes that range from about 130 to 275 feet above sea level. Although the Waianae Volcanics locally is present, the principal aquifer in the area is the Koolau Basalt. Regional ground-water movement is northwestward and southward from the central part of the plateau to adjacent ground-water areas. Ground-water inflow to the area from the adjacent Koolau and Waianae rift zones supplements recharge from direct infiltration of rainfall. The mean annual predevelopment recharge is estimated to have been about 79 million gallons per day. Discharge from the area is principally by ground-water outflow to downgradient ground-water areas, but some water is withdrawn by wells.

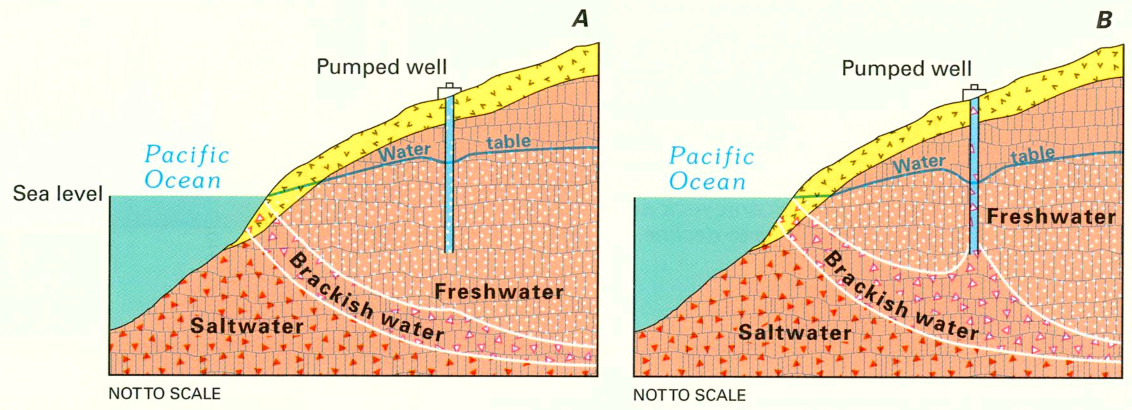
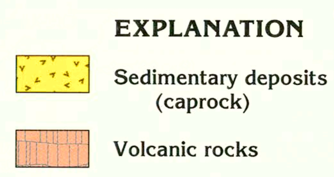


Figure 62. Saltwater intrusion is a potential problem near the coast. **A,** Diagram of a well completed in a volcanic-rock aquifer in which withdrawal is much less than recharge. Only limited saltwater intrusion has taken place. **B,** Diagram of the same well under conditions of large ground-water withdrawals. Saltwater has intruded the aquifer and brackish water has reached the well.



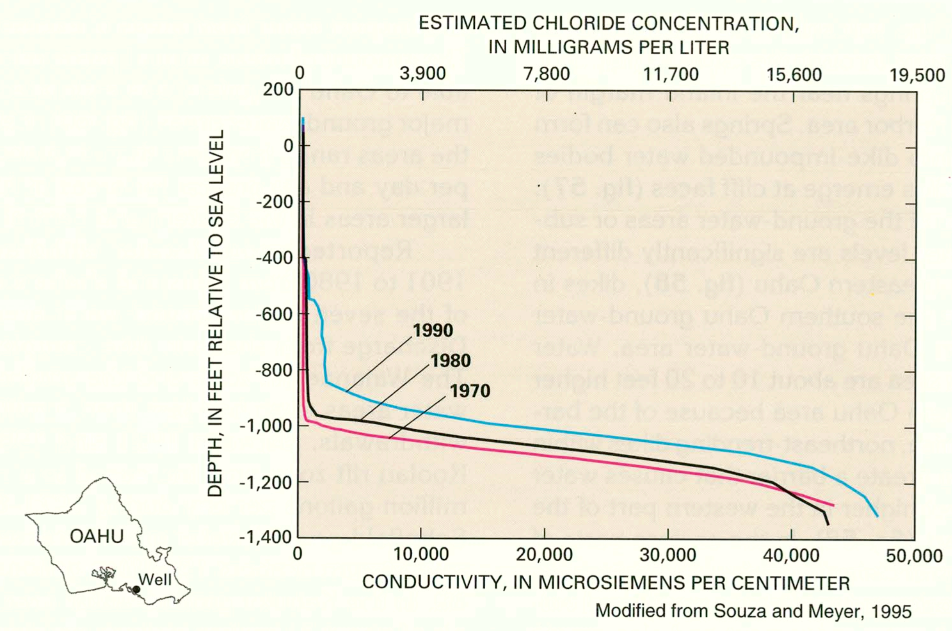


Figure 63. Vertical salinity profiles from deep monitor wells can be used to detect changes in the thickness of a freshwater lens over time. In the Honolulu area, the freshwater lens has thinned from 1970 to 1990 in response to increased withdrawals.

Ground-water problems

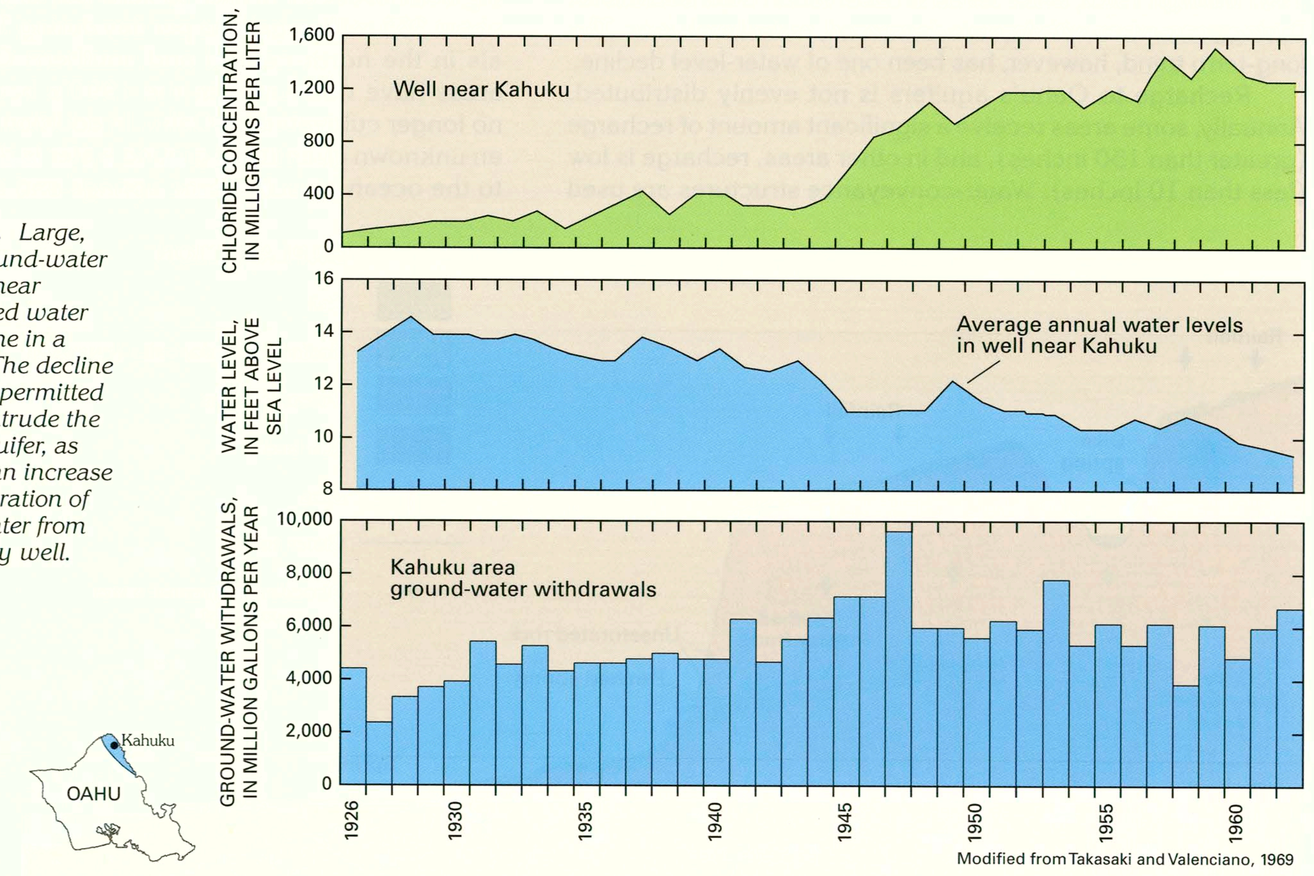


Figure 64. Large, sustained ground-water withdrawals near Kahuku caused water levels to decline in a nearby well. The decline in water level permitted saltwater to intrude the freshwater aquifer, as indicated by an increase in the concentration of chloride in water from another nearby well.

GROUND-WATER PROBLEMS

The two main ground-water-related problems in the State of Hawaii are contamination by organic or inorganic chemicals associated with both agricultural and non-agricultural activities, and the availability of potable fresh ground water. Both problems are ultimately related to ground-water quality. All of the main islands in the State of Hawaii have large amounts of ground water contained in volcanic-rock aquifers. However, the quality of the ground water may not be suitable for all uses. In particular, not all ground water is potable. Some of the ground water is contaminated by chemicals associated with human activities and some contains high concentrations of salts.

Contamination of ground water by human activities can take place in several ways. In some agricultural areas, crops are irrigated with water that might contain large concentrations of dissolved minerals. If such water percolates downward, an underlying aquifer can be contaminated. In addition, fertilizers and pesticides applied to crops can move downward through the unsaturated zone to an aquifer and affect the quality of the water in the aquifer. Wastes from septic-tank systems, sewers, industry, and storm runoff also can introduce undesirable constituents into the aquifers.

Each of the principal islands has some problems with the degradation of freshwater by saltwater. Smaller islands, such as Kahoolawe, Lanai, and Niihau, are more affected chiefly because they receive lesser quantities of recharge from rainfall.

Ground-water withdrawals induce upward and landward movement of saltwater. Wells completed in the freshwater lens near the coast (**fig. 62**) are particularly likely to induce brackish water or saltwater to move into the well as pumping continues. Saltwater-intrusion problems can be minimized by appropriately locating wells and by controlling withdrawal rates.

Monitor wells that are open to the aquifer in the freshwater, transition, and saltwater zones are used in Hawaii to evaluate the ground-water resources (**fig. 63**). By periodically obtaining vertical salinity profiles in these deep monitor wells, changes in the freshwater lens thickness can be estimated. Vertical salinity profiles from a deep monitor well located in the Honolulu area indicate that the salinity of water at any particular depth in the aquifer increased from 1970 to 1990. This increase indicates that the transition zone has moved upward between 1970 and 1990.

The chloride concentration in water from a well is a good indicator of saltwater intrusion. From 1926 to 1962, ground-water withdrawals in the Kahuku area increased (**fig. 64**) and the water level in a well near the major pumped wells declined from a high of about 15 feet above sea level in 1928 to about 9 feet above sea level in 1962. Chloride concentrations in water samples from a nearby well were less than 250 milligrams per liter before 1930 but slowly started to increase with increased withdrawals. Chloride concentrations had increased to about 400 milligrams per liter by 1939, increased rapidly after 1944, and reached a maximum concentration of 1,500 milligrams per liter in 1959, as water levels continued to decline.

The problem of saltwater intrusion is characteristic of the freshwater lens, but perched water and dike-impounded water bodies also have problems. Perched water bodies commonly are small and can be dewatered quickly. Dike-bounded compartments also can be dewatered quickly, particularly if a shaft dug into the compartment is permitted to drain the impounded water without control (**fig. 65**).

Water-availability problems arise locally when demands for water exceed supply. In some areas, water must be imported from other areas by ditches, tunnels, and pipelines to satisfy the demands. As with most areas of the world, when development increases, the demand for freshwater and ground water increases as does the potential for contamination and depletion of the water resources of the area. To alleviate some of these problems, efforts are being made to reclaim and recycle ground water in the State of Hawaii.

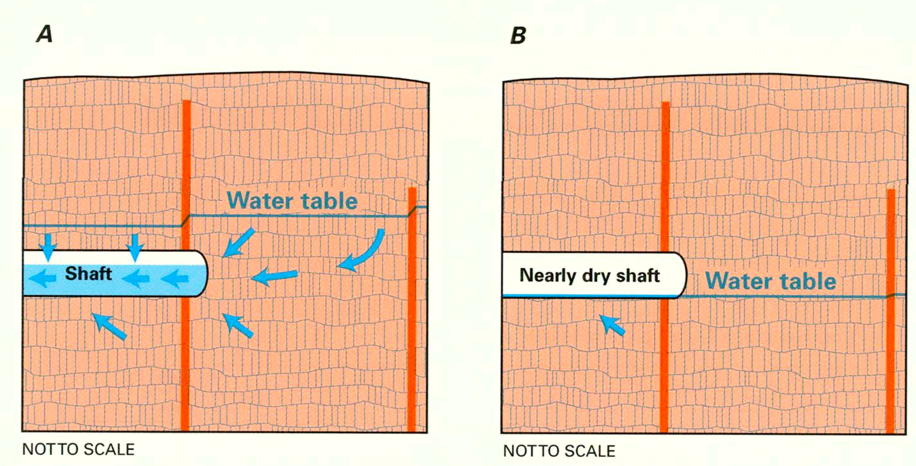
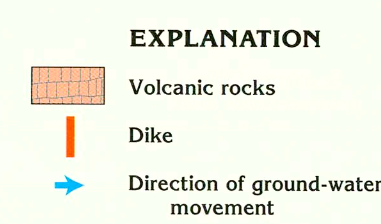


Figure 65. Shafts that supply water from dike-bounded compartments **(A)** can become nearly dry if the hydraulic head (water level) in the compartment of rock drops **(B)**. Uncontrolled flow of ground water from such a shaft can cause the hydraulic head to decrease rapidly.



Puerto Rico and the U.S. Virgin Islands

by Perry G. Olcott

Figure 66. Puerto Rico and the U.S. Virgin Islands are part of an island chain that separates the Atlantic Ocean from the Caribbean Sea.

CONTENTS

Regional Summary

INTRODUCTION

Puerto Rico and the Virgin Islands of the United States (**fig. 66**) are located about 1,100 miles east-southeast of Miami, Fla. The islands are part of the Greater Antilles island chain which, along with the Lesser Antilles island chain, separates the Caribbean Sea from the Atlantic Ocean. Puerto Rico and the Virgin Islands lie approximately 100 miles south of the Puerto Rico Trench, a depression of the ocean floor that reaches depths of 30,249 feet, the deepest known part of the Atlantic Ocean.

The main island of Puerto Rico is a rectangular-shaped island that extends approximately 110 miles from east to west and 40 miles from north to south (**fig. 67**). Puerto Rico and its three principal offshore islands—Vieques, Culebra, and Mona—have an overall area of about 3,471 square miles.

The Virgin Islands are about 50 miles east of Puerto Rico and consist of about 80 islands and cays. In this report, the Virgin Islands include only the three island territories of the United States—St. Croix, St. Thomas, and St. John. The three island territories also are the largest and most important of the Virgin Islands chain, with respective areas of approximately 84, 32, and 19 square miles.

The population of Puerto Rico was estimated to be about 3.4 million in 1985; approximately two-thirds of the people lived in cities, and the remaining one-third lived in rural areas. A population of about 104,000 inhabited the Virgin Islands in 1985; only about 30 percent of these people lived in urban areas. In Puerto Rico during 1985, ground water was the source of supply for approximately 16 percent of the population. Only a small percentage of the urban inhabitants of the Virgin Islands use ground water for water supply; however, ground water is an important supplemental source for rural inhabitants. Most of the population of Puerto Rico obtains its water supply from surface-water reservoirs. In the Virgin Islands, seawater desalination plants on St. Croix and St. Thomas are the principal sources of water supply for most urban areas; however, by law, all residences, hotels, and most public buildings are required to have cisterns supplied from rooftop precipitation collectors. Cruz Bay on St. John is primarily supplied by ground water. Culebra Island is primarily supplied by pipeline from Puerto Rico. Mona Island has no known source of water supply and is uninhabited.

Puerto Rico and the three principal U.S. Virgin Islands are mountainous with central highland areas that rise to a maximum altitude of about 4,400 feet above sea level in Puerto Rico and about 1,100, 1,560, and 1,280 feet above sea level on St. Croix, St. Thomas, and St. John, respectively. In Puerto Rico, the Cordillera Central, the Sierra de Luquillo, and the Sierra de Cayey generally are oriented east-west and dominate the mountainous southern two-thirds of the island (**fig. 67**). An area of gently dipping limestone that has been deeply dissected by dissolution forms a wide band of karst topography along most of the north coast. Flat-lying coastal plains and alluvial valleys compose a discontinuous belt around much of the periphery of the island. The coastal plain is especially prominent along part of the south coast where coalescing fan deltas were deposited by adjacent streams to form a broad, continuous plain.

In St. Thomas, flat, low-lying areas are limited to the Charlotte Amalie area and a few narrow beaches. St. John is similar to St. Thomas but has even less flat land; in St. John, flat land is limited mostly to the Cruz Bay and Coral Bay areas. The northwestern and eastern parts of St. Croix are formed by low mountains and rugged hills; however, the central and southwestern parts of the island are low-lying to gently rolling.

Drainage on each of the islands characteristically consists of short, deeply incised streams that have steep gradients in the upper reaches. Drainage generally is radial from the central highlands to the sea. Few of the streams along the southern coast of Puerto Rico, its offshore islands, or the U.S. Virgin Islands are perennial, but flow only after major precipitation and during sustained wet periods.

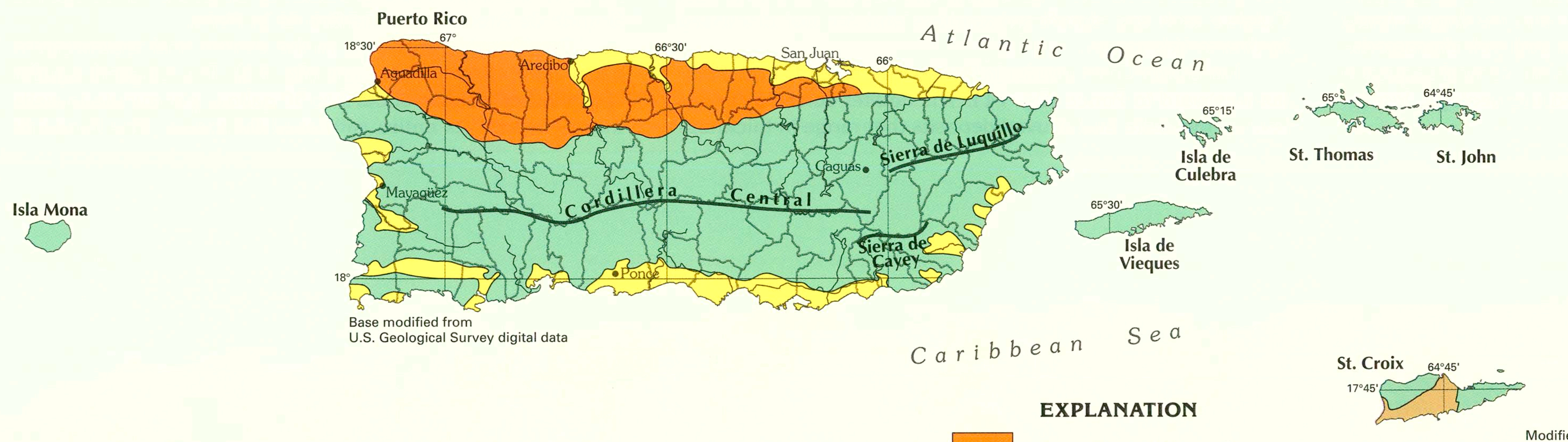


Figure 67. *The central part of Puerto Rico is mountainous, but the north coast is paralleled by a gently dipping belt of limestone with a well-developed karst topography. A flat-lying coastal plain lies along the southeastern coast. Alluvium-filled valleys are present intermittently on the periphery of the island. The Virgin Islands are mountainous except for small areas of gently sloping lowlands on St. Thomas and St. John and a larger lowland area on St. Croix.*

EXPLANATION

- Area of karst topography
- Mountainous area
- Discontinuous coastal plain
- Low-lying to gently rolling plain
- Approximate axis of mountain chain

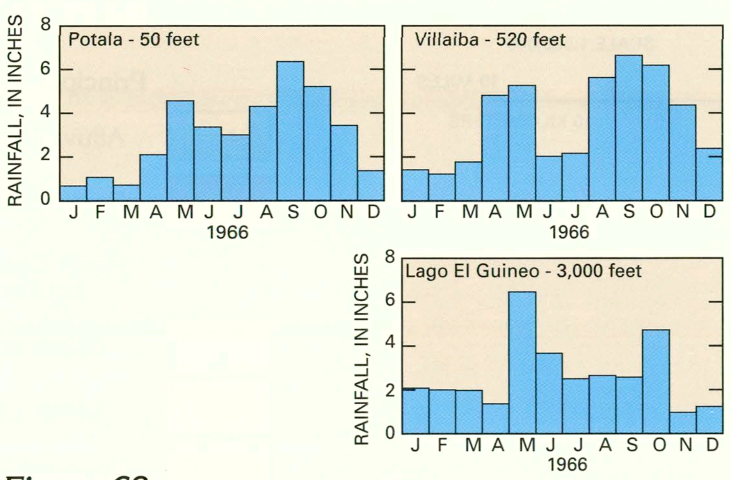


Figure 68. *Rainfall in Puerto Rico varies during the year and generally is greater at higher elevations. The location of the rainfall stations is shown in figure 69A.*

Precipitation in Puerto Rico and the Virgin Islands is highly variable, both seasonally and areally. Seasonally, a dry period begins in December and ends in March or April; it usually is followed by a period of intensive rainfall in April and May. A period of diminished rainfall in June and July is followed by the wet season that extends from August through November during which about 50 percent of annual rainfall occurs (**fig. 68**).

Areally, the orographic effect of the steep topography of highland areas causes average annual precipitation to vary almost in direct relation to altitude, but it also is affected by prevailing wind direction. Average annual precipitation in Puerto Rico ranges from less than 40 inches on the southern coastal plain to greater than 200 inches in the mountains (**fig. 69A**). Annual precipitation averages about 75 inches on the windward north coast of Puerto Rico compared to about 30 inches on the lee side of the island along the southwestern coast. Annual precipitation averages from less than 30 to greater than 55 inches in the Virgin Islands (**fig. 69B**).

Runoff in Puerto Rico and the Virgin Islands also varies seasonally and areally in response to fluctuations in precipitation. Average annual runoff (1951–80) in Puerto Rico ranges from about 20 inches on the northern and southern coasts to greater than 100 inches in the mountainous rain forest of the Sierra de Luquillo (**fig. 70**). In general, runoff is greatest during two periods that coincide with periods when precipitation is greatest—in August through November and April through May. Most streams have little flow during dry periods except for the larger streams on the north, west, and south coasts of Puerto Rico that originate in the igneous and volcanic rocks of the interior. The northern and southern coastal streams especially are perennial in coastal areas where they are underlain by limestone and thick alluvium, and water from the limestone and alluvial aquifers discharges to the streams as base flow.

Most of the precipitation is returned to the atmosphere by evapotranspiration—evaporation from the land and water surfaces and transpiration by plants. Average annual evaporation in Puerto Rico is estimated from pan evaporation to range from about 64 inches in the coastal areas to about 50 inches in the interior.

Some of the water from precipitation is stored in reservoirs on the land surface. There are 11 surface-water reservoirs in Puerto Rico with capacities in excess of 5,000 acre-feet. One acre-foot is the volume of water that would cover 1 acre to a depth of 1 foot. The water in some of these impoundments is used for hydroelectric power generation and irrigation water supplies. However, six of the island's reservoirs are used principally for public water supply. The impoundments also increase evaporation because they increase the area of standing water. This water loss is especially significant in the south coast area, where pan evaporation is almost twice the annual rainfall.

Some water from precipitation enters aquifers as groundwater recharge. Water that is stored in the aquifers might be released later either by withdrawal by wells, by evapotranspiration, or as seepage to streams.

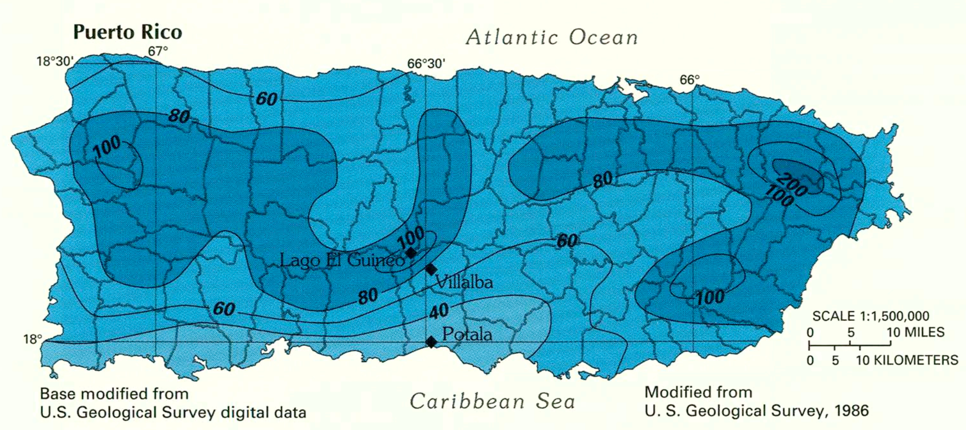


Figure 69A. *Average annual rainfall in Puerto Rico (1951–80) is greatest in the mountains where it is locally greater than 200 inches. Rainfall is least, less than 40 inches, in lowland areas along the south coast.*

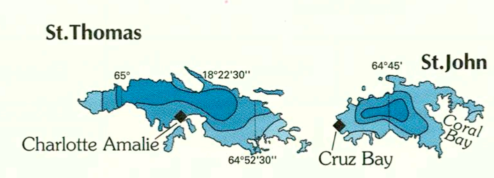
EXPLANATION

Average annual precipitation (1951–80), in inches

40
80
200

—40— Line of equal average annual precipitation—Interval, in inches, is variable

◆ National Weather Service precipitation gage



EXPLANATION

Average annual precipitation (1951–80), in inches

Saint Thomas	Saint John	Saint Croix
35	40	30
40	50	40
42	55	50

◆ National Weather Service precipitation gage

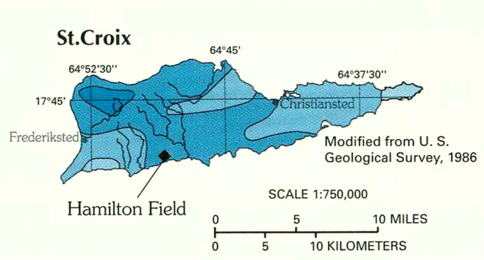


Figure 69B. *Average annual rainfall in the Virgin Islands (1951–80) ranges from less than 30 inches in eastern St. Croix to greater than 55 inches in the mountainous central part of St. John.*

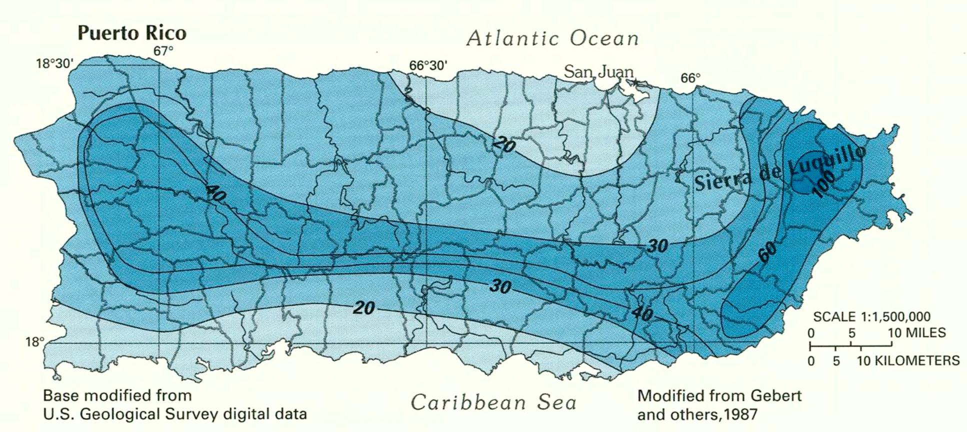


Figure 70. *Average annual runoff in Puerto Rico (1951–80) ranged from less than 20 inches in the low-lying San Juan area and most of the south coast to greater than 100 inches in the mountainous rain forest of Sierra de Luquillo.*

EXPLANATION

Average annual runoff (1951–80), in inches

20
30
60
100

—20— Line of equal average annual runoff—Interval, in inches, is variable

AQUIFERS AND CONFINING UNITS

Principal aquifers in Puerto Rico and the Virgin Islands consist mostly of limestone, alluvium, or volcanic rocks. The aquifers generally are limited in areal extent and generally yield 500 gallons per minute or less to wells, although higher yields are available locally. On all the islands, freshwater demand is high, and, on the Virgin Islands, freshwater is in short supply; thus, each of the aquifers is important as a source of water.

Principal aquifers and aquifer systems in Puerto Rico consist of the alluvial valley aquifers, the South Coast aquifer, and the North Coast Limestone aquifer system. An aquifer system consists of a heterogeneous body of interbedded permeable and poorly permeable material that functions regionally as a water-yielding hydraulic unit; it comprises two or more permeable beds (aquifers) separated at least locally by confining units that impede ground-water movement but that do not greatly affect the regional hydraulic continuity of the system. The North Coast Limestone aquifer system consists of an upper (mostly unconfined) and a lower (mostly confined) aquifer.

In the Virgin Islands, the only aquifer of major importance is the Kingshill aquifer on St. Croix. There are minor aquifers of three different types: alluvial valley aquifers, small alluvial aquifers called coastal embayment aquifers, and volcaniclastic-, igneous-, and sedimentary-rock aquifers that generally yield only enough water for domestic supply. The geographic distribution of the aquifers in Puerto Rico and the Virgin Islands is shown in **figure 71**, and some aquifer and well characteristics are listed in **table 4**. **Figure 72** shows the vertical sequence of the aquifers and confining units, and the geologic formations that compose them.

Alluvial valley aquifers in Puerto Rico consist of river alluvium along the lower part of major river valleys on the east, west, north, and southwestern coastal areas and in the east-central interior valleys of rivers near Cayey, Caguas, and Juncos (**fig. 71**). Water generally is unconfined in these aquifers. The alluvium is present in valleys incised into limestone bedrock on the north and south coasts and into volcaniclastic rocks in the interior. The alluvium is as much as 300 feet thick in the north coast valleys and as much as 150 feet thick in the southwestern coast valleys. Valleys on the east and west coasts are incised into volcaniclastic or igneous intrusive bedrock and contain as much as 150 to 300 feet of alluvium. Near Cayey, Caguas, and Juncos, the alluvium is about 150 feet thick. The alluvial valley aquifers are an important source of public water supply for numerous municipalities in the coastal areas of Puerto Rico. Saltwater intrusion and upconing are problems in areas of large withdrawals.

The Esperanza–Resolución Valley aquifer is an alluvial valley aquifer that extends across the western end and along part of the southern coast of the island of Vieques (**fig. 71**). This aquifer was the principal freshwater source on the island and supplied about 8,000 inhabitants with freshwater prior to installation of a pipeline from Puerto Rico in 1978. The aquifer is mostly fine-grained alluvium derived from the weathering of dioritic rock and is underlain by weathered and fractured dioritic rocks; it is mostly a semiconfined aquifer. Because the Esperanza–Resolución Valley aquifer is no longer used, it is not discussed further. Similarly, the islands of Mona and Culebra lack any significant aquifers and are not discussed further in this report.

The South Coast aquifer in Puerto Rico extends from Patillas westward to Ponce (**fig. 71**). The aquifer consists of coalescing fan-delta and alluvial deposits that range in thickness from about 300 feet near the coast at Ponce to as much as 1,000 feet near Santa Isabel. Near the coast throughout most of the western half of the aquifer, freshwater is underlain by saline water at depths of about 250 feet or less. The aquifer generally is unconfined, but semiconfined conditions are created locally by interbedded silt and clay layers. The aquifer consists of fine-grained material, especially near the coast and at the coalescing edges of the fans. Coarser grained material generally is present in the central and upper parts or apex of each fan. The South Coast aquifer supplies about one-half of the total public water supply and irrigation needs of the south coast. The remainder is from surface-water sources. Withdrawals from the aquifer were estimated to be about 74 million gallons per day in 1985.

The North Coast Limestone aquifer system in Puerto Rico consists of an upper and lower aquifer separated by a confining unit (**fig. 72**) and extends from the western end of Puerto Rico to east of San Juan (**fig. 71**). It is composed of limestone and some clastic rocks that dip oceanward at an average angle of about 4 to 5 degrees along the southern outcrop belt and 1 to 3 degrees along the northern part. The rocks that compose the aquifers range in composition from sand, clay, and marl to nearly pure limestone. Water contained in the upper aquifer and the outcrop areas of the lower aquifer is largely unconfined, but the water in the subsurface parts of the lower aquifer and in some coastal parts of the upper aquifer is confined. This limestone aquifer system is the principal source of water for most municipalities and industries located between the Río Grande de Arecibo and the Río de la Plata.

The Kingshill aquifer is in the central and southwestern parts of the island of St. Croix (**fig. 71**). The Kingshill aquifer is capable of yielding about 5 to 50 gallons per minute to wells that penetrate its entire saturated thickness. The Kingshill Limestone mostly comprises the Kingshill aquifer (**fig. 72**), which consists of beds of soft yellow-orange to white limestone, limey clay (marl), thin sandy interbeds, and conglomerates. A younger, unnamed carbonate-rock unit and unconsolidated alluvium overlie the Kingshill Limestone in some localities. The younger carbonate rock is a productive part of the Kingshill aquifer but is of limited areal extent and importance. Alluvium is of broader areal extent and fills dissected stream courses; alluvial deposits store and subsequently release water to recharge the Kingshill aquifer. The Kingshill aquifer is underlain by the Jealousy Formation, which is a poorly transmissive limestone (known locally by drillers as a blue clay) that functions as the base of the hydrologic system. The thickness of the Jealousy is unknown, but is estimated to be greater than 6,000 feet and the formation presumably rests on volcanic rocks.

Coastal embayment aquifers are minor aquifers present in bays and inlets on each of the three islands of the Virgin Islands (**fig. 71**) and consist of unconsolidated deposits of alluvial and (or) beach sands. The aquifers generally consist of fine-grained material and range in thickness from 30 to about 50 feet. They are unconfined where they consist of coarse material but are semiconfined to confined where they consist of fine-grained sediments. Yields of wells completed in these aquifers range from 5 to 50 gallons per minute, but, in many places, only a small part of a coastal embayment aquifer contains freshwater, and wells commonly produce brackish water.

The volcaniclastic-, igneous-, and sedimentary-rock aquifers also are minor aquifers (**fig. 71**). They are intensely faulted and folded rock masses that consist mostly of volcaniclastic, igneous, and sedimentary rocks exposed in the central part of each of the islands and comprise tuffaceous siltstone, tuff

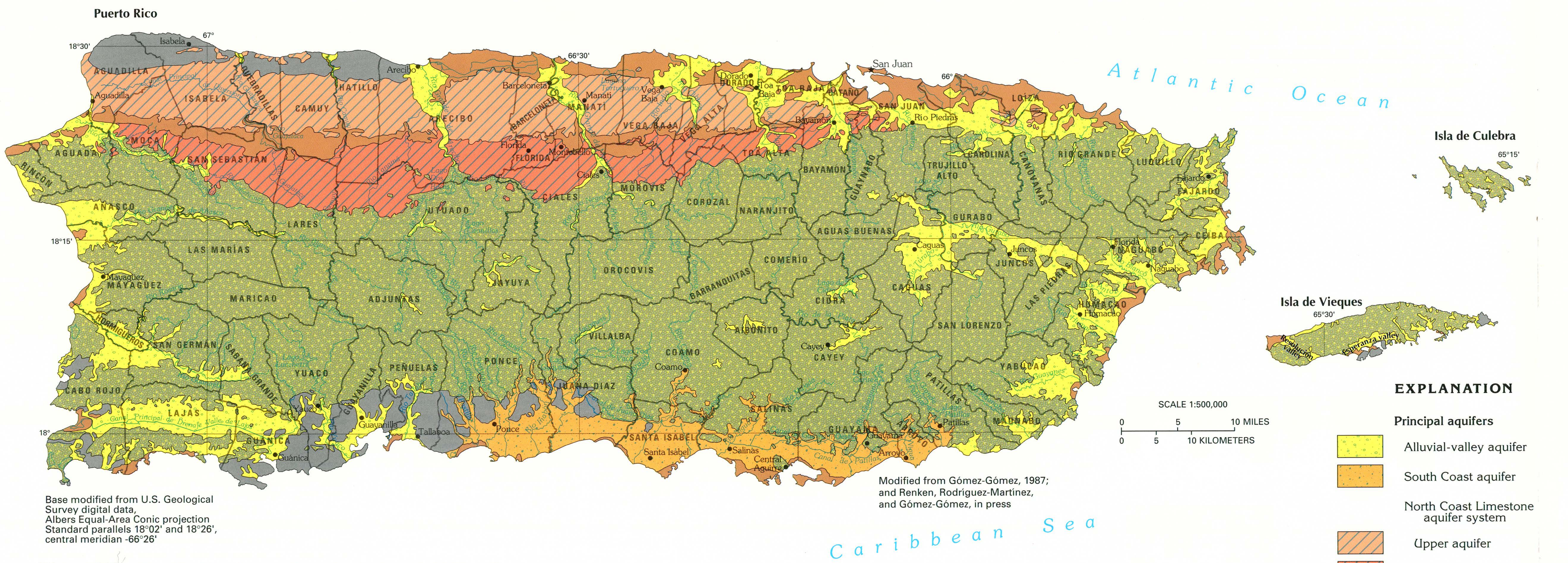
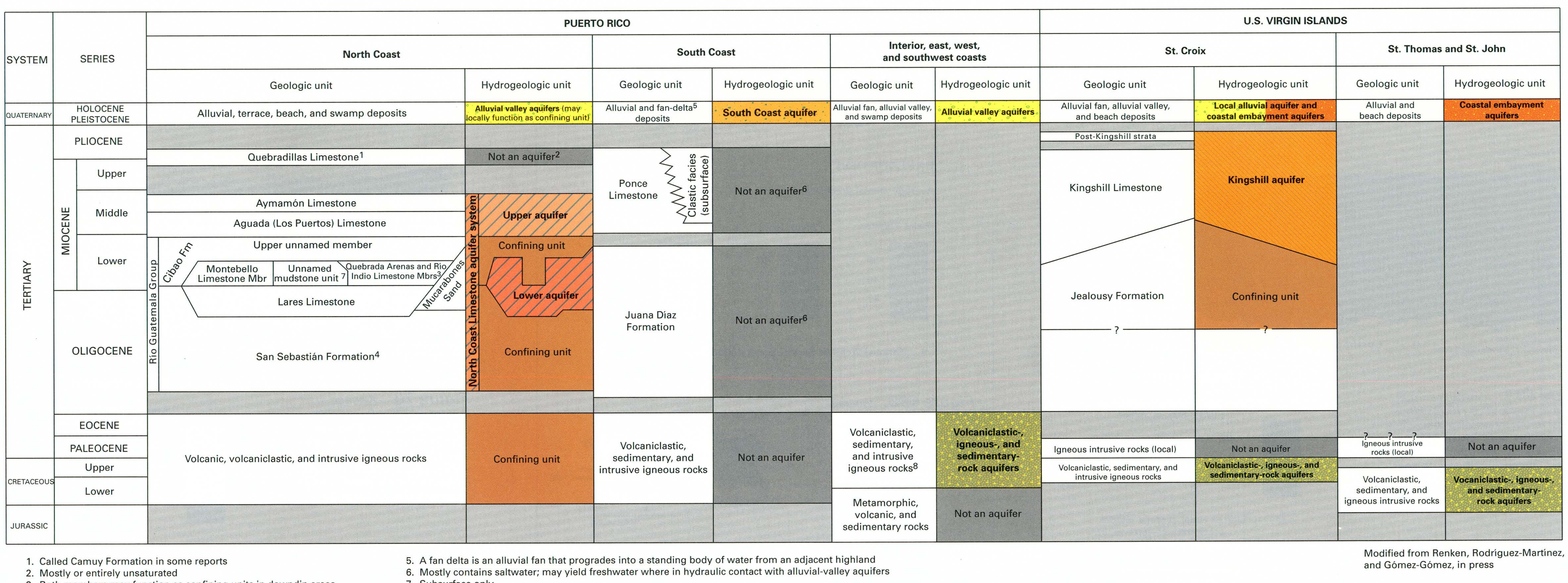


Figure 71. The alluvial valley aquifers, South Coast aquifer, and North Coast Limestone aquifer system of Puerto Rico, along with the Kingshill aquifer of St. Croix form the principal aquifers. The coastal embayment and the volcaniclastic-, igneous-, and sedimentary-rock aquifers are less important sources of water.



1. Called Camuy Formation in some reports
2. Mostly or entirely unsaturated
3. Both members may function as confining units in downdip areas
4. Contains local permeable beds in updip areas that may be hydraulically connected to the lower aquifer
5. A fan delta is an alluvial fan that progrades into a standing body of water from an adjacent highland
6. Mostly contains saltwater; may yield freshwater where in hydraulic contact with alluvial-valley aquifers
7. Subsurface only
8. Intrusive rocks are not considered water bearing

Modified from Renken, Rodríguez-Martínez, and Gómez-Gómez, in press

Figure 72. Most of the aquifers and aquifer systems in Puerto Rico and the Virgin Islands are separate water-yielding units, some of which are laterally equivalent. The light gray areas represent missing rocks.

stone, breccia, conglomerate, andesitic to basaltic lava, and minor limestone. The volcanic rocks have been intruded in places by plutonic rocks, such as granodiorite, quartz diorite, and serpentinized peridotite. In Puerto Rico, the volcani-clastic-, igneous-, and sedimentary-rock aquifers extend over nearly 2,000 square miles and constitute the major part of the island. The aquifers similarly extend over large parts of the Virgin Islands. The volcaniclastic rocks generally are not permeable, but where rainfall is significant, these rocks store and transmit water in fractures and other secondary openings. These rocks generally yield less than 10 gallons per minute to wells, especially in the areas intruded by plutonic rocks. However, where wells penetrate limestone beds or weathered intrusive rocks, they may yield moderate to large quantities of water to wells.

GEOLOGY

Puerto Rico and its outlying islands and St. Croix, St. Thomas, and St. John in the Virgin Islands are part of an island arc that largely consists of faulted and folded volcaniclastic and sedimentary rocks that have been locally intruded by igneous rocks. These rocks generally range in age from Cretaceous to Eocene, although some rocks of Early Cretaceous-Jurassic age are present in southwestern Puerto Rico. The volcaniclastic rocks form the mountainous and highly irregular central core of each of the islands. Sedimentary rocks, which are mostly limestones of Oligocene to Pliocene age, overlie the volcaniclastic and sedimentary rocks in isolated areas, and thick alluvial deposits of Quaternary age formed of material eroded from the volcaniclastic and sedimentary rocks are along many stream valleys, especially in coastal areas. Widespread unconsolidated deposits that consist of coalescing alluvial fans or fan deltas, dune and beach deposits, marine terrace deposits, and landslide, swamp, and other miscellaneous deposits also overlie older rocks, especially in the northern and southern coastal areas of Puerto Rico (**fig. 73**).

In Puerto Rico, a thick limestone sequence that ranges in age from Oligocene to Pliocene (**fig. 73**) overlies volcaniclastic rocks in a continuous belt along the north coast. Locally, limestone beds not differentiated on **figure 73** occur in a discontinuous belt along the southwestern coast and in isolated areas in the interior. The north coast limestones form important aquifers, but the southwestern coast and interior limestones generally yield significant quantities of water only locally.

The broad limestone belt in northern Puerto Rico extends west from Rio Espiritu Santo to Aguádilla, a distance of about 90 miles (**fig. 73**). The belt reaches its maximum width near Arecibo, where it is about 14 miles wide. Six formations are recognized above the volcaniclastic rocks on which the sedimentary rocks were deposited. They are, in ascending order, the San Sebastián Formation, Lares Limestone, Cibao Formation, Aguada (Los Puertos) Limestone, Aymamón Limestone, and Quebradillas Limestone. A seventh formation, the Mucarabones Sand, is the eastern lateral clastic equivalent of the Lares Limestone and the lower two-thirds of the Cibao Formation. The sequence of these formations and their grouping into hydrogeologic units of the North Coast Limestone aquifer system are shown in **figure 72**.

Limestones in Puerto Rico have been extensively eroded by dissolution. Nearly all these rocks on the north coast and some on the south coast have well-developed karst features, but the limestones of the north coast are a classic example of karst topography, which features cone, tower, mogote, doline, and cockpit karst. All of these features are well-developed on the north coast limestone. Cone karst is a type of karst topography characterized by many steep-sided, near-vertical, cone-shaped hills surrounded by star-shaped depressions. Tower karst is a karst terrain characterized by vertical-sided hills. Mogote karst is characterized by steep-sided, conical limestone hills surrounded by flat alluviated plains. Doline karst refers to karst topography characterized by a closed depression or sinkhole. Cockpit karst refers to these star-shaped or irregular depressions which are surrounded by conical hills in cone karst terrain.

The attitude of the north coast limestone sequence is that of a homocline gently dipping to the north. The average angle of dip of the rocks is about 4 to 5 degrees to as much as 10 degrees at the contact with volcanic rocks to only about 1 degree at the coast. The limestone beds are undeformed and relatively flat-lying with a nearly east-west strike. In contrast, the local limestone beds in southern Puerto Rico generally dip southeasterly at angles from 10 to 30 degrees and strike in directions that range from north to east. The limestones of the south coast are characterized by extensive faulting and by horst and graben structures.

Sedimentary rocks in southern Puerto Rico compose the Juana Diaz Formation of Oligocene and Miocene age and the Ponce Limestone of Miocene to Pliocene age (**fig. 73**). The Juana Díaz consists of clay, mudstone, sand, gravel, chalk, and limestone. Much of the limestone is chalky, except for a very pure limestone in some of the reef complexes that also has undergone some dissolution. The reported maximum thickness of the Juana Diaz is about 2,300 feet, but it appears to be highly variable from area to area. The Ponce Limestone unconformably overlies the Juana Díaz and consists of a hard light-grayish-orange fossiliferous limestone that was deposited mostly in a shallow marine environment. The exact thickness of the Ponce is unknown, but some wells drilled in the formation have penetrated more than 650 feet of limestone. The Ponce Limestone shows only minor karst features.

Alluvial deposits of Quaternary age are in the downstream reaches of the major river valleys around the periphery of Puerto Rico and in a broad area of coalescing fan-deltas along the south coast (**fig. 73**). The deposits consist of clay, silt, sand, gravel, and cobbles eroded from bedrock of the river basins. The river valleys generally are incised into volcaniclastic rocks, but the lower part of four valleys in the Guánica, Yauco, Guayanilla, and Tallaboa areas in southwestern Puerto Rico are underlain by Tertiary limestones. The maximum thickness of alluvium is about 150 feet in these four valleys. In the alluvial plain that extends from Ponce eastward to Arroyo, block faulting has produced an irregular bedrock surface, and the thicknesses of alluvium ranges from about 90 feet near the shoreline at Arroyo to about 1,000 feet near Santa Isabel. The alluvium is coarse grained at the apexes of individual fans, but becomes finer grained at coalescing edges of the fans and toward the coastline.

The highland areas of St. Croix, St. Thomas, and St. John consist mostly of volcanic, volcaniclastic and sedimentary rocks of Cretaceous and early Tertiary age. This sequence has been intruded on St. Croix by gabbro and diorite and on St. Thomas and St. John by dioritic rocks. The eastern and western highland areas of St. Croix are separated by a graben filled with marl or foraminiferal mud of the Jealousy Formation of Oligocene (?) to Miocene age conformably overlain by marl and limestone of the Kingshill Limestone of Miocene age (**fig. 73**). The Jealousy and Kingshill Limestone were mostly formed from deep ocean carbonate mud sediments. The Kingshill Limestone extends over an area of about 30 square miles and also includes some terrigenous and carbonate turbidite deposits that occur as sandy interbeds. Unnamed post-Kingshill carbonate rocks locally overlie the Kingshill. Although the extent of these rocks is poorly known, they probably lie along the southern and western coastlines.

The Hans Lollik Formation of Cretaceous age consists of breccia and tuff but is largely limited to offshore islands that lie to the north of St. Thomas. The Outer Brass Limestone is a thin-bedded limestone that contains minor beds of tuff and has an estimated maximum thickness of 600 feet. The Tutu Formation of Cretaceous age is mostly a tuffaceous conglomerate that contains a few limestone beds (**fig. 73**). The maximum thickness of the Tutu is not known, but the formation is estimated to be more than 6,000 feet thick. The Louisenhoj Formation consists mostly of volcanic breccia and tuff. The Water Island Formation consists of extrusive volcanic rocks with minor intrusive dikes and plugs. Except for the Outer Brass Limestone, which yields small amounts of water to wells, none of the formations constitute an important source of water.

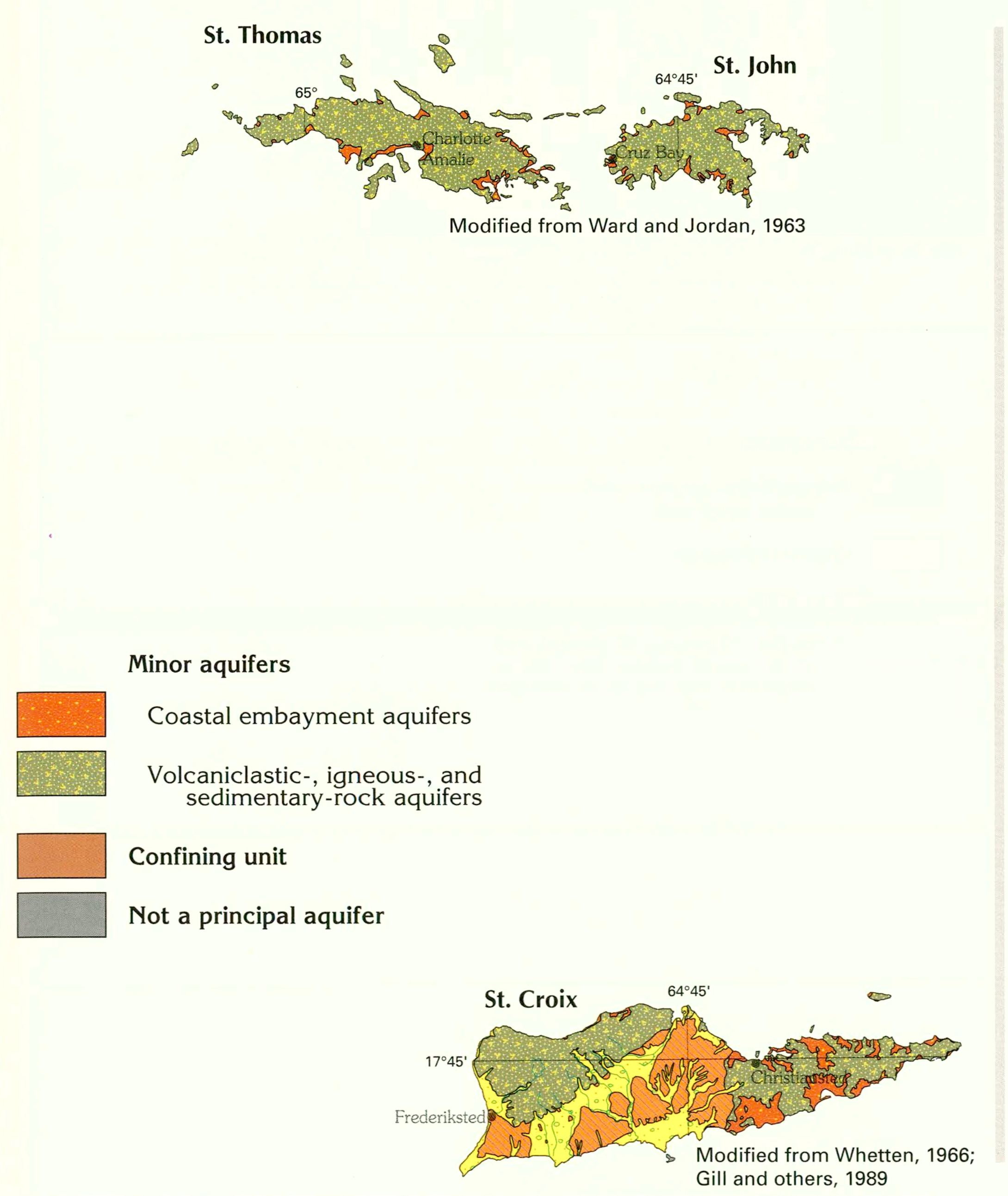
Quaternary deposits in the Virgin Islands consist of unconsolidated material that accumulated near the mouths of streams where they enter the ocean; beach deposits that surround ocean bays; and extensive alluvial fan, debris fan, and alluvial deposits of clay, silt, sand, and gravel that overlie the Kingshill and post-Kingshill Limestones on St. Croix. In the upstream reaches, the stream deposits typically consist of fine-grained alluvial material eroded from volcanic rocks in the stream basin. The stream deposits interfinger with coarser-grained beach deposits of sand and shell fragments in downstream reaches. The stream deposits typically are less than 30 to 50 feet thick and decrease in thickness to a featheredge upstream. They occupy valleys eroded into the volcanic-rock surface during an earlier period when sea level was lower than at present. The alluvial deposits generally are at an altitude of less than 100 feet above sea level.

Alluvium covers about one-fourth of the Kingshill Limestone in central St. Croix. This alluvium has an estimated maximum thickness of about 80 feet and consists mostly of clay, silt, and sand. Locally, the alluvium contains thin, discontinuous beds of sand and gravel. Silt- and clay-rich alluvial fan and debris flow deposits are usually less than 30 feet thick and are located along the northern margin of the central plain adjacent to the highlands.

Table 4. *There are four principal aquifers or aquifer systems and two minor aquifers in Puerto Rico and the Virgin Islands. Yields to wells range from less than 5 to more than 2,000 gallons per minute and well depths are commonly less than 150 feet.*

[Gómez-Gómez and Heisel, 1980; Gómez-Gómez and others, 1983; Ward and Truxes, 1964]

Aquifer	Aquifer Characteristics	Well characteristics: Depth (feet): Common range	Depth (feet): May exceed	Yield (gallons per minute): Common range	Yield (gallons per minute): May exceed	Remarks
Alluvial valley aquifers	Unconfined; interior valleys semiconfined	100–150	200	50–150	1,000	Important source of public water supply.
South Coast aquifer	Unconfined; locally semiconfined near coast	100–150	200	150–500	1,000	Approximately 90 percent of withdrawals are used for irrigation. Important source of public water supply.
North Coast Limestone aquifer system:						
Upper aquifer; Aymamón Limestone	Unconfined; locally confined near coast	150–250	300	250–500	1,000	Ground water exists as a freshwater lens over saltwater. Important source of public water supply.
Aguada (Los Puertos) Limestone	Ditto	100–200	250	100–250	1,000	Same conditions as with Ayamamón Limestone. Important source of public water supply.
Lower aquifer; Montebello Limestone Member of Cibao Formation	Unconfined at outcrop; confined at depth	100–300	2,000	50–100	500	Wells in confined or artesian zone used mainly by industry and for public supply.
Lares Limestone	Ditto	300–400	400	0–50	50	At the outcrop area, wells must be more than 300 feet deep to reach the water table. Near the coast, few wells are completed in this aquifer exclusively, except near Laguna Tortuguero, where it is the only water-producing artesian zone.
Kingshill aquifer	Unconfined	15–30	100	5–50	100	Most important aquifer in the Virgin Islands. Located on St. Croix.
Minor aquifers: Coastal embayment aquifers	Mostly confined	30–50	80	5–50	75	Minor aquifer on each of the Virgin Islands. Important only for domestic supply.
Volcaniclastic-, igneous-, and sedimentary rock aquifers	Unconfined	50–150	300	5–10	450	Important source of domestic water supply. Only source of water over large areas of Puerto Rico and the Virgin Islands.



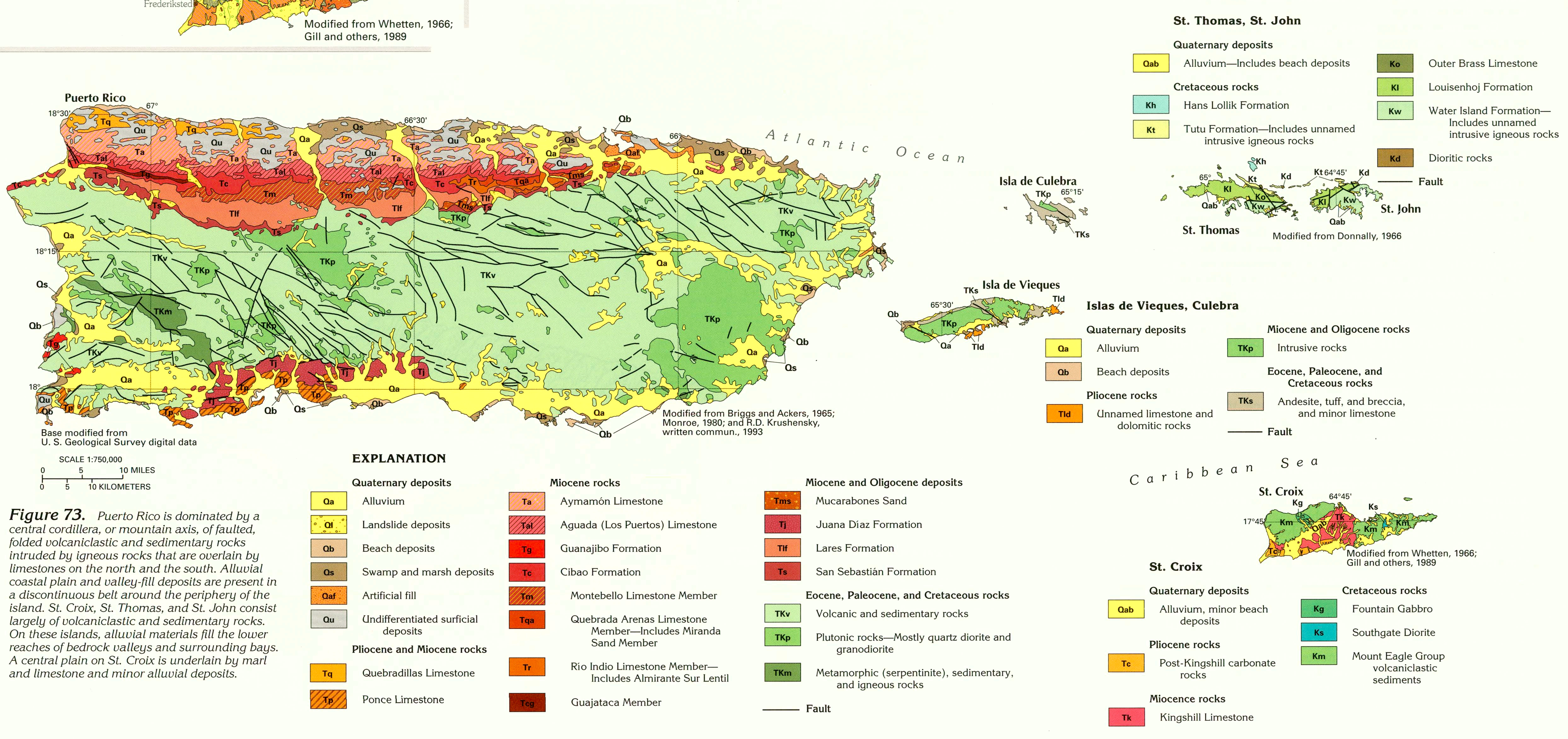


Figure 73. Puerto Rico is dominated by a central cordillera, or mountain axis, of faulted, folded volcaniclastic and sedimentary rocks intruded by igneous rocks that are overlain by limestones on the north and the south. Alluvial coastal plain and valley-fill deposits are present in a discontinuous belt around the periphery of the island. St. Croix, St. Thomas, and St. John consist largely of volcaniclastic and sedimentary rocks. On these islands, alluvial materials fill the lower reaches of bedrock valleys and surrounding bays. A central plain on St. Croix is underlain by marl and limestone and minor alluvial deposits.

VERTICAL SEQUENCE OF AQUIFERS, AQUIFER SYSTEMS, AND WELL YIELDS

Most of the aquifers and aquifer systems in Puerto Rico and the Virgin Islands are separate water-yielding units, some of which are laterally equivalent. They are discussed in descending order from geologically youngest to oldest. The vertical sequence of aquifers, aquifer systems, and confining units is shown in **figure 72**.

The alluvial valley aquifers, South Coast aquifer, and coastal embayment aquifers all consist of unconsolidated deposits of Holocene to Pleistocene age that generally overlie volcaniclastic or igneous intrusive rocks. Exceptions in Puerto Rico are alluvial valley aquifers in river valleys along the north coast, the western third of the South Coast aquifer, and four valleys in southern Puerto Rico where the unconsolidated deposits overlie limestone and some siliciclastic rocks. Alluvial valley aquifers along the east and west coasts and in the interior of Puerto Rico generally are in river valleys eroded into volcaniclastic rocks. The aquifers consist of fine to coarse sand and gravel, clay, and silt. Water in these aquifers generally is unconfined. The alluvium that composes the aquifers is local, exceeds 200 feet thick in some places, and yields of wells completed in the alluvium commonly are 50 to 150 gallons per minute.

In the limestone belt along the north coast of Puerto Rico, unconsolidated alluvial deposits of clay, silt, sand and gravel in the major river valleys are as much as 300 feet thick and yield from 50 to 150 gallons per minute to wells. These unconsolidated deposits contain water under unconfined conditions and are hydraulically connected to the parts of the underlying North Coast Limestone aquifer system that also contain water under water-table conditions. Wells that penetrate both aquifers have yields as high as 800 gallons per minute.

Four valleys in southern Puerto Rico are filled with alluvium that consists primarily of permeable sand and gravel with hydrogeologic characteristics similar to the alluvium of the adjacent South Coast aquifer. The valley-fill alluvium is as much as 150 feet thick and yields from 150 to as much as 1,000 gallons per minute to wells. The Ponce Limestone and limestone beds of the Juana Diaz Formation underlie the four alluvial valleys. The combined thickness of the Ponce Limestone and the Juana Diaz Formation may be more than 2,500 feet in the Ponce–Tallaboa area. The limestones yield some water to wells, but the water mostly is highly mineralized with dissolved-solids concentrations that range from 1,500 to as much as 6,500 milligrams per liter. These limestones generally are not considered to be aquifers; however, where the limestone is tapped by wells that penetrate the overlying alluvium, yields of such wells generally are higher than those of wells open only to the alluvium. The clastic beds of the Juana Diaz Formation are not an considered to be an aquifer because of their low hydraulic conductivity and the high dissolved-solids concentrations of the water they contain.

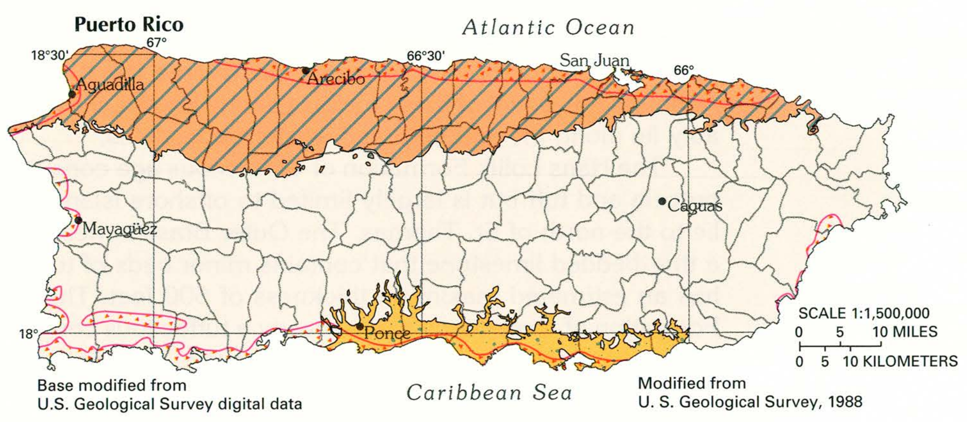
The wide band of alluvial material along the south coast of Puerto Rico is called the South Coast aquifer. The boulder- to silt-size material that composes the aquifer overlies volcanic rocks except in the western part, where it overlies the Ponce Limestone and the Juana Diaz Formation. The South Coast aquifer consists of a series of coalescing fans or fan-deltas (fans in which alluvium in the seaward part of the fan was deposited in standing water) formed by fast-flowing streams. The sediments are of Holocene to Miocene age. They are mostly coarse-grained sand and gravel at the apex of each major fan but become finer-grained near the coast and in interfluvial areas. The alluvium ranges in thickness from about 350 feet near Ponce to as much as 1,000 feet near Santa Isabel. Yields of wells completed in the South Coast aquifer commonly range from 150 to 500 gallons per minute and might exceed 1,000 gallons per minute.

Coastal embayment aquifers, which are minor, are located mostly at the mouths of small streams that flow into bays and estuaries of the Virgin Islands. Freshwater from these aquifers is used mainly for domestic supplies and as feed water for reverse osmosis desalination plants. The aquifers contain water under unconfined conditions and consist largely of sand and gravel in beach and alluvial deposits that overlie weathered bedrock. The aquifers generally are 30 to 50 feet thick. Yields to wells are only about 5 to 50 gallons per minute, and the water generally is brackish.

The North Coast Limestone aquifer system consists of an upper and a lower aquifer separated by a confining unit. The upper aquifer consists of the Aymamón and Aguada (Los Puertos) Limestones and contains water under mostly unconfined conditions. The productive upper aquifer commonly yields 100 to 500 gallons per minute to wells and might yield as much as 1,000 gallons per minute (**table 4**). However, saline water generally is present in the aquifer within a mile or two of the coast. Underlying the upper aquifer, the clayey, poorly permeable upper unnamed member of the Cibao Formation (**fig. 74**) confines the lower part of the Cibao Formation (principally the Montebello Limestone Member, but locally also the Quebrada Arenas and Rio Indio Limestone members), the underlying Lares Limestone, and the Mucarabones Sand, all of which form the lower aquifer. Where these older rocks crop out south of the confining unit in the Cibao Formation, they contain water under unconfined conditions; however, in most places, the water in the lower aquifer is confined. Yields of wells completed in the unconfined part of the lower aquifer seldom exceed 100 gallons per minute and generally are much less than yields of wells completed in the upper aquifer. However, within its confined parts, wells that tap the Montebello Limestone Member locally yield as much as 500 gallons per minute.

The Kingshill aquifer consists of the Kingshill Limestone and an overlying unnamed post-Kingshill carbonate-rock unit which form an unconfined aquifer that yields from 5 to 100 gallons per minute to wells. The aquifer consists mostly of marl and foraminiferal limestone and extends over about one-third of St. Croix. The Kingshill aquifer is overlain by and is in hydraulic connection with alluvium that infills river valleys cut into the limestone. The Kingshill aquifer is conformably underlain by the Jealousy Formation, a thick blue to blue-gray limestone and marl unit. Faulting has horizontally juxtaposed the entire sequence with volcanic rocks to the east and northwest.

The volcaniclastic-, igneous-, and sedimentary-rock aquifer is an unconfined fractured-rock aquifer that is present throughout large parts of each of the islands. Volcanic rock that has been folded, faulted, and intruded by diorite, gabbro, and other types of igneous rocks forms the central core of each of the islands and underlies all other aquifers. Fractures in these rocks store and transmit water in small quantities, and yields of wells completed in the aquifer generally range from 5 to 10 gallons per minute. The aquifer also includes small areas of limestone.



EXPLANATION

North Coast Limestone aquifer system

South Coast aquifer

Saline water

Figure 74. *In Puerto Rico, saltwater is present near the coast in aquifers in limestone and alluvial deposits.*

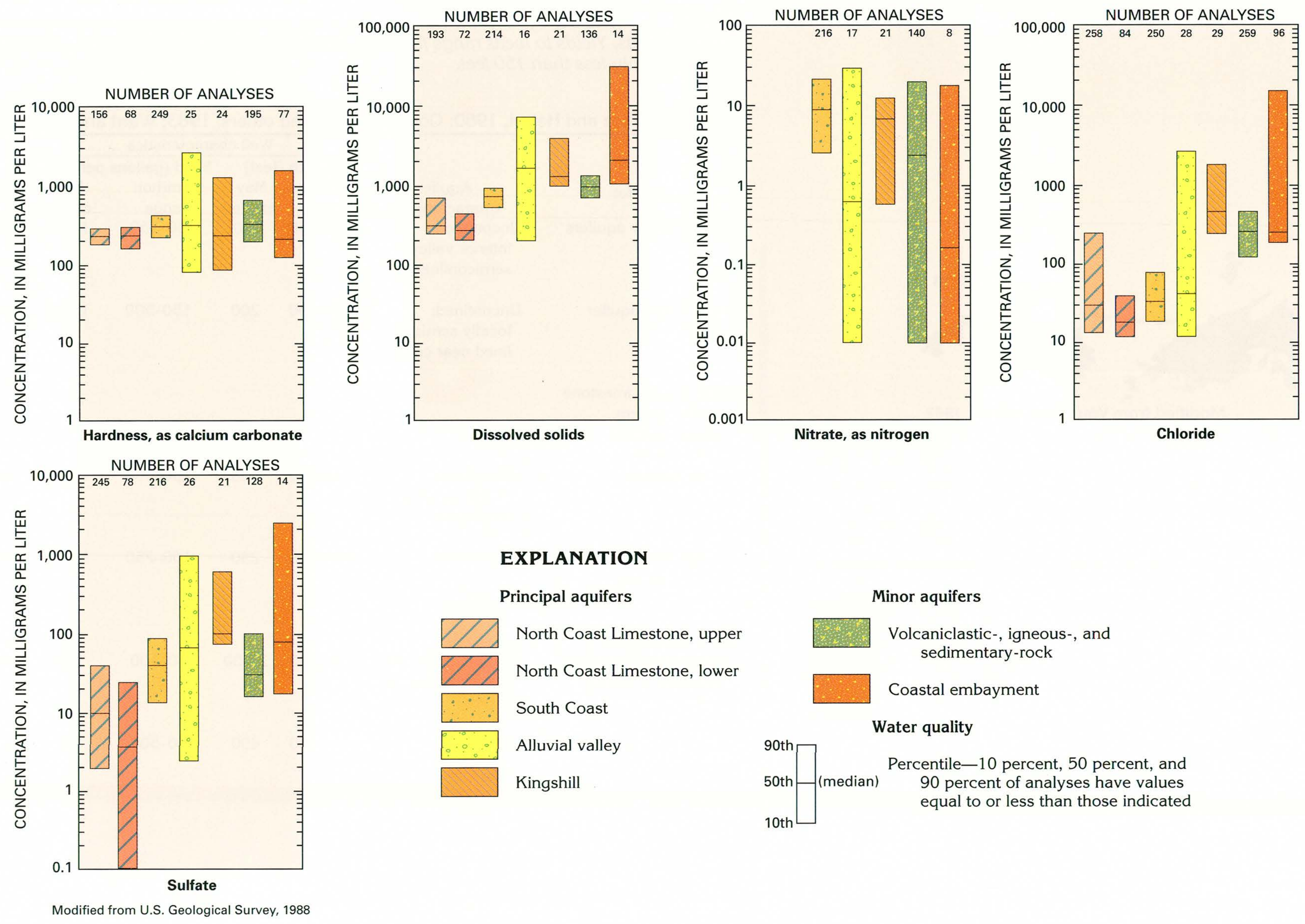


Figure 75. *The dissolved constituents in water in aquifers of Puerto Rico and the Virgin Islands have a considerable range of concentrations.*

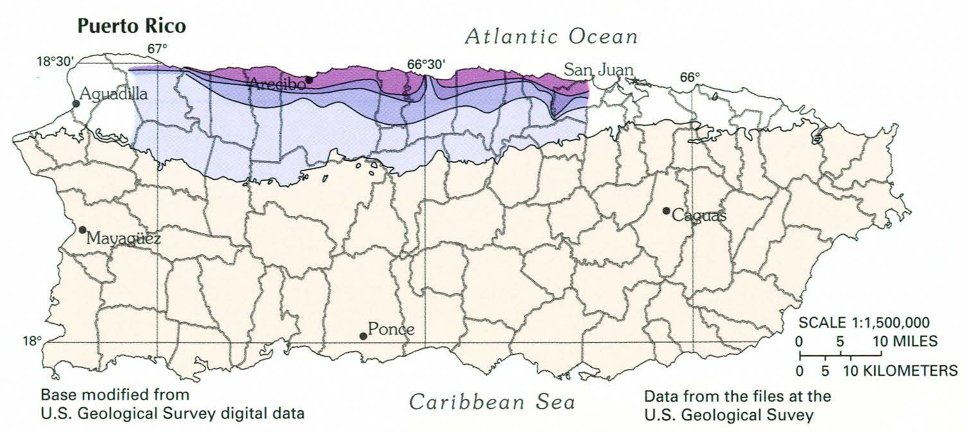
GROUND-WATER QUALITY

The natural chemical quality of water in the aquifers of Puerto Rico generally is suitable for most uses. However, saltwater (water with dissolved-solids concentrations in excess of 1,000 milligrams per liter) is present in parts of each of the aquifers except the artesian part of the lower aquifer of the North Coast Limestone aquifer system and alluvial valley aquifers in the interior of the island. The quality of the water in aquifers of the Virgin Islands generally is not suitable for many uses, including drinking water. In the Virgin Islands, water with dissolved-solids concentrations of less than 1,000 milligrams per liter is not readily available; accordingly, water with chloride concentrations of more than 500 milligrams per liter is used for drinking water.

Contamination of aquifers from accidental spills of organic chemicals and from waste disposal is a widespread problem on each of the islands and has adversely affected a resource already in short supply. Excessive withdrawals from some aquifers, especially near the coasts, also have induced the intrusion of saltwater into freshwater aquifers in some places. In Puerto Rico, saltwater is present in the upper aquifer of the North Coast Limestone aquifer system and in alluvial aquifers adjacent to the ocean (**fig. 74**).

The chemical quality of water from the several aquifers of Puerto Rico and the Virgin Islands shows a considerable range in the concentration of principal ions, as illustrated in **figure 75**. In general, water contained within Caribbean Island aquifers tends to be more mineralized as the water moves downgradient toward the sea (**fig. 76**). Water in all the aquifers generally is a calcium magnesium bicarbonate type; concentrations of calcium and bicarbonate ions are sufficient to cause the water to be very hard. In some aquifers that are connected to the ocean, the freshwater head within the aquifers is in equilibrium with the saltwater head from the ocean (**fig. 77**). The freshwater-saltwater interface in the permeable parts of the alluvium generally is a short distance inland from the coast and is roughly wedge-shaped; the saltwater extends farther inland in the underlying upper aquifer of the North Coast Limestone aquifer system. Near the interface, the calcium magnesium bicarbonate freshwater typically changes to a calcium chloride type and then to a sodium chloride type over a short distance.

Distinct chemical environments have been recognized in each of the aquifers and are determined by a combination of aquifer mineralogy, permeability, and position in the ground-water-flow system. Generally in Puerto Rico, the least mineralized water, as indicated by dissolved-solids concentrations (**fig. 75**), is present in the lower aquifer of the North Coast Limestone aquifer system; water from the upper aquifer of this system, from the South Coast aquifer, and from the volcaniclastic-, igneous-, and sedimentary-rock aquifers is slightly more mineralized. Mineralization is successively greater in water from the Kingshill, the alluvial valley, and the coastal embayment aquifers. Mineralization of water in the aquifers of the Virgin Islands generally is greater than that of water in aquifers in Puerto Rico; however, the alluvial valley aquifers of Puerto Rico generally exhibit the largest range of concentrations of dissolved solids.



EXPLANATION

Dissolved-solids concentrations, in milligrams per liter, in the North Coast Limestone aquifer system

300

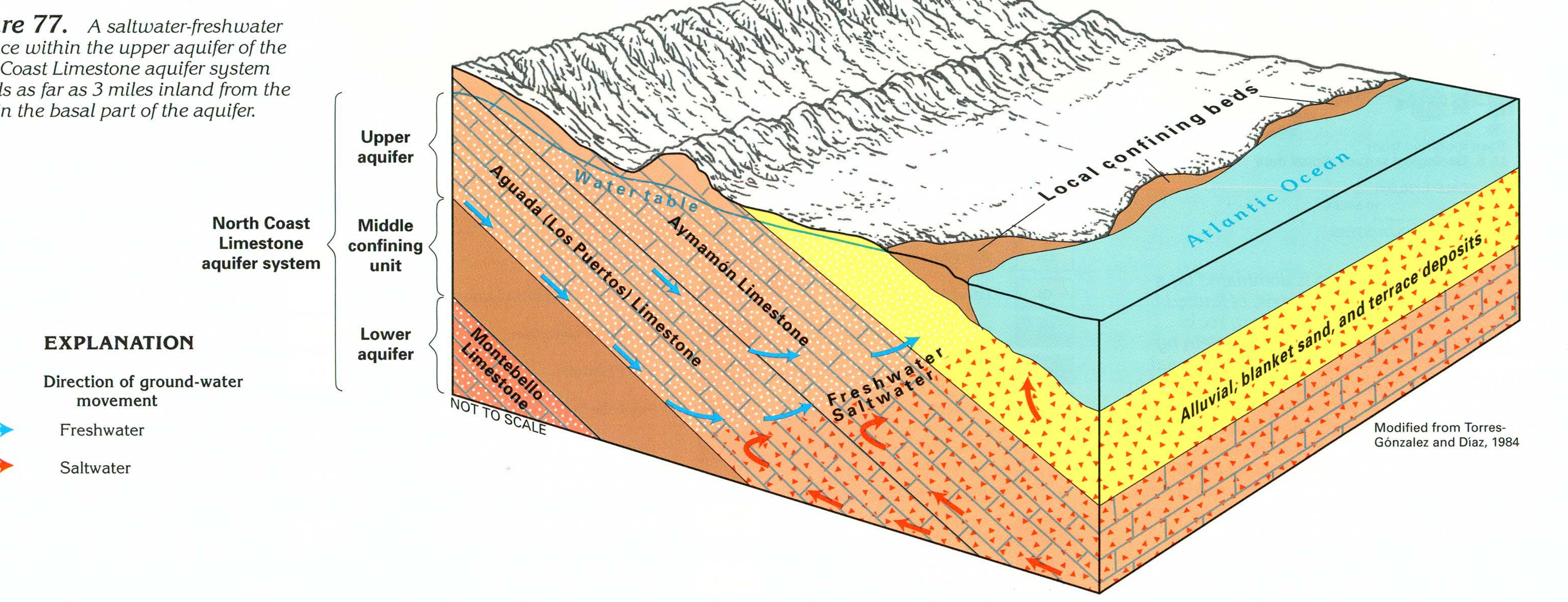
500

1,000

Insufficient data

Figure 76. *Mineralization of water in the North Coast Limestone aquifer system aquifers generally increases as the water moves down the hydraulic gradient toward the sea. The dissolved-solids concentrations mapped here increase as mineralization increases.*

Figure 77. *A saltwater-freshwater interface within the upper aquifer of the North Coast Limestone aquifer system extends as far as 3 miles inland from the coast in the basal part of the aquifer.*



Alluvial valley aquifers

FRESH GROUND-WATER WITHDRAWALS

Total freshwater withdrawals from all sources in Puerto Rico and the Virgin Islands were about 605 million gallons per day during 1985 and supplied a population of about 3.5 million people. Of this total, ground-water withdrawals were about 29 percent, or 176.4 million gallons per day. In Puerto Rico, ground-water withdrawals during 1985 were about 175 million gallons per day, of which about 48 percent (about 84 million gallons per day) was used for public supply, largely in urban areas. Urban areas in the Virgin Islands depend, for the most part, on desalination of seawater for all uses. Ground-water withdrawals were about 1.4 million gallons per day in the Virgin Islands during 1985.

Fresh ground-water withdrawals in Puerto Rico during 1985, shown in **figure 78** by municipio (generally equivalent to a county), were concentrated in areas underlain by the principal aquifers. These areas also contain most of the population and industrial centers along the northern and southern coasts. The principal urban area of San Juan is supplied mostly by surface water. In the large rural area of the central mountains, on the eastern and western coasts, and on the offshore islands, ground-water use is minimal because of sparse population and the lack of productive aquifers. Similarly, in the Virgin Islands, the limited areal extent and low productivity of the aquifers, and the generally marginal chemical quality of the ground water available have resulted in the use of desalinated seawater as the principal source of potable water.

During 1985, the South Coast aquifer was the most heavily used of the principal aquifers (**fig. 79**). Fresh ground-water withdrawals from this aquifer amounted to about 74 million gallons per day, or about 42 percent of total withdrawals in the islands. About 66 million gallons per day, or about 38 percent, was withdrawn from the North Coast Limestone aquifer system. A much smaller, but still significant, amount of about 24 million gallons per day, or about 14 percent of the total, was withdrawn from alluvial valley aquifers in Puerto Rico. The volcaniclastic-, igneous-, and sedimentary-rock aquifers, which underlie the largest area of the islands, also produced a significant amount of water (about 11 million gallons per day, or about 6 percent of total withdrawals). Withdrawals from the Kingshill aquifer on St. Croix were about 1 million gallons per day, or only about 0.6 percent of total withdrawals. Small amounts of water were withdrawn from the coastal embayment aquifers in the Virgin Islands.

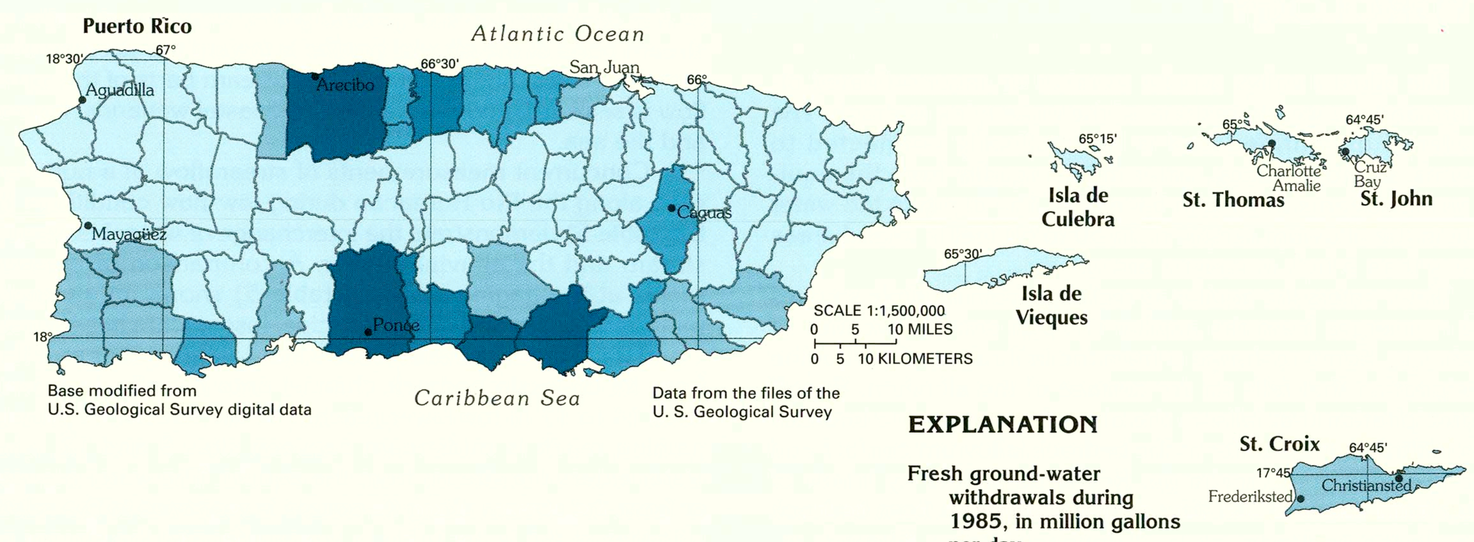


Figure 78. *Fresh ground-water withdrawals, by municipio, in Puerto Rico during 1985 were concentrated in population and industrial centers in areas underlain by productive aquifers along the north and south coasts. High demand for potable water and the absence of areally extensive productive freshwater aquifers in the Virgin Islands has led to the use of desalinated seawater as the principal source of potable water.*

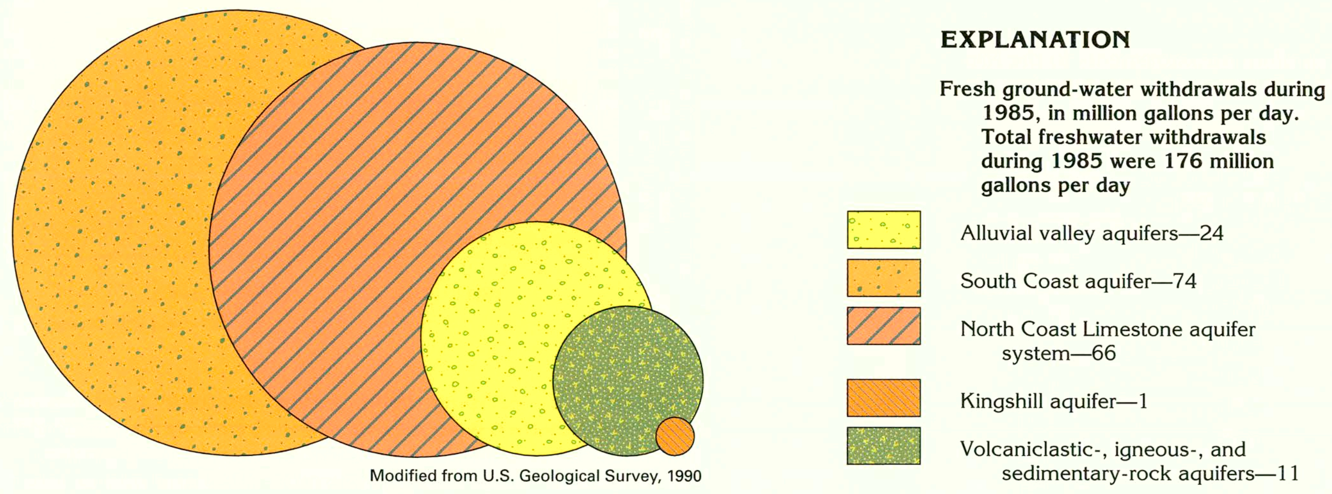


Figure 79. *The North Coast Limestone aquifer system and South Coast aquifer were the most heavily used of the principal aquifers and produced similar amounts of water during 1985. These two important aquifers, along with the alluvial valley and coastal embayment aquifers, produced about 93 percent of the 176 million gallons per day of ground water withdrawn in Puerto Rico and the U.S. Virgin Islands during 1985.*

GROUND-WATER PROBLEMS

Water availability and chemical quality are the principal ground-water problems in Puerto Rico and the U.S. Virgin Islands. The estimated maximum withdrawal rate of fresh ground water in Puerto Rico is 440 million gallons per day; withdrawals during 1985 were about 175 million gallons per day, and projected development of agriculture, industry, and domestic facilities might require an additional 100 million gallons per day by the year 2000. Ground water generally is available in large quantities only on the periphery of the island and especially along the northern and southern coasts. On the Virgin Islands, freshwater aquifers are limited in extent and ground water supplies only about 10 percent of the total water use. The Kingshill aquifer on St. Croix is the most productive aquifer, with a yield of about 1 million gallons per day.

Ground-water quality problems result from point sources of contamination and from saltwater intrusion. There are more than 100 solid-waste disposal sites in Puerto Rico, as well as an unknown number of wells used for the disposal of industrial wastes. These sources of pollution, coupled with the presence of karst features such as sinkholes that breach limestone aquifers and the fracture system of the volcaniclastic-, igneous-, and sedimentary-rock aquifers, make these aquifers extremely susceptible to contamination and indicate the widespread potential for ground-water contamination. In a recent reconnaissance study of ground-water quality in Puerto Rico, a variety of organic pollutants were detected. In places, the organic compounds were present in concentrations that exceed secondary maximum contaminant levels established by the U.S. Environmental Protection Agency. Six water-supply wells have been abandoned because of unacceptable levels of organic pollutants, and water from 13 other wells is being closely monitored. In St. Thomas, productive wells in the volcaniclastic-, igneous-, and sedimentary-rock aquifers were shut down because of contamination from oil and other organic compounds.

The proximity or direct connection of aquifers to the sea in Puerto Rico and the Virgin Islands makes upconing of saltwater as a result of excessive withdrawals, or saltwater intrusion as a result of decreased recharge during dry periods, a perpetual concern. Large concentrations of sodium and chloride in ground water can result from salt that enters the shallow aquifers from windborne sea spray, which is a ubiquitous problem near the coasts.

INTRODUCTION

River alluvium that fills bedrock valleys located in the interior and coastal areas of Puerto Rico (**fig. 80**) forms small aquifers that are locally important sources of water for industrial, municipal, and domestic supplies. The aquifers, which characteristically fill valleys incised into volcaniclastic, igneous intrusive, or limestone bedrock, generally are less than 110 to 150 square miles in area and extend over less than 50 percent of their respective drainage basins. They typically supply less than 15 percent of the total water used in the drainage basin.

Most of the alluvial valley aquifers are located in the generally flat-lying coastal areas of streams that originate on the steep-sided Cordillera Central and other mountain ranges. The seaward extent of these aquifers is bounded in the subsurface by a freshwater-saltwater interface and on the surface by brackish-water wetlands or lagoons. The maximum thickness of the aquifers is about 270 feet on the east coast, 300 feet on the west coast, 300 feet on the north coast, and about 150 feet on the southwestern coast. In the Caguas–Gurabo–Juncos area of the east-central interior (**fig. 80**), the aquifers are less than 150 feet thick. Aquifer materials are predominantly sand and gravel interlayered with clay and silt.

The natural chemical quality of water in the alluvial valley aquifers generally is suitable for most uses. However, excessive concentrations of dissolved iron and manganese are a problem in the east coast area. Contamination of the aquifers by pollutants that result from human activities is a universal concern because of the high population density.

Although each alluvial aquifer is unique in dimension, hydraulic characteristics, hydrogeology, and water quality, the aquifers generally share a similar setting, origin, composition, and hydrologic character. Thus, because they are too numerous to describe in detail, the aquifer in the Humacao–Naguabo area (***I*** **on fig. 80**) is presented as a characteristic example of the alluvial valley aquifers.

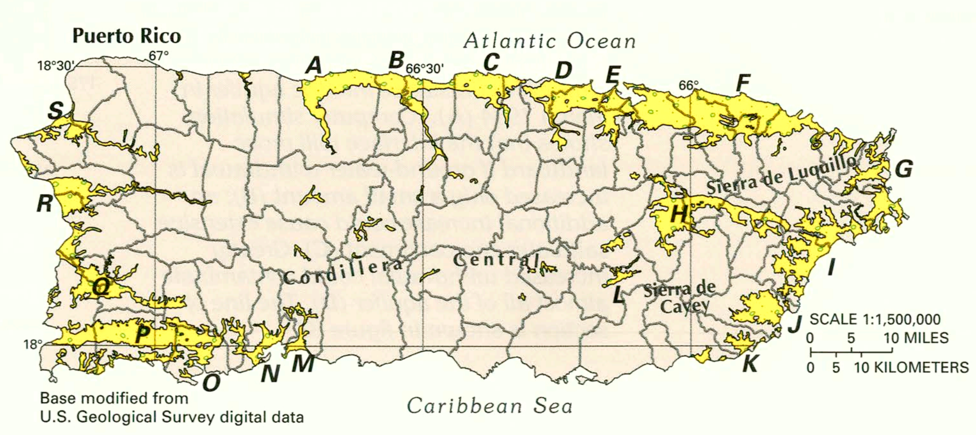


Figure 80. *Alluvium that fills valleys incised into bedrock in the interior and coastal areas of Puerto Rico forms small aquifers that are locally important for industrial, municipal, and domestic supplies.*

GENERAL SETTING

The Humacao–Naguabo area, which is made up of six distinct drainage basins that total about 90 square miles in area, is located in the southeastern part of the east coast of Puerto Rico (**fig. 80**). The principal streams that drain the area are the Rio Humacao and the Rio Blanco (**fig. 81**), which originate in the eastern foothills of the Sierra de Cayey and the Sierra de Luquillo, respectively. The drainage basins are divided by sharp, steeply sloping ridges that range in altitude from 300 to 500 feet above mean sea level.

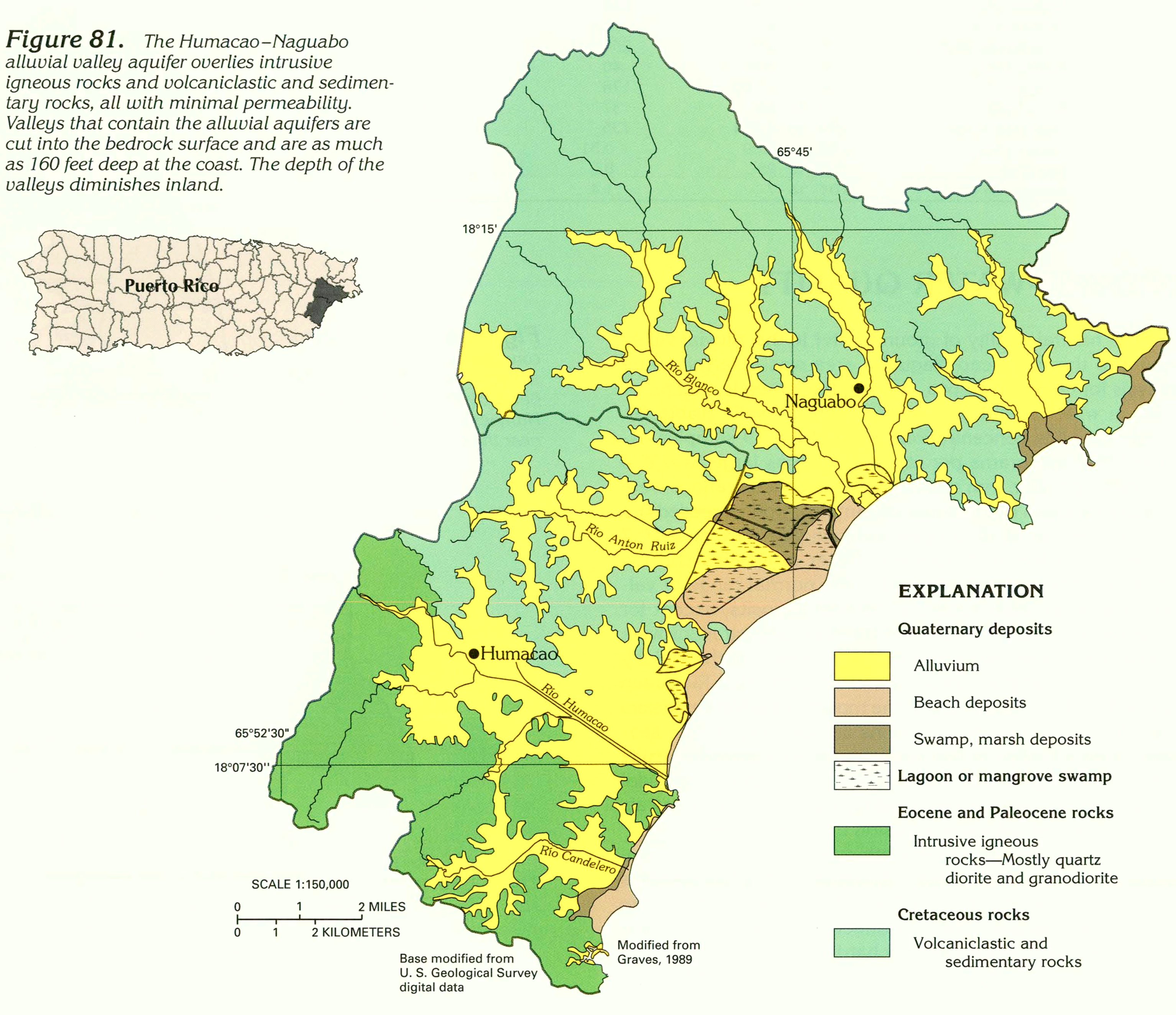
The alluvial valley aquifer, which extends over approximately 40 percent of the area of the drainage basins, is widest in the broad, flat valley floor near the coast and extends up the river valleys (**fig. 81**). The top of the alluvium ranges in altitude from sea level to about 160 feet above mean sea level. A mangrove swamp is present along the mouth of the Rio Antón Ruiz, and two brackish-water lagoons are in depressions along the coast.

The Humacao–Naguabo area recently has undergone rapid development of light industry that has contributed to a significant population growth and placed large demands on local water supplies. Most of the demand (93 percent) has been met from surface-water sources. Total freshwater use in the area during 1985 was 14.6 million gallons per day, of which fresh ground-water withdrawals were only 0.93 million gallons per day.

GEOLOGY

Extensively faulted and fractured volcaniclastic rocks of Cretaceous age and intrusive igneous rocks of Tertiary age underlie the alluvial aquifer (**fig. 81**). The plutonic rocks consist mostly of granodiorite and quartz diorite; the volcanic rocks are a mixture of sandstone, conglomerate, tuff, breccia, and andesitic lava flows. A weathered zone is characteristically developed on the bedrock. The thickness of this zone is 20 feet or more under the alluvial deposits and as much as 40 feet in bedrock outcrop areas. Where it is covered by alluvium, the weathered zone forms part of the aquifer. Alluvium-filled valleys, which were eroded into the bedrock along fault traces at a time when sea level was much lower than at present, underlie the principal streams. The bedrock valley near the Rio Humacao is incised to a depth of about 160 feet below mean sea level at the coast but is less deeply incised inland. Thus, the aquifer, which consists of poorly sorted sand, silt, and clay, forms a wedge that ranges from about 160 feet thick at the coast to a featheredge inland.

Figure 81. *The Humacao–Naguabo alluvial valley aquifer overlies intrusive igneous rocks and volcaniclastic and sedimentary rocks, all with minimal permeability. Valleys that contain the alluvial aquifers are cut into the bedrock surface and are as much as 160 feet deep at the coast. The depth of the valleys diminishes inland.*



HYDROLOGY

The alluvial valley aquifer consists of unconsolidated alluvium and the weathered part of the underlying bedrock. The aquifer is unconfined and is hydraulically connected to streams. In most places, water moves readily from the aquifer to the streams to sustain base flow. The depth to the water table in the alluvium ranges from 50 to 60 feet in inland areas to less than 5 feet in coastal areas.

Water enters the aquifer as recharge from multiple sources and reemerges from the aquifer through several avenues of discharge. Some recharge is from the infiltration of part of the precipitation that falls on the surface of the alluvium. Runoff of precipitation that falls on the almost impermeable bedrock hills infiltrates the aquifer at the bedrock/alluvium contact and also provides some recharge. Recharge also is by inflow of water from streams that flow onto the alluvium from bedrock areas in the upstream parts of drainage basins. Streams recharge the aquifer principally in upstream areas as they cross the alluvium, where stream levels are higher than water levels in the aquifer. The aquifer discharges by seepage to streams, wetlands, and lagoons; by withdrawals from wells; by evapotranspiration in areas where the water table is very shallow; and by seepage to the ocean.

The water table in the alluvial aquifer slopes seaward from an altitude of about 80 to 100 feet above sea level in the upstream part of each of the valleys to sea level at the coast (**fig. 82**). Thus, the hydraulic gradient is seaward and ground-water movement generally is toward the sea. However, in each of the drainage basins, ground-water movement in the upstream parts of the alluvial aquifer is toward the streams where the water is discharged. In the downstream parts of the aquifer, flow is seaward, and discharge is to coastal wetlands, lagoons, and the sea.

Concurrent measurements of streamflow at a number of sites along the Rio Humacao during low-flow conditions (**fig. 82; table 5**) demonstrate the interchange of water between the stream and the alluvial aquifer. A comparison of measurements at the gaging stations (**table 5**) shows an alternating pattern of losses and gains; principal losses were between sites 1 and 2 where the stream loses water to the aquifer as it flows from its up-basin bedrock channel onto the alluvium and at sites 14 to 17 in the lower reaches of the stream. A principal gaining reach is midstream between sites 9 and 12, where water enters the stream from the aquifer. The water moves to or from the stream along its course in response to the relative altitudes of the water table in the aquifer and the stream surface. Where the water level in the aquifer is higher than that in the stream, water moves from the aquifer to the stream; movement is reversed where the relative altitudes of the stream surface and water table are reversed.

The exchange of water between a stream and the alluvial aquifer can change as hydrologic conditions change (**fig. 83**). Throughout most of the year, the water table is higher in Arroyo well 1, which is near the Rio Blanco (**fig. 82**), than the water level in the stream, and water moves from the aquifer to the stream. However, during periods of intense rainfall, as indicated by sharp peaks on the graph in **figure 83**, the stream level and the water table rise. In some instances (for example, early November 1983 and early June 1984), the stream level rises until it is temporarily higher than the water table. Under these conditions, the normal direction of water movement is reversed, and water moves into the aquifer from the stream. Note that ground-water levels in this area fluctuate as much as 8 feet and that stream levels fluctuate as much as 12 feet (**fig. 83**).

A freshwater-saltwater interface is present at the coast in the upper part of the alluvial aquifer. In the deeper parts of the aquifer, the interface extends inland as a wedge-shaped body of saltwater. The approximate position of the interface in March 1984 is shown in **figure 84*A***. The interface is maintained because of the difference in the density of freshwater and saltwater. Because the freshwater is lighter, a 41-foot column of freshwater is necessary to balance a 40-foot column of seawater. As a result, for each foot of freshwater above sea level, there is a 40-foot column of freshwater below sea level. Under natural (March 1984) conditions, fresh ground water moves toward and up the sloping interface to discharge to the sea floor. The position of the interface is maintained by an equilibrium of freshwater flow toward the sea and saltwater flow toward the land. Saltwater movement is constant because of constant sea level; however, excessive ground-water withdrawals would lower the column of freshwater, reduce freshwater flow, and cause the interface to move landward (**fig. 84*B***), thus contaminating the aquifer with saltwater. Progressive landward migration of the interface would occur if successively larger quantities of water are withdrawn from the aquifer. If withdrawals in the Rio Humacao Valley were increased 0.72 million gallons per day beyond 1984 withdrawals (**fig. 84*C***), computer simulation indicates that excessive saltwater encroachment would occur. If 1984 withdrawals were increased by 1.08 million gallons per day, simulation indicates that saltwater would occupy almost all of the aquifer (**fig. 84*D***).

HYDRAULIC PROPERTIES

The availability of ground water depends on the ability of an aquifer to store, transmit, and release water to wells; this ability can be described by the hydraulic properties of the aquifer. Transmissivity is a measure of the ability of an aquifer to transmit water. The greater the transmissivity, the more water the aquifer can yield. The storage coefficient of an aquifer is a measure of the volume of water an aquifer can release from or take into storage per unit surface area per unit change in hydraulic head. Transmissivity values determined from aquifer tests of the alluvial valley aquifer in the Humacao–Naguabo area range from 200 to 2,000 feet squared per day, which are relatively low values. The storage coefficient of the aquifer is about 0.02, which is a low value for an unconfined aquifer. With these hydraulic properties, well yields are not expected to be more than 30 to 100 gallons per minute.

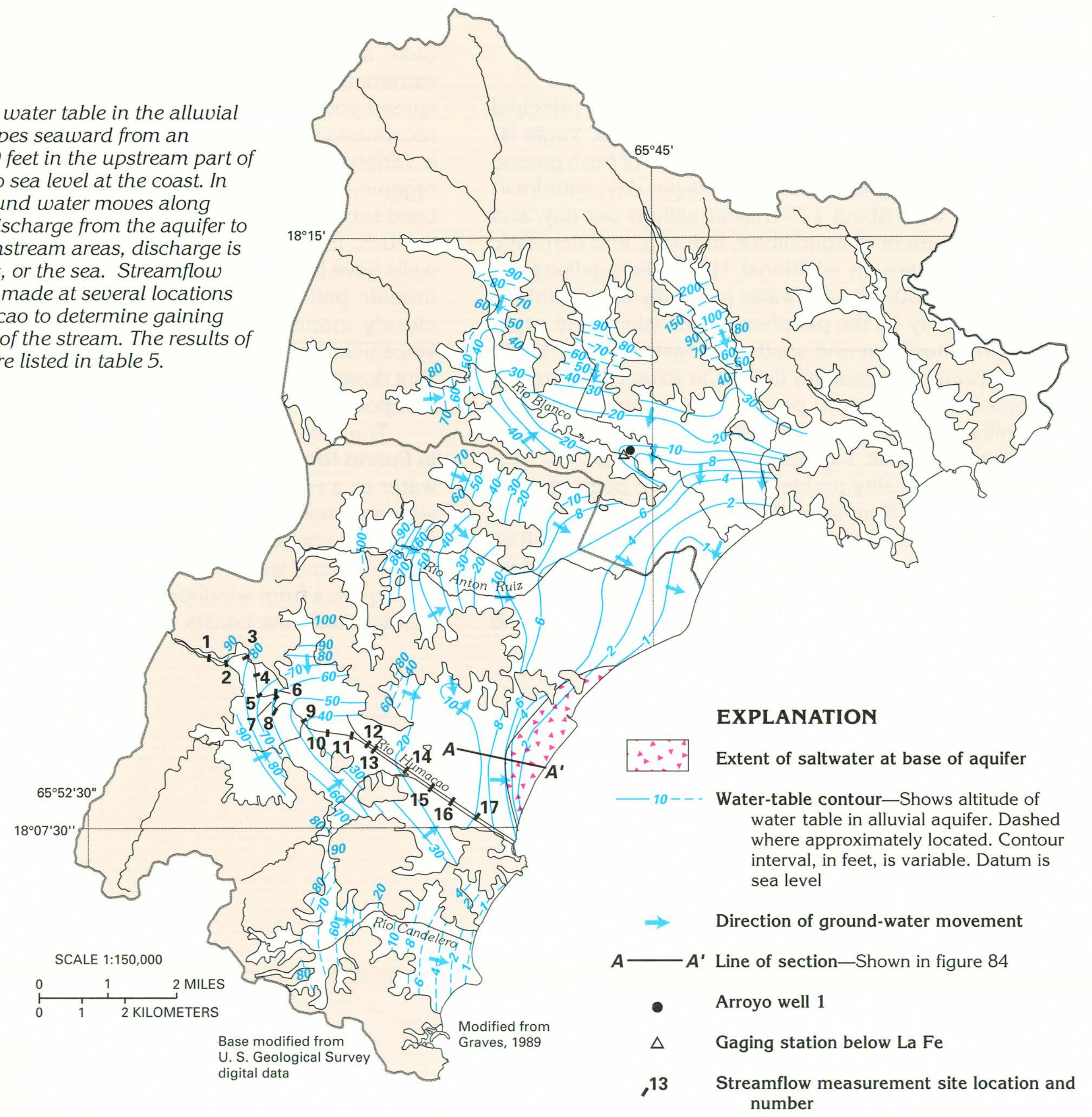


Figure 82. *The water table in the alluvial aquifer generally slopes seaward from an altitude of about 100 feet in the upstream part of each of the valleys to sea level at the coast. In upstream areas, ground water moves along short flowpaths to discharge from the aquifer to the streams. In downstream areas, discharge is to wetlands, lagoons, or the sea. Streamflow measurements were made at several locations along the Rio Humacao to determine gaining and losing stretches of the stream. The results of the measurements are listed in table 5.*

Table 5. *Streamflow measurements in the Rio Humacao indicate gaining and losing stretches of the stream.*

[Modified from Graves, 1980; ft^3/s, cubic feet per second; measurements made April 3, 1984]

Stream measurement site (see fig. 82)	Measured discharge (ft^3/s)	Stream gains (+) or losses (–) between sites (ft^3/s)
1	6.90	
		–1.53
2	5.37	
		+1.18
3	6.55	
		–.21
4	6.34	
		+.32
5	6.66	
		+.88
7	7.54	
		–.03
9	7.51	
		+5.65
10	13.16	
		+.60
11	13.76	
		+2.98
12	16.74	
		–.53
13	16.21	
		+2.00
14	18.21	
		–.45
15	17.76	
		–.51
16	17.25	
		–1.34
17	15.91	

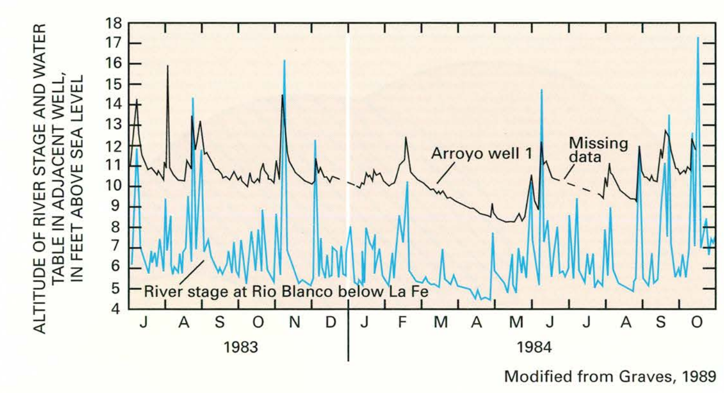


Figure 83. *Although the altitude of the water level in a well near the Rio Blanco is above that of the stream during most of the year, the relative altitudes can reverse during high streamflow periods such as those in early November 1983 and mid-October 1984. Such reversals temporarily reverse the normal movement of water from the aquifer toward the stream. The locations of the well and stream measuring station are shown in figure 82.*

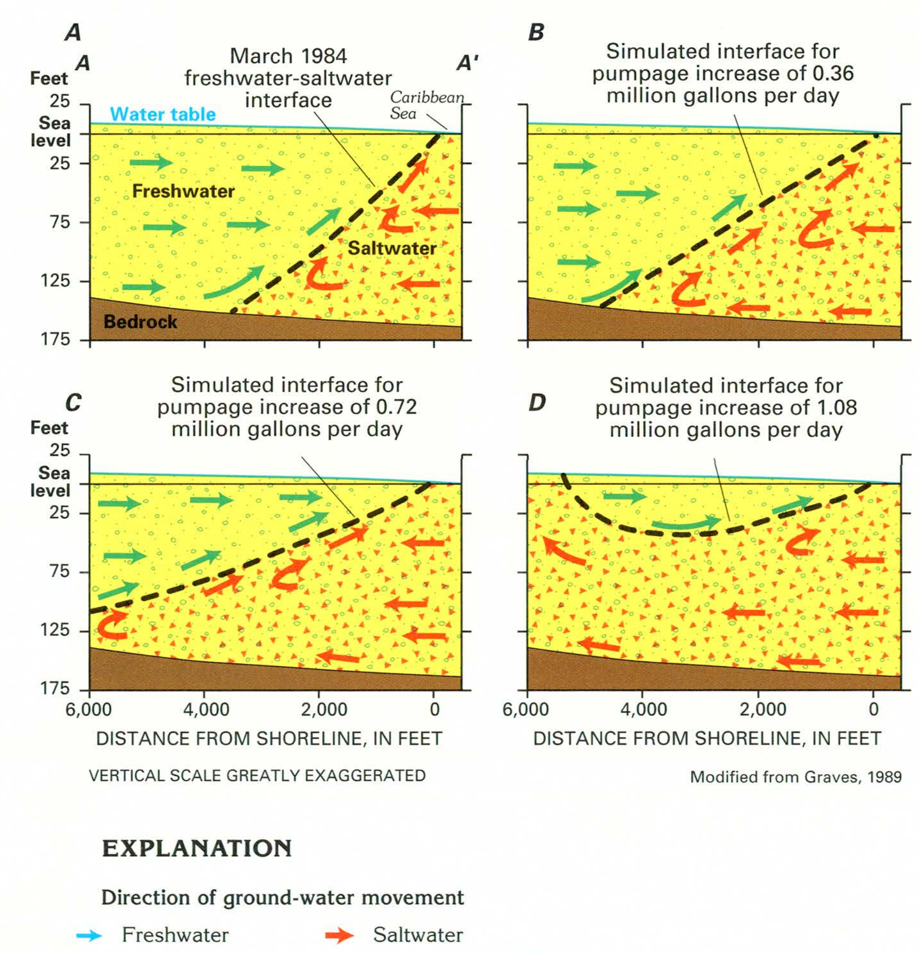


Figure 84. *Fresh ground water that moves seaward meets saltwater that moves landward and comes to equilibrium as a freshwater-saltwater interface in the Rio Humacao Valley. Saltwater extended only a short distance into the aquifer in March 1984 (**A**). Computer simulation shows that the interface will move landward if ground-water withdrawal is increased only a small amount (**B**); an additional increase could cause extensive saltwater encroachment (**C**). Greatly increased withdrawal could contaminate almost all of the aquifer (**D**). The line of section is shown in figure 82.*

Table 6. *Ground water in the Humacao–Naguabo area is very hard and locally contains large concentrations of sodium, chloride, iron, and manganese.*

[Data from Graves, 1980; concentrations in milligrams per liter, unless otherwise specified]

Constituent	Range	Average	Number of samples
pH (standard units)	6.1 to 7.7	6.8 median	19
Hardness, as $CaCO_3$	80 to 1,100	98	19
Calcium (Ca)	13 to 150	55	19
Magnesium (Mg)	8.2 to 180	33	19
Sodium (Na)	17 to 1,600	150	19
Potassium (K)	0.2 to 60	4.8	19
Bicarbonate (HCO_3)	126 to 475	254	19
Sulfate (SO_4)	3.6 to 200	40	19
Chloride (Cl)	18 to 1,700	178	19
Silica (SiO_2)	13 to 65	37	19
Dissolved solids	259 to 4,274	735	19
Nitrate (NO_3)	0.08 to 2.09	0.51	19
Iron (Fe)	0.1 to 25	8.2	11
Manganese (Mn)	0.01 to 7	1.4	8

GROUND-WATER QUALITY

The natural quality of ground water in the alluvial valley aquifer in the Humacao-Naguabo area was determined by analysis for common anions, cations, trace metals, and properties in water samples collected from 19 wells (**table 6**). Dissolved-solids concentrations in 10 of the 19 samples exceeded 500 milligrams per liter and were as large as 4,274 milligrams per liter. Iron and manganese concentrations were similarly elevated in a number of samples; iron exceeded 0.3 milligram per liter in 10 samples and manganese exceeded 0.2 milligram per liter in 8 samples. Other properties and ion concentrations generally are within the normal range of values for a water-table aquifer in alluvial deposits, except for sodium and chloride. Sodium and chloride concentrations were large in water from two areas near the coast—in the vicinity of the coastal mangrove swamps at the mouth of the Rio Antón Ruiz and the Rio Blanco, and at the mouth of the Rio Candelero (**fig. 85**). The large concentrations are probably due to seawater contamination of the aquifer, which apparently results from the seepage of seawater into the aquifer from large tidal fluctuations in coastal areas. Fresh ground-water withdrawals have not caused saltwater intrusion into the aquifer.

The large concentrations of sodium and chloride in the 19 water samples (**table 6**) result from a few samples that have very large concentrations of these ions. Water in the alluvial valley aquifer, where unaffected by saltwater, generally can be characterized as very hard and as a calcium magnesium bicarbonate type with excessive local concentrations of iron and manganese.

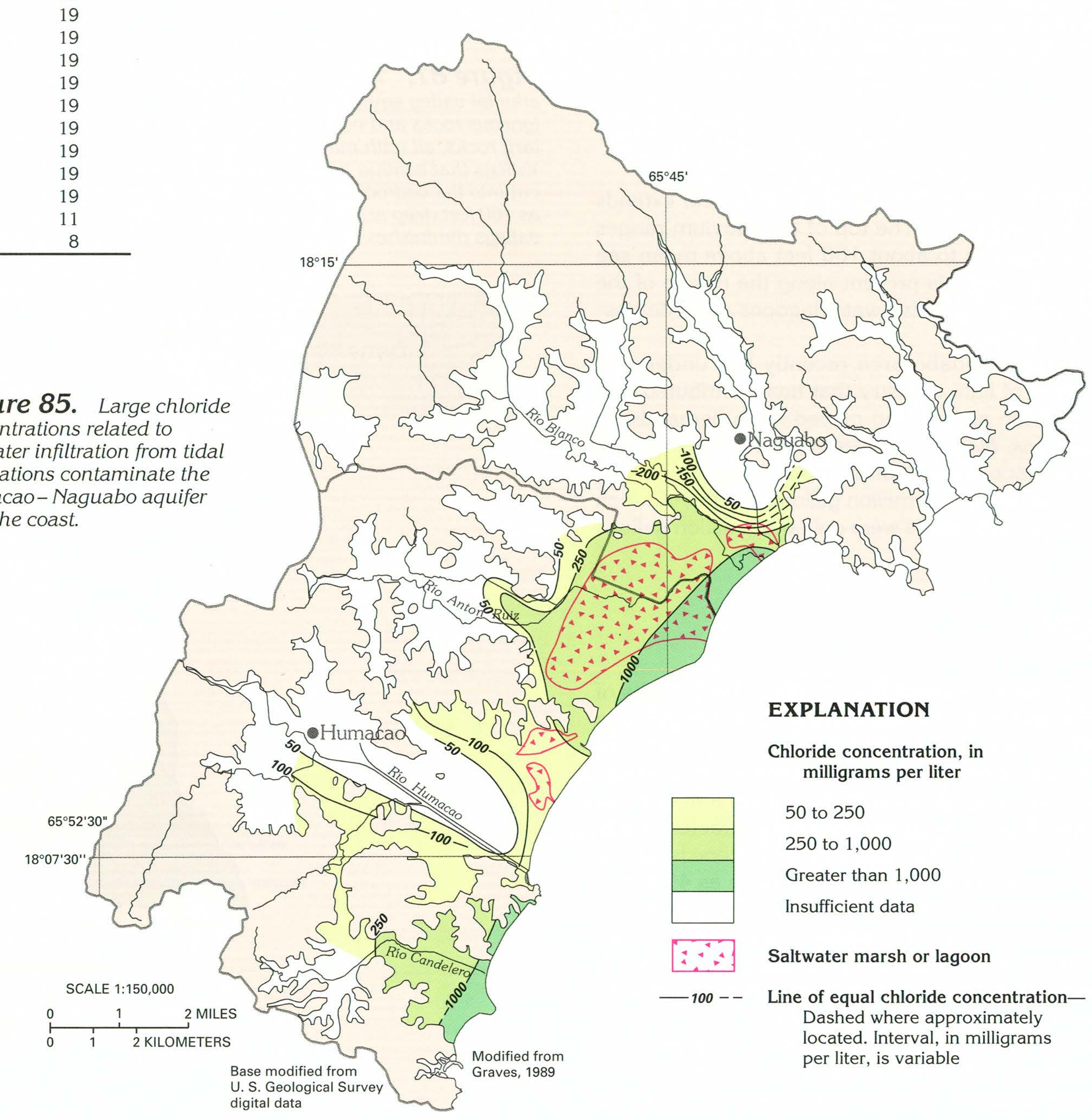


Figure 85. *Large chloride concentrations related to seawater infiltration from tidal fluctuations contaminate the Humacao–Naguabo aquifer near the coast.*

FRESH GROUND-WATER WITHDRAWALS

Fresh ground-water withdrawals from alluvial aquifers throughout Puerto Rico during 1985 were about 24 million gallons per day, or nearly 14 percent of the total ground water withdrawn on the island. Withdrawals from the alluvial valley aquifer in the Humacao–Naguabo area were 0.93 million gallons per day during 1985. Only one public supply well withdrew water from the aquifer in 1985; nine other public supply wells were abandoned because of excessive concentrations of iron and manganese. Many wells that withdraw water for other uses have been abandoned for similar reasons. Although many industrial wells have been constructed, the well yields are often inadequate and the industries continue to depend largely on public supply systems for water.

Nearly 68 percent of the ground water withdrawn in the Humacao–Naguabo area was used for industrial supply during 1985 (**fig. 86**). The remaining withdrawals were roughly equally divided between public-supply, domestic, and agricultural uses. No water was withdrawn for commercial, mining, or thermoelectric power uses.

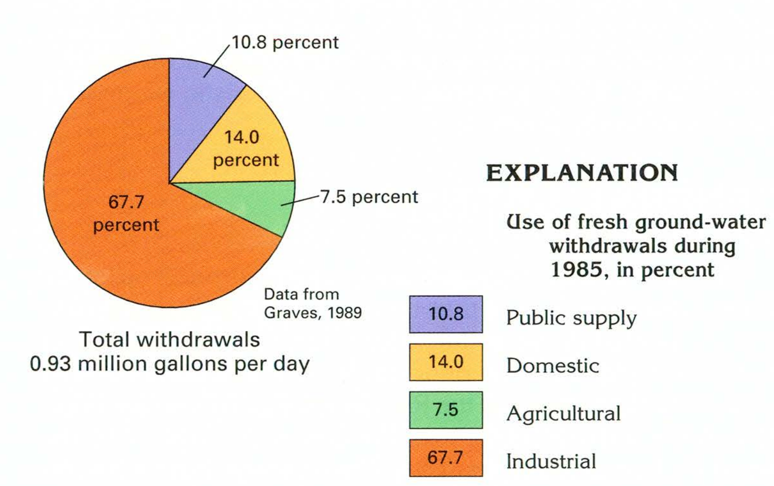


Figure 86. *About two-thirds of the freshwater withdrawn from the alluvial valley aquifer in the Humacao–Naguabo area during 1985 was used for industrial purposes.*

South Coast aquifer

INTRODUCTION

The South Coast aquifer is an alluvial aquifer that underlies the broad coastal plain that extends from Patillas westward to Ponce in southern Puerto Rico (**fig. 87**). The aquifer averages about 4 to 5 miles in width and extends east-west for about 40 miles. The alluvium that composes the aquifer was deposited mostly in a number of coalescing fan-deltas that built seaward from the mouths of major streams (**fig. 88**).

The south coastal plain of Puerto Rico is, and historically has been, an important agricultural area and in recent years has been a growing industrial area. Irrigation structures, including an extensive network of canals and reservoirs, were constructed as early as the late 1800's between the Rio Jacaquas and Ponce, and smaller structures for diversion of base flow of streams were built in the areas of Santa Isabel, Salinas, and Guayama. In 1914 the first large-scale surface-water irrigation system was completed and included the Canal de Patillas and the Lago Patillas reservoir, the Lago Carite reservoir in the Rio de la Plata watershed north of the island's principal surface-water divide and diversion tunnel to the Rio Guamani, the Canal de Juana Diaz, and the Lago Guayabal and Lago Coamo reservoirs. With the completion of the Lago El Guineo and Lago de Matrullas reservoirs in the Rio Grande de Manatí watershed north of the principal divide and a diversion tunnel to Rio Jacaquas, the system of reservoirs, tunnels, pump stations, and canals conveyed an average of 123 cubic feet per second by 1935.

Ground-water development began in the coastal plain in about 1910 with the construction of wells furnished with steam-operated pumps powered by kerosene. The use of ground water for irrigation expanded greatly in the 1930's with the extension of electrification, installation of generators at several sugar mills, and introduction of deep-well turbine pumps. Large-scale dewatering works were also constructed during the late 1930's to control the spread of malaria and to reclaim additional land for sugar cane cultivation.

The canal network is supplied by surface water and has augmented recharge to the aquifer. Consequently, aquifer discharge, which mainly occurs as ground-water withdrawals and as seepage to local streams and to the sea, has increased. During 1982, water deliveries, used largely for growing sugar cane, were about 40 cubic feet per second through the government-operated irrigation canal network east of Rio Jacaquas and about 20 cubic feet per second through a private network west of the river. Total ground-water withdrawals during 1980 averaged approximately 86 cubic feet per second; 62 percent of the water withdrawn was used for irrigation and the remainder was used for public supply.

Water movement through the part of the aquifer from Salinas to Patillas prior to development was estimated to be 43 cubic feet per second. During full development of the canal system in the 1950's and 1960's, water movement in the aquifer in the Salinas to Patillas area increased to an estimated 126 cubic feet per second. With a reduction in sugar production and conversion to a drip irrigation system, there was a reduction of water delivered by the canal system. The amount of water movement in the aquifer during 1986 was estimated to be only about 88 cubic feet per second.

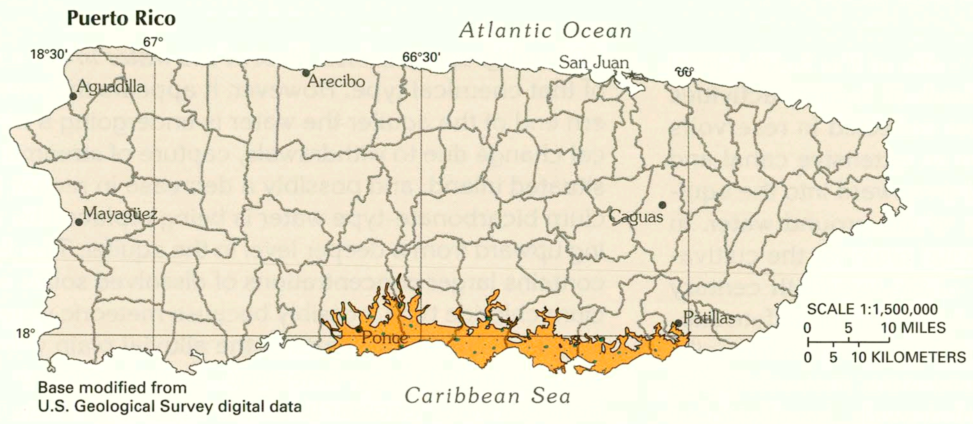


Figure 87. The South Coast aquifer extends from Patillas to Ponce in southern Puerto Rico.

EXPLANATION

South Coast aquifer

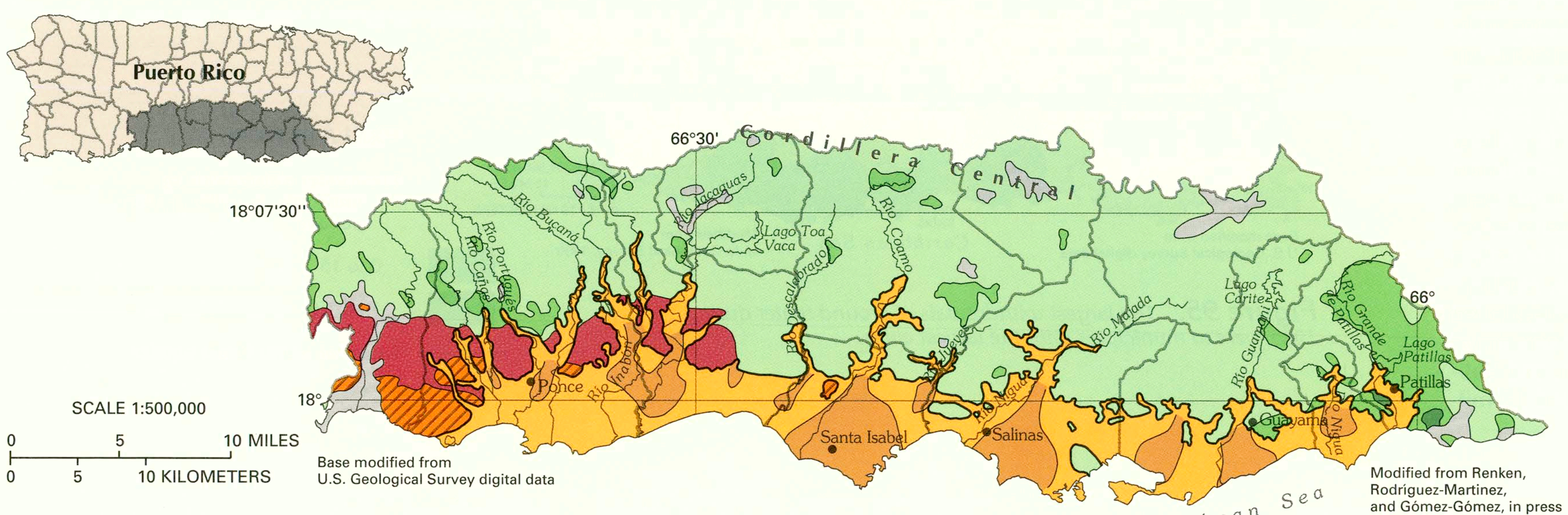


Figure 88. Fan deltas, formed at the mouths of principal rivers, have coalesced to form a continuous fan-delta plain that averages about 4 to 5 miles in width and 40 miles in length. The fan-delta plain laps onto volcaniclastic and sedimentary rocks of the Cordillera Central and limestone of the Ponce Limestone and Juana Diaz Formation.

EXPLANATION

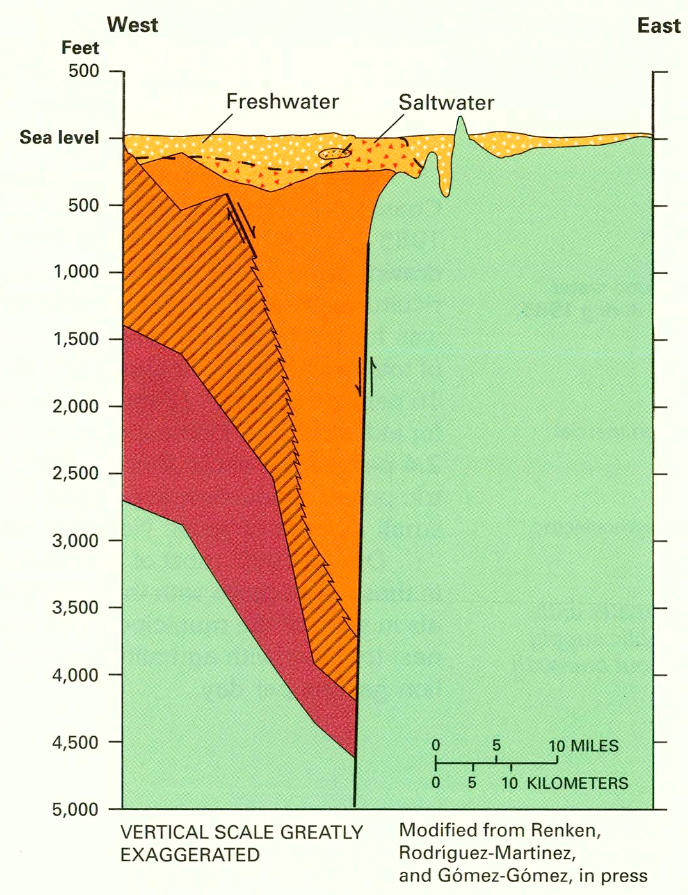
Quaternary deposits
- Fan delta
- Interfan or alluvial plain
- Undifferentiated surficial deposits—not part of South Coast aquifer

Miocene rocks
- Ponce Limestone

Miocene and Oligocene rocks
- Juana Diaz Formation

Eocene to Cretaceous rocks
- Volcaniclastic and sedimentary rocks
- Plutonic rocks, mostly quartz diorite and grandiorite
- Metamorphic (serpentinite), sedimentary, and igneous rocks

Extent of South Coast aquifer



EXPLANATION
- Alluvial and fan-delta deposits—Poorly consolidated where patterned
- Ponce Limestone
- Unnamed clastic facies of Ponce Limestone and younger rocks
- Juana Diaz Formation
- Volcaniclastic and sedimentary rocks
- Fault—Arrows show relative movement

Figure 89. Alluvial and fan-delta deposits are thicker on the downfaulted block that underlies the west end of the South Coast aquifer than on the upfaulted block to the east.

HYDROGEOLOGY

The South Coast aquifer consists of alluvial and fan-delta deposits derived from erosion of the volcanic and sedimentary rocks of the Cordillera Central. The alluvium was transported and deposited by numerous steep-gradient, high-energy, south-flowing streams that originate at altitudes above 1,000 feet within 15 to 20 miles of the coast (**fig. 88**). The alluvial deposits below an altitude of 100 to 150 feet are of Holocene age. Above this altitude and extending to the bedrock foothills, the deposits are of Holocene and Pleistocene (?) age, and erosional terraces have developed on them.

Fan-deltas and alluvial deposits rest on a south-sloping bedrock shelf that has been subjected to subaerial erosion and is extensively faulted in a horst and graben, or block-fault, pattern. East of Salinas, the bedrock surface is relatively smooth and alluvial deposits range in thickness from about 90 to 150 feet near the coast to about 250 feet where bedrock is more deeply incised or downfaulted. West of Salinas to Ponce, the alluvium ranges in thickness from about 100 to more than 1,000 feet near the coast. An oil-test well drilled near Santa Isabel is reported to have penetrated more than 2,500 feet of unconsolidated and poorly consolidated Pliocene (?) to Miocene clastic deposits which underlie Quaternary deposits and might indicate a deep basin formed by a graben structure in the bedrock.

Bedrock that underlies the coastal plain consists principally of volcaniclastic and sedimentary rocks of Tertiary and Cretaceous age in areas east of Salinas and sedimentary rocks of Tertiary age in areas west of Salinas (**fig. 88**). The Tertiary sedimentary rocks consist of the Juana Diaz Formation of Oligocene and Miocene age, which overlies the volcaniclastic and sedimentary rocks, and the Ponce Limestone of Miocene and Pliocene age, which overlies the Juana Diaz Formation. The Juana Diaz Formation and Ponce Limestone are in fault contact with older volcaniclastic and sedimentary rocks in places (**fig. 89**).

The volcaniclastic and sedimentary rocks consist of massive to thick bedded andesitic tuff, welded tuff, porphyritic basalt, volcanic breccia, sandstone, and siltstone. The Juana Diaz Formation consists of thin-bedded sandy to shaly, fossiliferous limestone interbedded with marl, shale, and conglomerate. The Ponce Limestone unconformably overlies the Juana Diaz Formation and consists of a shallow-marine, fossiliferous limestone that grades to clastic facies in subsurface areas to the east (**fig. 89**). Total thickness of the formation is uncertain but may exceed 1,000 feet.

The alluvial material that makes up the South Coast aquifer was largely deposited as a series of fan-deltas (**fig. 88**), each heading at a stream channel incised into bedrock and some widening downstream to coalesce with neighboring fans from adjacent channels. The downstream parts of the fan-deltas were deposited in the sea. The result is a broad alluvial plain that gently slopes and thickens southward to the Caribbean Sea. The method of deposition of the alluvial sediments has imposed a characteristic grain-size distribution within the alluvium that is significant hydrologically. The coarsest sediments (sand and gravel) were deposited as the streams emerged from their incised channels onto the alluvial plain. Sediment grain size decreases to silt and clay both laterally at the coalescing edges of adjoining fan-deltas and seaward; thus, the percentage of coarse sediment is greatest near the central part of the fan where the streams first diverged and spread out across the coastal plain (**fig. 90**).

The areas of greatest hydraulic conductivity (**fig. 91**) coincide with areas where the percentage of sand and gravel is highest. Hydraulic conductivity is a measure of the rate at which water will pass through an aquifer; the greater the hydraulic conductivity, the more water the aquifer will yield to wells. Hydraulic conductivities are highest in plume-shaped areas that head at major stream channels, and diminish laterally and in a downstream direction (**fig. 91**).

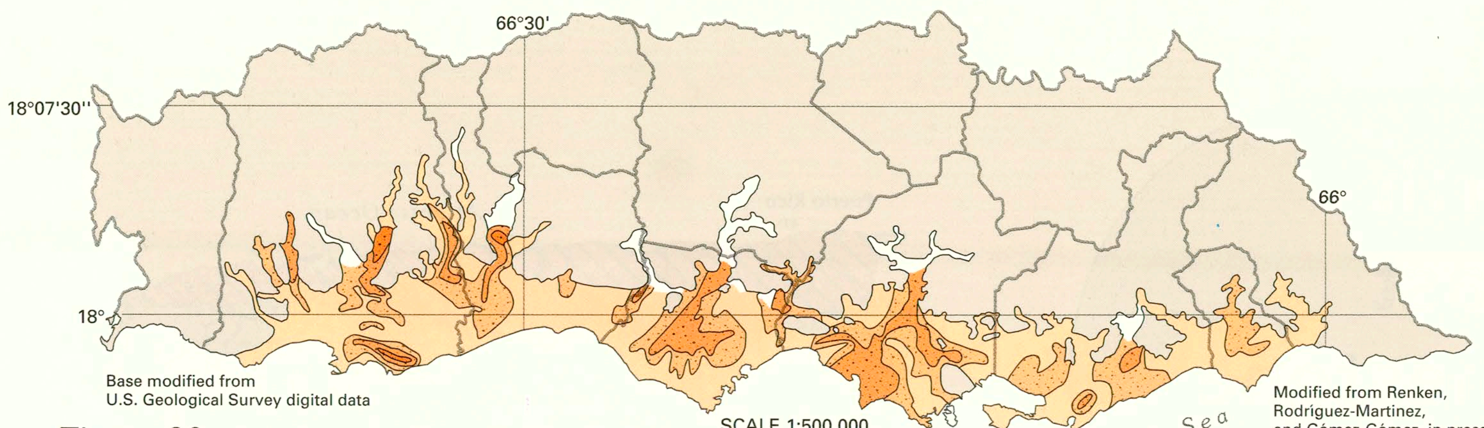


Figure 90. The coarsest grain sizes within the fan-delta plain are concentrated at the apex and central part of each fan-delta. Grain size decreases laterally and downstream from the central parts of the fan-deltas.

EXPLANATION

Percentage of sand in sediments that compose the aquifer
- Less than 20
- 20 to 40
- 40 to 60
- Greater than 60
- Insufficient data

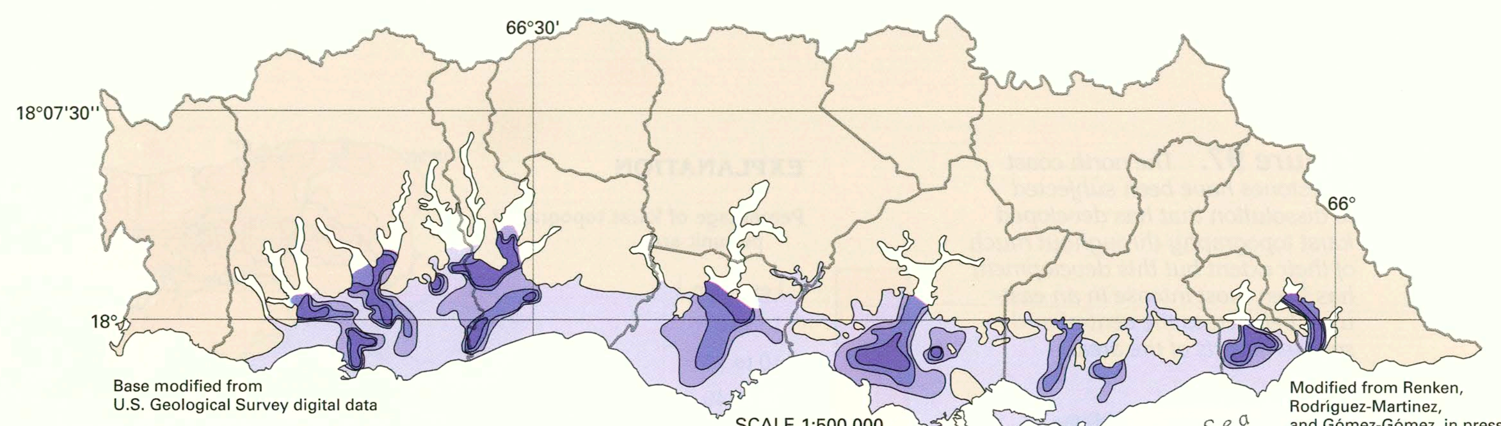


Figure 91. Hydraulic conductivities are greatest in the central parts of the fan deltas and diminish coastward and in interfan areas.

EXPLANATION

Approximate hydraulic conductivity, in feet per day
- Less than 25
- 25 to 50
- 50 to 100
- Greater than 100
- Insufficient data

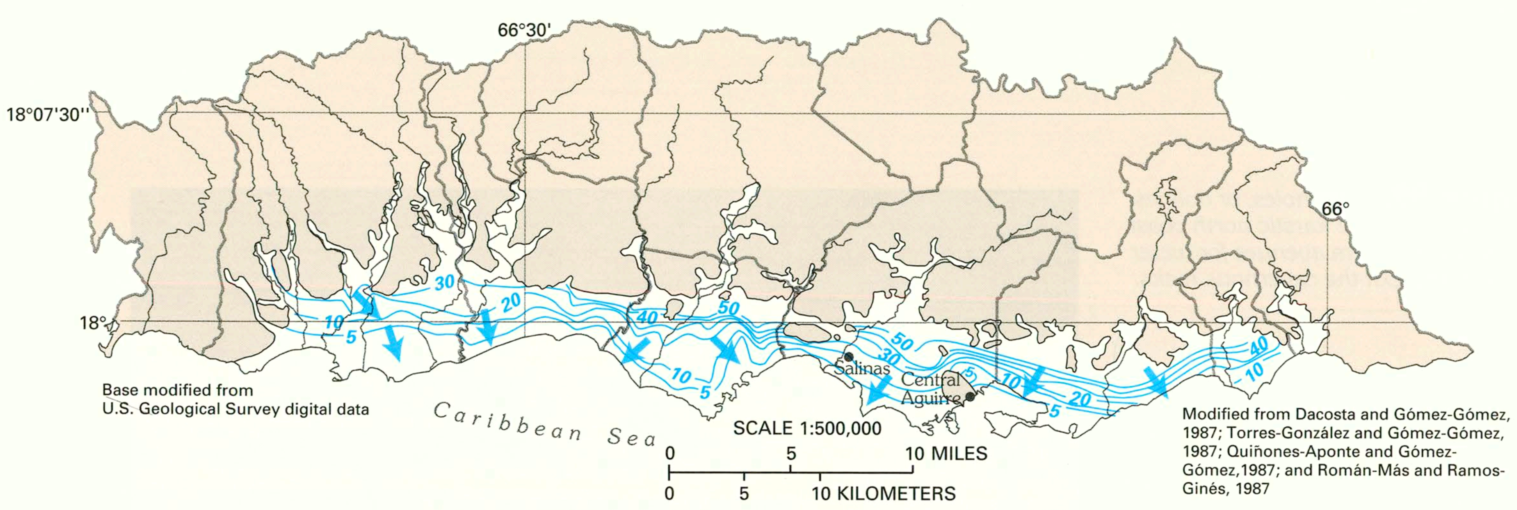


Figure 92. The regional movement of water in the South Coast aquifer is southward to the sea; local movement is to streams. Ground-water withdrawals in some areas have changed the gradient locally to the extent that water moves toward the wells.

EXPLANATION

20 Water-table contour—Shows altitude of water table. Contour interval, in feet, is variable. Datum is mean sea level

Direction of ground-water movement

GROUND-WATER FLOW

Ground water in the alluvial deposits generally is under water-table (unconfined) conditions, except in some areas near the coast where silt or clay beds locally create confined conditions. A freshwater-saltwater interface is assumed to be present near the coast in the alluvial sediments, but the thickness of the freshwater zone generally is poorly known. The water table generally slopes southward from the foothills to the Caribbean Sea (**fig. 92**).

Before development, regional ground-water movement was from recharge areas southward to the coast; locally, some water moved laterally to major streams, mostly in downstream reaches. Recharge to the aquifer was from infiltration of precipitation that fell directly on the alluvium and from streamflow seepage. Discharge was to streams and the sea and as direct evapotranspiration from the aquifer where the water table was shallow. The long history of construction of drainage ditches and irrigation canals and withdrawal of ground water in this agricultural and industrial area, however, has greatly altered natural ground-water flow. Recharge has been augmented by seepage of surface water transported in the several irrigation canals that cross the alluvium and from the practice of furrow irrigation. During 1985, irrigation deliveries from the canal network operated by the government were approximately 60 million gallons per day, of which an estimated 30 percent recharged the aquifer. Although most ground water moves toward the sea and locally to streams (**fig. 92**), development has partially altered the direction of flow. For example, some water moves toward well fields, such as the one just north of Central Aguirre near Salinas. Discharge from the aquifer is mainly as ground-water withdrawals; withdrawals during 1985 were about 74 million gallons per day.

GROUND-WATER QUALITY

The natural chemical quality of water in the South Coast aquifer has changed greatly as a result of human activities during the last century. Surface water collected in reservoirs in the mountains and channeled into an extensive canal and furrow irrigation network has seeped downward into the aquifer and altered the chemical quality of the ground water. In addition, the intensive use of the coastal plain for the cultivation of sugar cane throughout most of the twentieth century required the use of fertilizers (generally a calcium sulfate substance) and lime (calcium carbonate) to reclaim saline soils. The direction of predevelopment ground-water movement also has been changed by large-scale withdrawals. Locally, these changes in the flow system have moved and mixed waters of different chemical qualities within the aquifer.

Prior to development of the aquifer, water in the South Coast aquifer was probably a calcium bicarbonate type (**fig. 93**) with dissolved-solids concentrations generally less than 600 milligrams per liter. Most of the water in the aquifer is still of that chemical type. However, it appears that near the western end of the aquifer the water is undergoing a major chemical change due to withdrawals, capture of streamflow by wells situated inland, and possibly a decrease in recharge. The calcium bicarbonate-type water is being replaced by water moving upward from a deeper level in the aquifer. The deeper water contains larger concentrations of dissolved solids and is a calcium chloride type, possibly because meteoric water enters the aquifer at the higher parts of the alluvial plain where the alluvium is underlain by limestone. Sodium chloride-type water from seawater encroachment is replacing calcium chloride-type water adjacent to the coast at the extreme western end of the coastal plain. Sodium bicarbonate-type water in interfluvial areas may result from a high percentage of sodium-rich clay, silt, and volcanic particles in the alluvium that composes the aquifer in these areas.

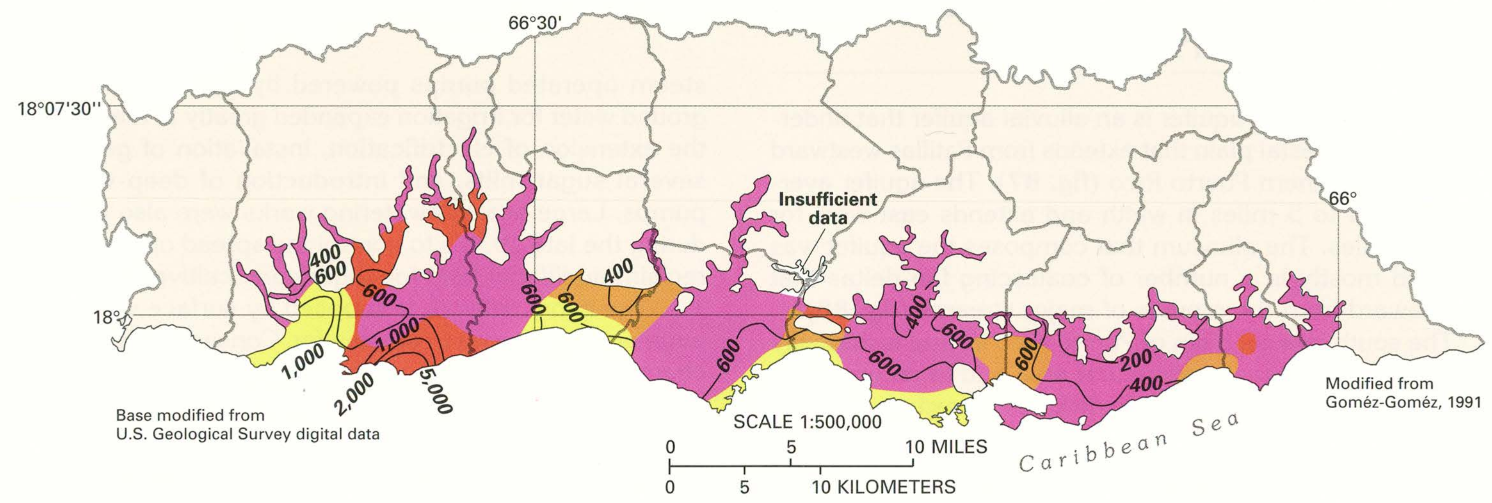


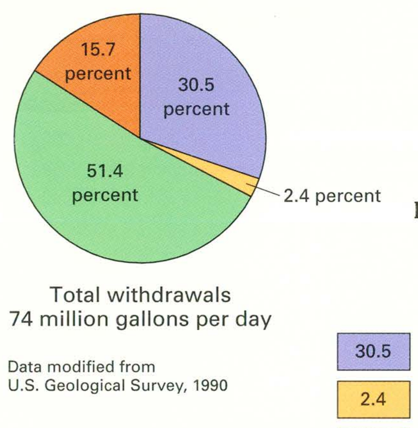
Figure 93. The most extensive chemical type of ground water in the South Coast aquifer is a calcium bicarbonate type with dissolved-solids concentrations generally less than 600 milligrams per liter. Development of the aquifer has caused upwelling of calcium chloride-type water from deeper levels in the aquifer and has allowed encroachment of sodium chloride-type water with large dissolved-solids concentrations from the sea.

EXPLANATION

Prevalent water type in wells completed at depth of less than 150 feet

- Calcium chloride
- Sodium chloride
- Calcium bicarbonate
- Sodium bicarbonate

—400— **Line of equal dissolved solids**— Contour interval, in milligrams per liter, is variable



EXPLANATION

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

30.5	Public supply
2.4	Domestic and commercial
51.4	Agricultural
15.7	Industrial and thermoelectric power

Figure 94. Slightly more than half of the ground water withdrawn during 1985 was used for irrigation of crops. Public supply accounted for about one-third and industrial use for about one-sixth of the total withdrawals.

FRESH GROUND-WATER WITHDRAWALS

Total fresh ground-water withdrawals from the South Coast aquifer were about 74 million gallons per day during 1985 (**fig. 94**). Slightly more than one-half the water withdrawn, or about 38 million gallons per day, was used for agriculture, primarily irrigation of crops. The other principal use was for public supply, which amounted to about 31 percent of total withdrawals, or about 23 million gallons per day. About 16 percent, or about 12 million gallons per day, was withdrawn for industrial use. Domestic and commercial withdrawals were 2.4 percent, or about 2 million gallons per day. Thermoelectric power production accounted for the withdrawal of only a small amount of water. No water was withdrawn for mining.

During 1985, most of the water withdrawn was distributed in those municipios with the largest cities (**fig. 95**). Withdrawals in each of the municipos of Ponce, Santa Isabel, and Salinas, together with agricultural withdrawals, exceeded 15 million gallons per day.

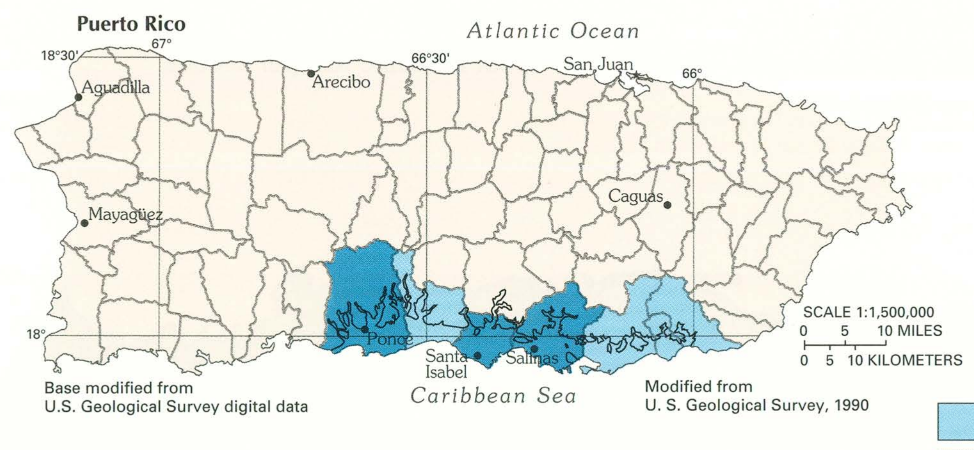


Figure 95. The largest withdrawals of ground water during 1985 were in municipios with the largest cities.

EXPLANATION

Freshwater withdrawals by municipio, in million gallons per day

- 0 to 15
- 15 to 30

—— Extent of South Coast aquifer

North Coast Limestone aquifer system

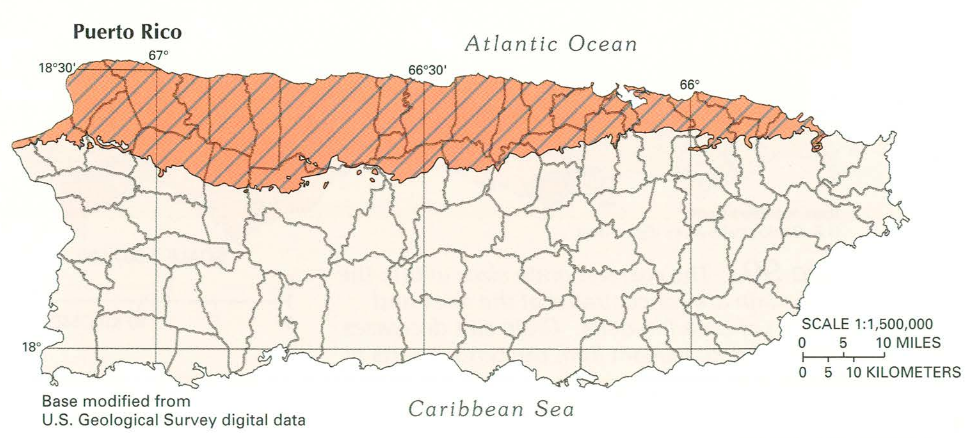


Figure 96. The North Coast Limestone aquifer system underlies a populous and industrialized area that extends approximately 90 miles along the north coast of Puerto Rico.

EXPLANATION

North Coast Limestone aquifer system

INTRODUCTION

The North Coast Limestone aquifer system in Puerto Rico is one of the largest and most productive sources of ground water on Puerto Rico and the Virgin Islands. The aquifer system underlies a populous and industrialized area that extends approximately 90 miles along the north coast of Puerto Rico (**fig. 96**) and encompasses an area of nearly 700 square miles. The aquifer system consists of two limestone aquifers separated by an intervening confining unit. About 66 million gallons per day was withdrawn from the two limestone aquifers during 1985 for public-supply, industrial, agricultural, and domestic uses.

The limestones that compose the aquifer system are undeformed and relatively flat-lying with a dip of less than 5 degrees to the north. They range in altitude from about 1,300 feet above sea level to the south, where they overlie volcanic rocks, to below sea level at the north coast, where they extend under the Atlantic Ocean. All of the limestone formations, where they crop out at the land surface, have been subject to intense dissolution which has developed widespread karst topography (**fig. 97**). The rocks exhibit such unusual karst features as cone-shaped hills called mogotes (**fig. 98**), cockpit karst, and zanjón-type karst, which is characterized by parallel solutional trenches that range in width from a few inches to tens of feet and from 1 to 12 feet deep. Sinkholes, or dolines, similar to the one shown in **figure 99** are extremely common and form avenues through which water can rapidly and directly enter and exit the cavernous limestones.

Figure 97. The north coast limestones have been subjected to dissolution that has developed karst topography throughout much of their extent but this development has been most intense in an east-west belt across the central and southern parts of the area.

EXPLANATION

Percentage of karst topography per unit area

- Less than 1
- 1 to 10
- 10 to 20
- 20 to 40
- 40 to 60
- 60 to 100
- No data

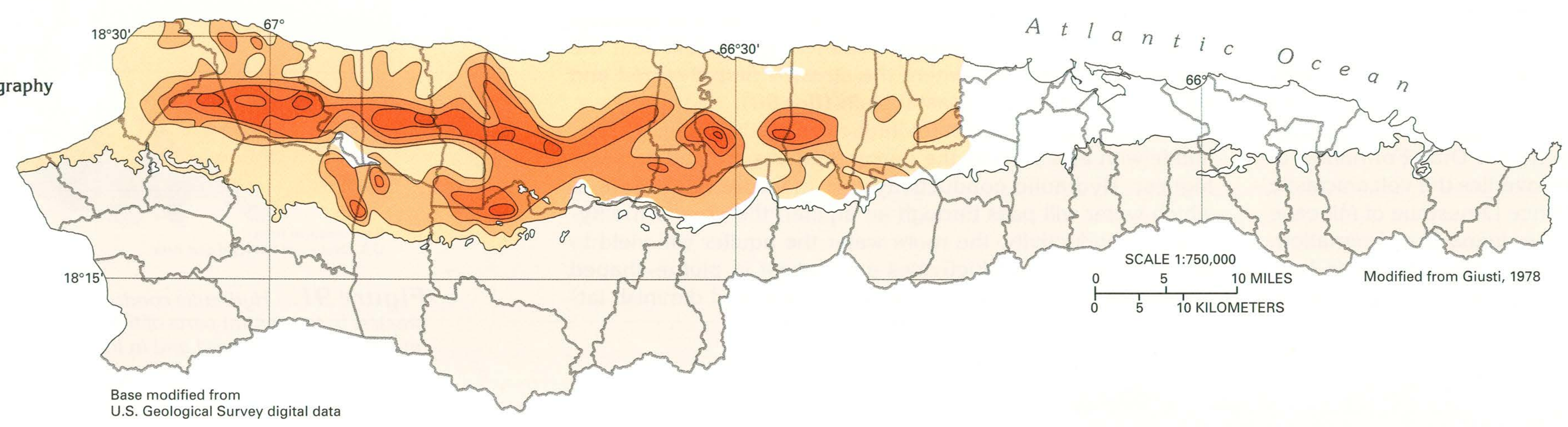


Figure 98. Karst features, such as this conical mogote, are typical of much of the north coast limestone area.

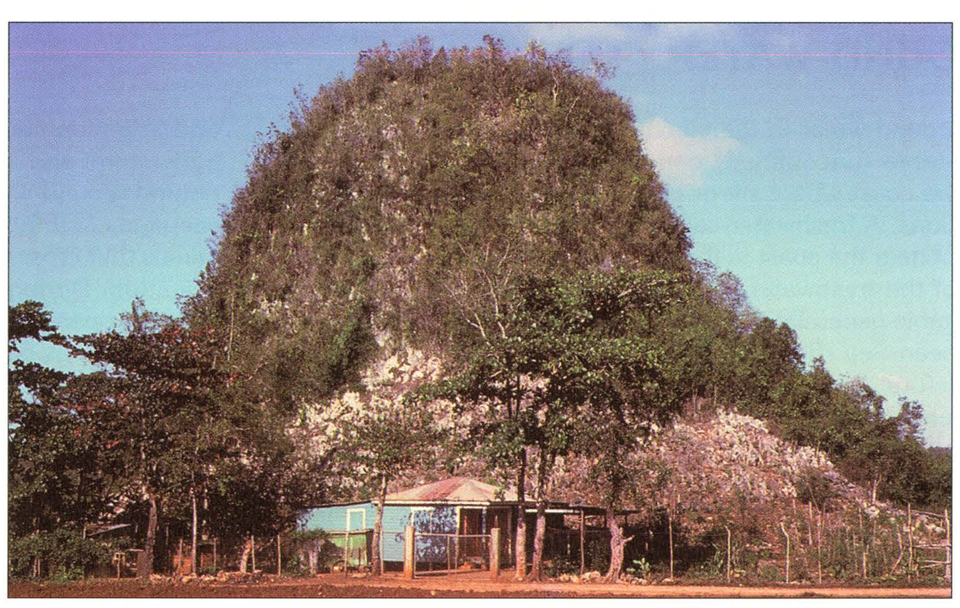


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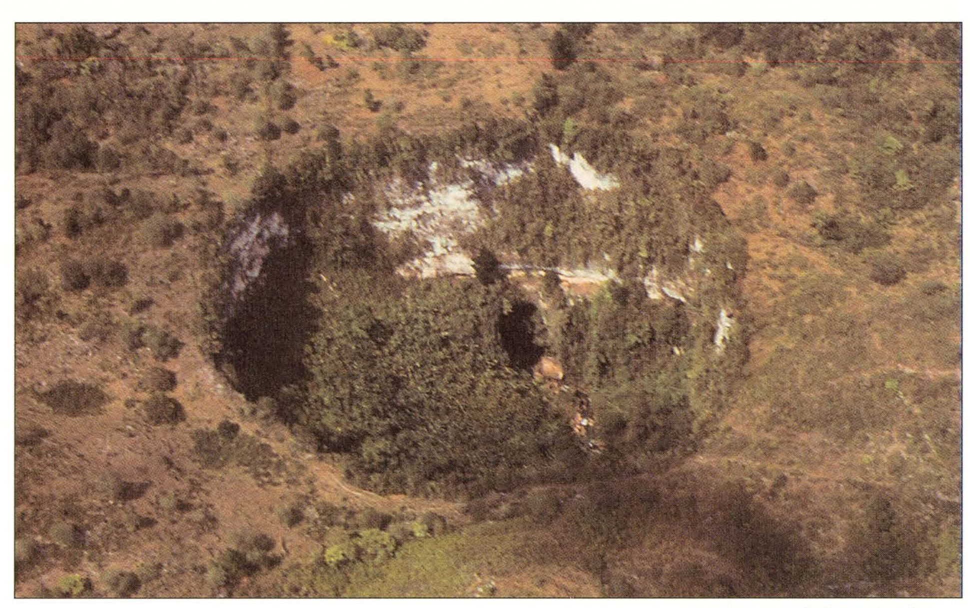
Figure 99. Sinkholes, or dolines, are common in the karstic north coast limestone and form avenues for water to enter and exit the cavernous rocks.



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HYDROGEOLOGIC UNITS

The North Coast Limestone aquifer system consists of a thick sequence of carbonate rocks of Miocene to Oligocene age that formed as platform deposits on the south flank of a broad depositional basin that extends from Puerto Rico about 100 miles northward to the southern slope of the Puerto Rico Trench. The aquifer system consists mostly of limestone; however, not all strata yield water. Maximum known onshore thickness of the limestones is about 5,600 feet, but their maximum estimated offshore thickness is 11,500 feet. The outcrop extent of the principal geologic units that compose the aquifer system is shown in **figure 100**. These numerous geologic units have been combined into an upper and a lower aquifer, separated by a confining unit (**fig. 101**). The vertical sequence and hydrogeologic grouping of the rock units are described in **figure 72**.

Rocks of the aquifer system overlie volcanic rocks of Eocene to Cretaceous age that have been intensely faulted, folded, and intruded by multiple plutons. The lowermost geologic unit of the aquifer system is the San Sebastián Formation (**fig. 102**) that unconformably overlies volcanic, volcaniclastic, and intrusive igneous rocks. The San Sebastián crops out in two discontinuous bands of clayey, silty conglomerate and feldspathic sandstone along the southwestern and southeastern edges of the North Coast Limestone aquifer system. It extends into the subsurface where it is more laterally extensive but grades into glauconitic mudstone and marl. The San Sebastián meets the Mucarabones Sand on the east (**fig. 102**) but its exact relation with that unit is unknown. The San Sebastián ranges in thickness from a featheredge where it crops out to about 1,000 feet in the deep subsurface. It yields small quantities of water in outcrop areas but is poorly transmissive and functions mostly as a confining unit, especially in downdip areas.

The Lares Limestone is predominantly a thick-bedded, fine- to medium-grained fossiliferous limestone that conformably overlies the San Sebastián Formation (**figs. 72, 102**). The Lares contains abundant reefal limestone but no biohermal masses. It crops out in a nearly continuous band that extends eastward from Aguadilla on the west coast to the Río de la Plata where it grades laterally eastward into the Mucarabones Sand (**fig. 102**). In the subsurface, to the west of Arecibo, the upper part of the Lares is similar to carbonate rocks of the Cibao Formation. Farther west, time-equivalent rocks grade to a lithology typical of the upper part of the San Sebastián. On the basis of lithology, the Lares west of Arecibo probably does not constitute an aquifer. The Lares ranges from about 150 to 650 feet in thickness at outcrop to about 950 feet downdip near Arecibo.

The Cibao Formation is divided into a number of members (**fig. 72**) that represent a variety of depositional environments. The Río Indio Limestone Member and the overlying Quebrada Arenas Limestone Member, located approximately between the Río Cibuco and the Río de la Plata (**fig. 102**), are marginal marine and biostromal carbonates that unconformably overlie the Lares Limestone. The Montebello Limestone Member, which is an extensive carbonate buildup sequence, is present to the west between the Río Camuy and the Río Grande de Manatí and also overlies the Lares (**fig. 102**). A poorly transmissive mudstone unit that has been identified only in the subsurface in the vicinity of Manatí is the equivalent of the Río Indio and Montebello Limestone Members. It lies between and separates these two carbonate units. The uppermost and most extensive part of the Cibao Formation is the upper unnamed member, a carbonaceous mudstone and limestone sequence that overlies the other members to the east and composes the entire Cibao to the west (**fig 102**).

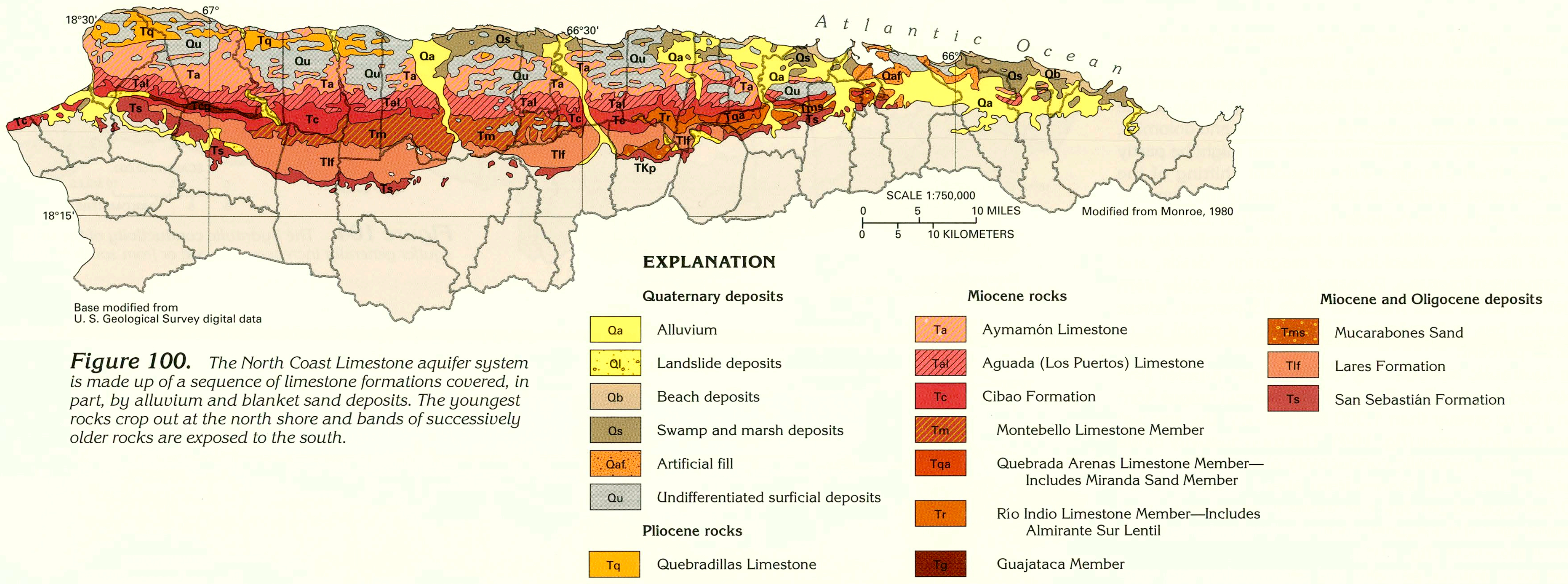


Figure 100. The North Coast Limestone aquifer system is made up of a sequence of limestone formations covered, in part, by alluvium and blanket sand deposits. The youngest rocks crop out at the north shore and bands of successively older rocks are exposed to the south.

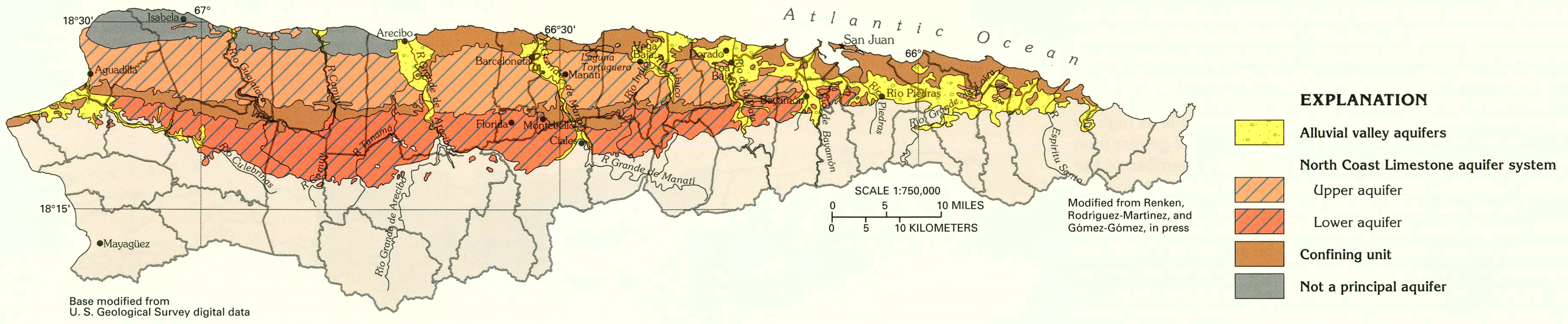


Figure 101. The North Coast Limestone aquifer system consists of an upper aquifer and a lower aquifer, separated by a confining unit that is mostly marl, clay, and mudstone. Marsh and other surficial deposits locally confine the upper aquifer in some coastal areas.

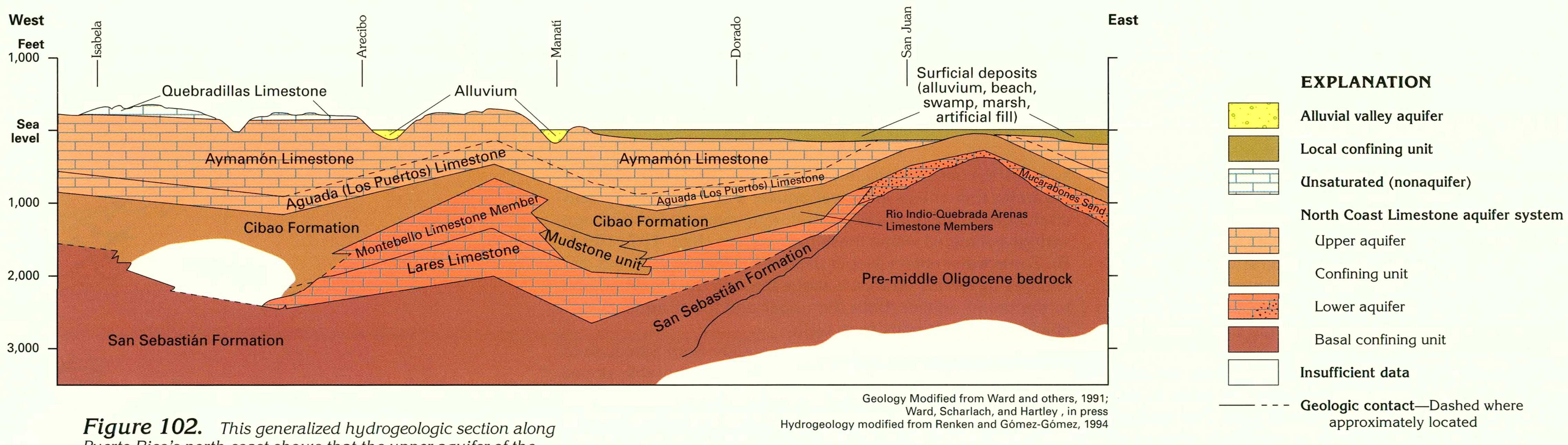


Figure 102. This generalized hydrogeologic section along Puerto Rico's north coast shows that the upper aquifer of the North Coast Limestone aquifer system extends from the west coast to east of San Juan. The lower aquifer is confined and ends just west of Arecibo. Eastward, it thins and grades into the Mucarabones Sand.

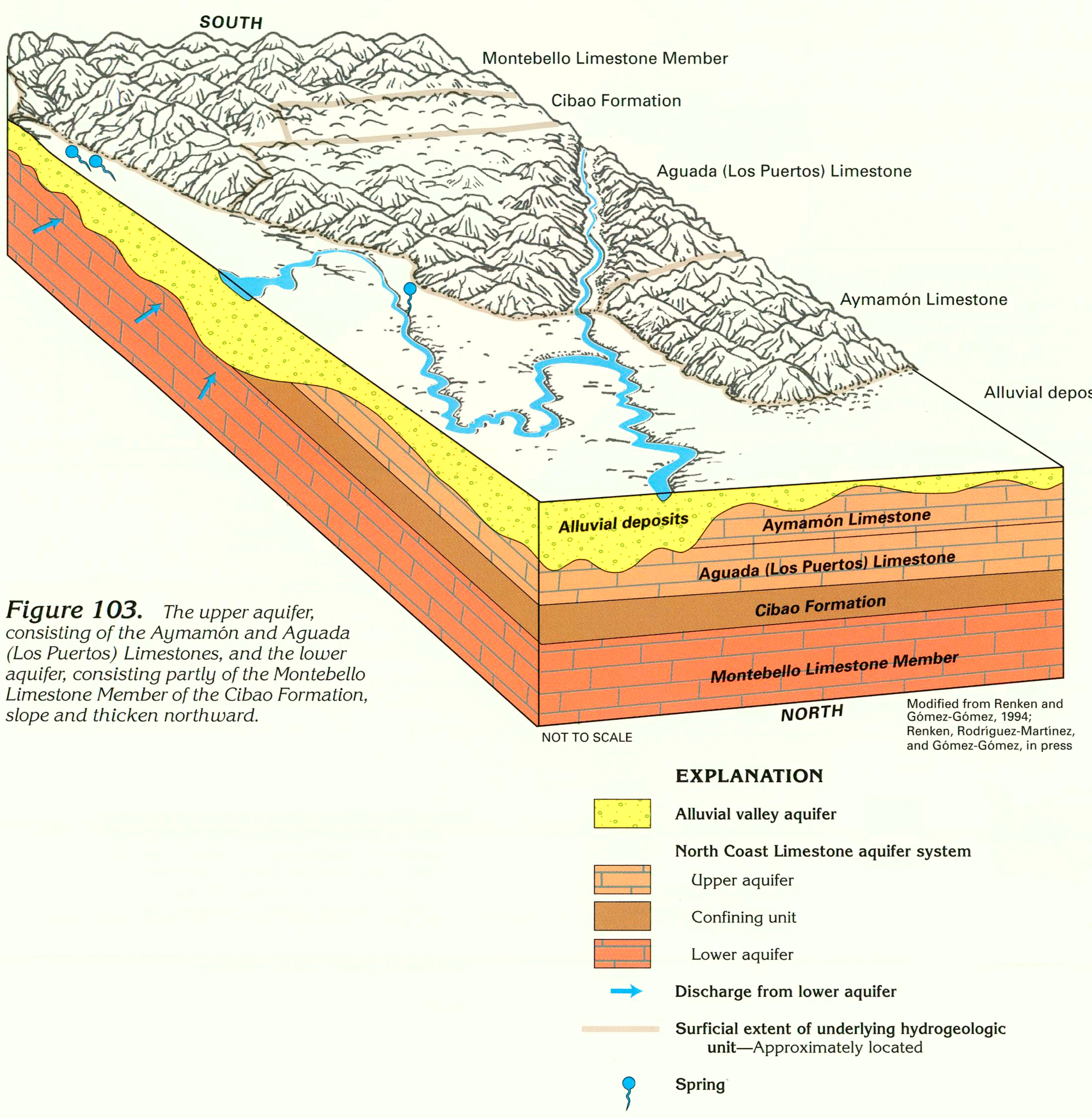


Figure 103. The upper aquifer, consisting of the Aymamón and Aguada (Los Puertos) Limestones, and the lower aquifer, consisting partly of the Montebello Limestone Member of the Cibao Formation, slope and thicken northward.

The Mucarabones Sand consists predominantly of cross-bedded, fine to medium quartz sand that grades upward into sandy limestone near the top. The sand is moderately to poorly sorted and a clay matrix in the lowermost part is replaced by a calcite cement higher in the section. Local conglomerates in the formation contain volcanic-rock cobbles up to 1.5 inches in diameter. The formation overlies, in part, the San Sebastián Formation and, in part, volcanic rocks (**fig. 102**). The Mucarabones Sand ranges in thickness from about 33 feet at its western extent (near Ciales) to about 400 feet near Bayamón. The Mucarabones is a stratigraphic equivalent of both the Lares Limestone and the Cibao Formation (**fig. 72**).

The Aguada (Los Puertos) Limestone conformably overlies the Cibao Formation and the Mucarabones Sand and crops out in a narrow belt that extends from the west coast to east of the Río de la Plata (**fig. 100**). The Aguada consists of dolomitic limestone and massive recrystallized limestone with some quartz sand. East of the Río de la Plata, the formation grades laterally into a chalky limestone and calcareous clay that is indistinguishable from the unnamed upper member of the Cibao Formation. The Aguada (Los Puertos) ranges in thickness from about 200 to 380 feet.

The Aymamón Limestone overlies the Aguada (Los Puertos) Limestone (**fig. 72**) and is described in outcrop as a thick to massively bedded, nearly pure limestone that becomes dolomitic near the coast. The Aymamón Limestone crops out in a broad belt from the west coast eastward to Toa Baja (**fig. 100**). In the subsurface, the Aymamón is as much as 1,000 feet in thickness in northwestern Puerto Rico. East of Toa Baja, dissolution has reduced the thickness and areal extent of the formation, and it is not hydrologically significant. The Aymamón is covered in this area by alluvium and blanket sand deposits.

The Quebradillas Limestone unconformably overlies the Aymamón Limestone (**figs. 72, 102**) and crops out as a discontinuous belt along the north coast from Isabela eastward to Dorado (**fig. 101**). East of the Río Grande de Manatí, the Quebradillas is present only as outliers on hills of Aymamón Limestone. The maximum thickness of the Quebradillas is about 300 feet, and it is predominantly a chalky, deep-water limestone but contains considerable quartz sand and is iron-rich, especially in the lower part. The Quebradillas Limestone is largely unsaturated in northwestern Puerto Rico and, therefore, generally yields no water.

To the east of Manatí, the limestones are directly overlain by as much as 100 feet of unconsolidated deposits consisting of alluvial, terrace, beach, and swamp deposits collectively referred to as blanket sands in some reports. The principal river valleys drain northward; they have been incised into the limestones and are filled with as much as 300 feet of river alluvium. The unconsolidated deposits may be partially saturated and are in hydraulic connection with the limestones.

AQUIFERS AND CONFINING UNITS

The North Coast Limestone aquifer system consists of two aquifers separated by a confining unit. The upper aquifer contains water mostly under unconfined conditions and consists primarily of the Aymamón and Aguada (Los Puertos) Limestones (**fig. 103**). The aquifer extends from Aguadilla on the west coast to the vicinity of San Juan (**fig. 101**). The extent of the aquifer east of San Juan is unknown. The valleys of principal rivers that have been incised into the Aymamón and Aguada Limestones are filled with partially saturated alluvium that is in hydraulic connection both with the rivers and the upper aquifer. Similarly, where they are saturated, the Quebradillas Limestone and unconsolidated deposits that overlie the upper aquifer near the coast are in hydraulic connection with the aquifer.

The confining unit in the middle of the aquifer system is complex. It consists of the upper unnamed member of the Cibao Formation, a mudstone unit that appears to be present only in the subsurface near Manatí, and the Quebrada Arenas and Río Indio Limestone Members of the Cibao Formation in downdip coastal areas (**fig. 72**). West of Arecibo, the confining unit is very thick. Water-bearing rocks of the Montebello Limestone Member and Lares Limestone grade to a Cibao lithology in northwestern coastal areas and are considered part of the middle confining unit.

The lower aquifer is formed primarily of the Montebello Limestone Member of the Cibao Formation and the Lares Limestone (**figs. 102, 103**). However, the aquifer includes the Mucarabones Sand and water-yielding parts of the Río Indio and Quebrada Arenas Limestone Members to the east, and the San Sebastián Formation in areas of outcrop. Where the formations that compose the lower aquifer crop out at the southern part of the limestone belt, water in the aquifer is under water-table, or unconfined, conditions. However, as the aquifer extends northward under the Cibao Formation, the water is under confined conditions. In the subsurface to the west of Arecibo, the Lares Limestone and Montebello Limestone take on the character of the upper unnamed member of the Cibao Formation and are of such low transmissivity that they do not constitute an aquifer.

HYDRAULIC PROPERTIES

The upper 100 to 300 feet of the Aymamón Limestone is a dense, recrystallized, and chalky limestone in which extensive cavernous porosity has developed. The openings are the result of solution enlargement of secondary openings in the rock, as well as solution of aragonite fossil shells and dolomite, by circulating, slightly acidic ground water and might be partly related to sea level changes with attendant shifting of the saltwater-freshwater interface. In the lower part of the Aymamón Limestone and in the Aguada (Los Puertos) Limestone, porosity is extremely variable and is largely controlled by the presence of dolomite, dissolution of aragonitic fossils, and solution-enhanced fractures. Porosity that results solely from dissolution of fossils is as much as 10 to 15 percent; where dolomitization has further increased porosity, it might be as much as 25 percent.

The hydraulic conductivity of the upper aquifer [the Aymamón and Aguada (Los Puertos) Limestones] ranges from less than 100 to greater than 1,000 feet per day; the greatest values are near the ocean (**fig. 104**). The transmissivity of the upper aquifer (the hydraulic conductivity of the aquifer times the saturated thickness) ranges from about 1,000 to about 100,000 feet squared per day; the greatest values are located in the central part of the aquifer where the freshwater lens has the greatest thickness (**fig. 105**).

In the lower aquifer, porosity and permeability vary considerably as a result of vertical and lateral changes in rock type. The rocks have some primary intergranular porosity, but most of the porosity is secondary and results from dissolution of fossils and from dolomitization. Fracturing does not appear to substantially enhance permeability in the lower aquifer. Most of the rocks that compose the lower aquifer typically have a porosity of 10 to 15 percent but locally porosity is as high as 20 to 25 percent. Individual beds with a porosity of greater than 10 percent are in the Montebello Limestone Member of the Cibao Formation and the Lares Limestone east of Arecibo.

The transmissivity of the lower aquifer, shown in **figure 106**, ranges from less than 50 to greater than 1,000 feet squared per day. Transmissivity may be as high as 10,000 feet squared per day in local subsurface areas and locally as high as 14,000 feet squared per day where the aquifer crops out. In general, transmissivity of the lower aquifer is greatest where the Montebello Limestone Member is present.

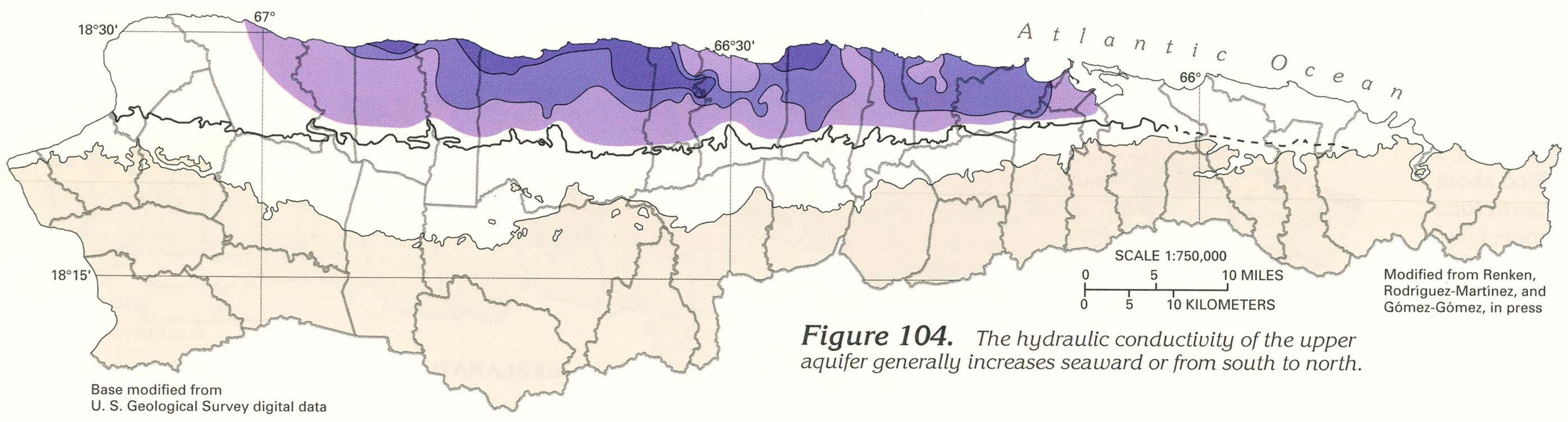


Figure 104. The hydraulic conductivity of the upper aquifer generally increases seaward or from south to north.

EXPLANATION

Estimated hydraulic conductivity of the upper aquifer of the North Coast Limestone aquifer system, in feet per day

- Less than 100
- 100 to 1,000
- Greater than 1,000
- Insufficient data

Limit of upper aquifer—Dashed where approximately located

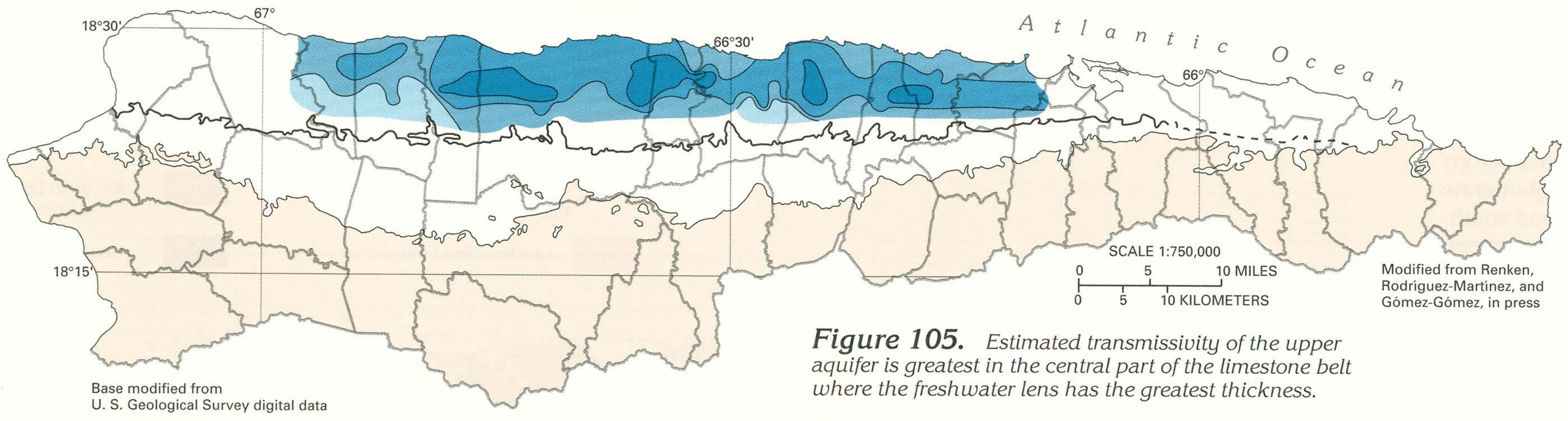


Figure 105. Estimated transmissivity of the upper aquifer is greatest in the central part of the limestone belt where the freshwater lens has the greatest thickness.

EXPLANATION

Estimated transmissivity of the upper aquifer of the North Coast Limestone aquifer system, in feet squared per day

- Less than 1,000
- 1,000 to 10,000
- 10,000 to 100,000
- Greater than 100,000
- Insufficient data

Limit of upper aquifer—Dashed where approximately located

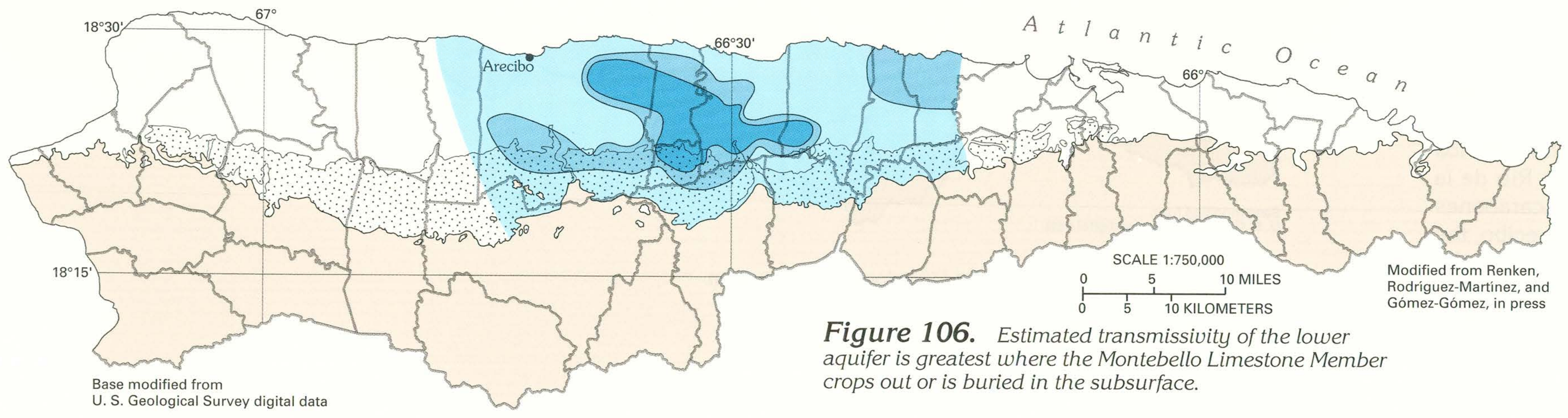


Figure 106. Estimated transmissivity of the lower aquifer is greatest where the Montebello Limestone Member crops out or is buried in the subsurface.

EXPLANATION

Estimated transmissivity of the lower aquifer of the North Coast Limestone aquifer system, in feet squared per day

- Less than 500
- 500 to 1,000
- Greater than 1,000
- Insufficient data

Lower aquifer outcrop

GROUND-WATER FLOW

Ground-water flow in the North Coast Limestone aquifer system is not well documented because of the difficulties in accurately defining flow in a karst environment; the lack of an adequate distribution of observation wells, as well as the lack of wells in the lower aquifer; and the lateral variability and complexity of the geology, especially in the lower aquifer. However, a generalized concept of ground-water flow was determined from available geologic and hydrologic information and well data.

Recharge to the upper aquifer is primarily from the part of the precipitation that infiltrates to the water table in the Aymamón and Aguada (Los Puertos) Limestones. The precipitation either enters the aquifer directly or percolates downward through overlying alluvial and blanket sands, the Quebradillas Limestone, or both. Recharge also occurs as leakage from streams in areas where streambeds are at a higher altitude than the water table, and some water from the lower aquifer might leak upward and enter the upper aquifer.

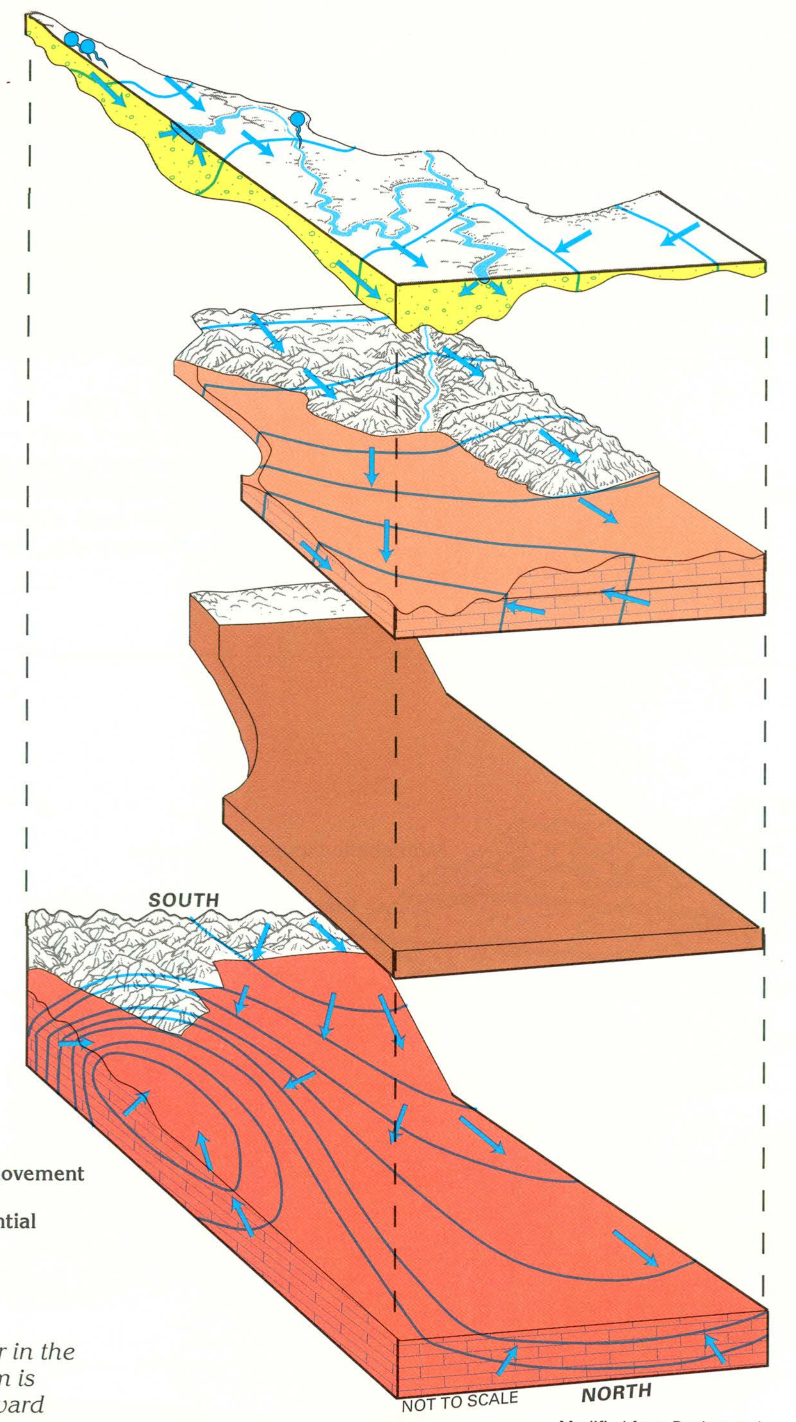
The Lares Limestone, Montebello Limestone, Río Indio Limestone, and the Quebrada Arenas Members of the Cibao Formation, the Mucarabones Sand, and local permeable beds of the San Sebastián Formation that compose the lower aquifer, are unconfined in their outcrop areas. Where they are exposed at the land surface, they are recharged from precipitation and possibly from streams.

A freshwater-saltwater interface is present at the coast in the upper part of the upper aquifer (**fig. 77**). Near the base of the aquifer, the interface extends from 1 to 3 miles inland; the conditions shown in **figure 77** are representative of the Vega Baja area. The interface is at sea level near the coast and becomes progressively deeper inland. Freshwater is present at the coast in the lower aquifer because the higher hydraulic head in the lower aquifer prevents saltwater from moving into the aquifer. A freshwater-saltwater interface probably is present in the lower aquifer an unknown distance seaward from the coast.

Regional ground-water flow in each of the aquifers follows the slope of the land surface and is northward and toward the Atlantic Ocean (**figs. 107, 108, 109*A***). Water in the upper aquifer discharges primarily to springs, to wetlands and swamps in coastal areas, and to streams (**fig. 108**). Much of the water that enters the lower aquifer's shallow flow system discharges to the principal north-flowing rivers and some large springs contained within these river valleys (**figs. 107, 109*A*, *B***). Some water enters deeper parts of the flow system and discharges by diffuse upward leakage through the confining unit to the upper aquifer. Both the upper and lower aquifers discharge by withdrawals from wells.

A water-table map of the upper aquifer from San Juan to the west coast is shown in **figure 108**. The water table slopes northward from an altitude of greater than 700 feet above sea level on the southern boundary of the aquifer to sea level at the coast. Thus, ground-water movement generally is northward toward the ocean and locally toward the major rivers. A large potentiometric depression which extends over a 14 square mile area northwest of Barceloneta is caused by agricultural dewatering in the Caño Tiburones area. Caño Tiburones is the site of a former shallow brackish water coastal lagoon that accumulated freshwater from adjacent springs and rivers. Drainage of the area caused soil shrinkage and land subsidence and gradually lowered the water table to sea level. Gravity drainage became less effective and a drainage system of canals, tidal gates and coastal pump stations was installed to water levels below sea level. The potentiometric depression has caused a reversal in gradient of the water table, and has caused intrusion of sea water into Caño Tiburones. Smaller cones of depression resulting from withdrawals between Barceloneta and Vega Baja have likewise caused a reversal in the regional gradient.

Little is known about ground-water flow in the area from the west coast to Isabella. Much of the area is a limestone plateau with an altitude typically greater than 300 feet above sea level. It is bordered on the north and west by seaward-facing cliffs and, therefore, has a deep water table. Chemical analysis of water from a well drilled near Isabella indicates that the upper aquifer in this area contains saltwater beneath a lens of freshwater that is only about 25 feet thick. The extent of this saltwater is unknown. Ground water contained in the lower aquifer in the extreme western part of the area probably moves toward the Rio Culebrinas and the ocean.



EXPLANATION

- Direction of ground-water movement
- Line of equal hydraulic potential
- Spring

Figure 107. Movement of water in the North Coast Limestone aquifer system is regionally northward and locally toward streams.

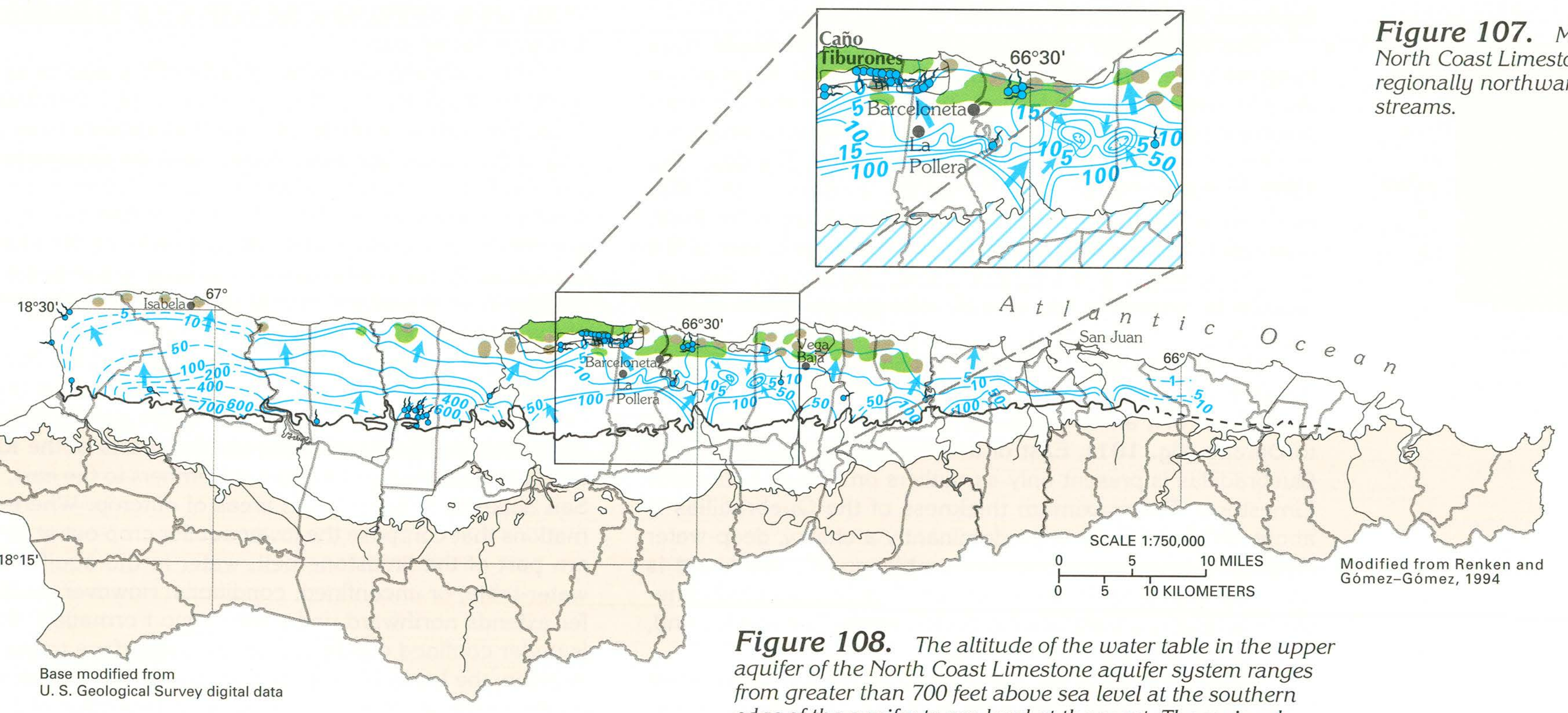


Figure 108. The altitude of the water table in the upper aquifer of the North Coast Limestone aquifer system ranges from greater than 700 feet above sea level at the southern edge of the aquifer to sea level at the coast. The regional gradient is northward toward the sea and locally is toward major rivers and areas of significant withdrawals by wells.

EXPLANATION

- Wetland or marsh
- Swamp
- Limit of upper aquifer—Dashed where approximately located
- Water-table contour—Shows altitude of the water table in the upper aquifer of the North Coast Limestone aquifer system during the period 1980–1990. Dashed where approximately located. Hachures indicate depressions. Contour interval, in feet, is variable. Datum is sea level.
- Direction of ground-water movement
- Spring

Water in the lower aquifer flows from the outcrop area of the Montebello Limestone Member of the Cibao Formation and the Lares Limestone, where it is under water-table conditions, northward and becomes confined by the upper, unnamed member of the Cibao Formation. The predevelopment potentiometric surface of the lower limestone aquifer from the west coast to San Juan is shown in **figure 109*A***. The maximum altitude of the potentiometric surface in the unconfined area on the south exceeds 1,250 feet above mean sea level and the gradient generally is northward toward the coast. Thus, regional ground-water movement is seaward, but deeply entrenched river valleys such as the Rio Grande de Arecibo and the Rio Grande de Manati are major discharge areas. Other rivers, such as the Rio Camuy, also appear to receive some discharge from the lower limestone aquifer. Ground-water movement in the outcrop area on the west end of the aquifer appears to be southward to the Rio Culebrinas. Ground-water movement in the area of Vega Baja and eastward generally appears to be eastward and locally to the Rio Hondo and other streams in that area.

Large cave systems represent major ground-water drains in some areas where the lower aquifer crops out. This is evident in the Rio Camuy cave system and the Rio Encantado cave system where potentiometric contours show a pattern indicative of ground-water discharge (**fig. 109*A***).

Ground-water development within confined parts of the lower aquifer are largely restricted to an area that extends eastward from Rio Grande de Arecibo to Laguna Tortuguero and southward to Florida and Montebello. Ground-water withdrawals from the lower aquifer for industrial and municipal purposes have caused a decline in the potentiometric surface of the lower aquifer (**fig. 110**). Well withdrawals in the Barceloneta area have drawn down water levels more than 150 feet during the period 1968 to 1987. However, the regional pattern ground-water flow in this area has not been greatly altered (**fig. 109*B***).

In the eastern end of the island between the Rio de la Plata and the Rio Espíritu Santo, the aquifer system is covered by unconsolidated blanket sands and alluvial deposits that range in thickness from about 100 feet in upland areas to about 300 feet in stream valleys. Ground water is under water-table conditions in the sands and alluvial deposits and the underlying upper aquifer of the limestone aquifer system. The lower aquifer is represented by the Mucarabones Sand and contains freshwater under confined conditions from the Rio de Bayamón to the Rio Piedras. In much of this area, the Aymamón Limestone of the upper aquifer contains saltwater because of its proximity to the sea. Ground-water discharge in this area is predominantly to streams that drain to the ocean; however, there also may be direct discharge from the aquifers to the ocean.

The area from the Rio de la Plata to the Rio Espíritu Santo has a long history of water-resources development. Large ground-water withdrawals, wetland drainage projects, dredging of San Juan Bay, channelization of the Rio Hondo and the Rio de Bayamón, and other developments have caused saltwater intrusion from the ocean. Although there is some freshwater in unconsolidated deposits, saltwater is present at depths of only about 100 feet; thus, ground-water development is now limited to small domestic wells. Generally, only small volumes of ground water are withdrawn in this area, and surface water is the principal source of supply. However, some wells are used as emergency sources of water for the city of San Juan.

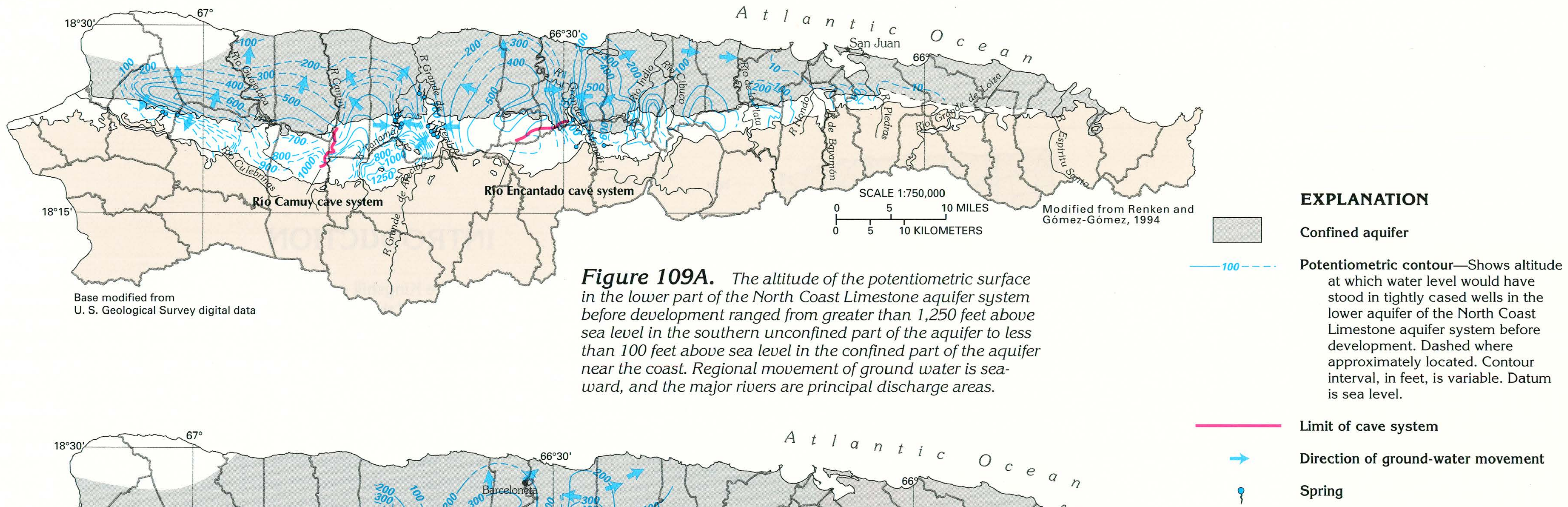


Figure 109A. *The altitude of the potentiometric surface in the lower part of the North Coast Limestone aquifer system before development ranged from greater than 1,250 feet above sea level in the southern unconfined part of the aquifer to less than 100 feet above sea level in the confined part of the aquifer near the coast. Regional movement of ground water is seaward, and the major rivers are principal discharge areas.*

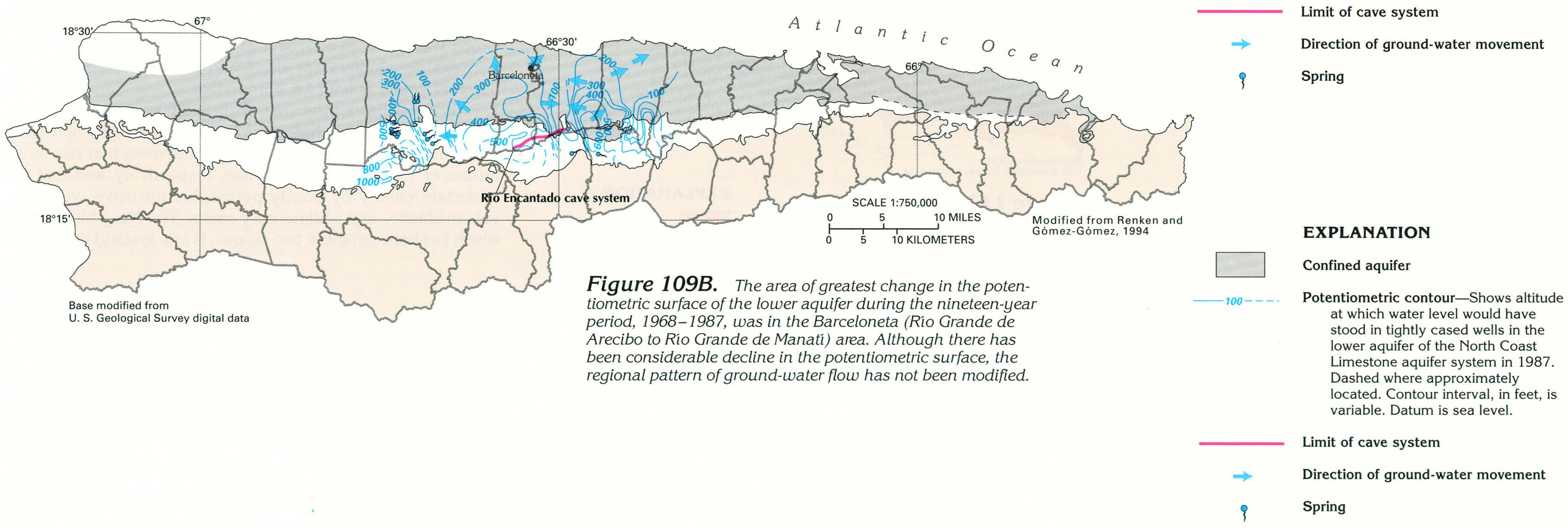


Figure 109B. *The area of greatest change in the potentiometric surface of the lower aquifer during the nineteen-year period, 1968–1987, was in the Barceloneta (Rio Grande de Arecibo to Rio Grande de Manati) area. Although there has been considerable decline in the potentiometric surface, the regional pattern of ground-water flow has not been modified.*

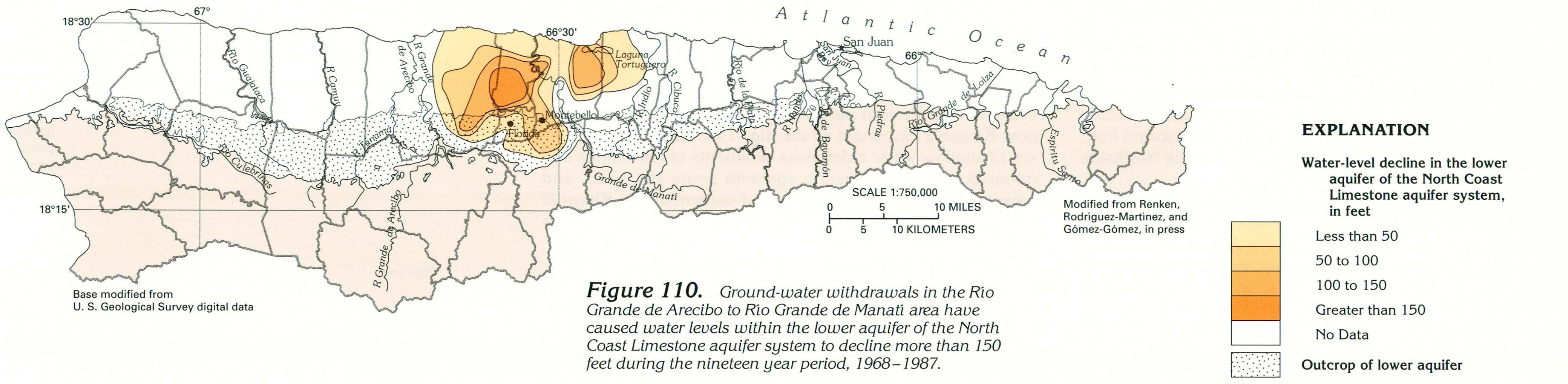


Figure 110. *Ground-water withdrawals in the Rio Grande de Arecibo to Rio Grande de Manati area have caused water levels within the lower aquifer of the North Coast Limestone aquifer system to decline more than 150 feet during the nineteen year period, 1968–1987.*

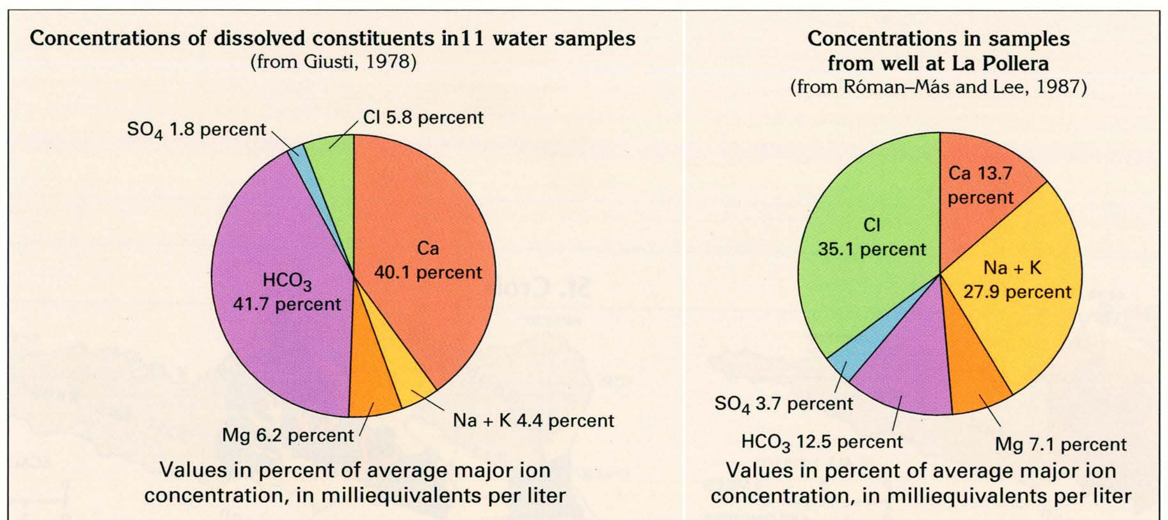
GROUND-WATER QUALITY

The natural chemical quality of water in inland areas of each of the aquifers of the North Coast Limestone aquifer system is suitable for most uses. The dominant chemical process that has affected the water in the aquifer is dissolution of the limestone. As a result, calcium and bicarbonate ions dominate the dissolved constituents in the water, and the water is slightly alkaline (**fig. 111**). Average concentrations of chloride, sulfate, sodium, and potassium total only about 12 percent of the dissolved ions. Average magnesium concentration is greater in water from the lower aquifer than in water from the upper aquifer but generally is small (about 6 percent), which reflects the small amount of dolomite in the rocks.

The chemical quality of the water changes as it moves from aquifer outcrop areas downgradient toward the Atlantic Ocean. Concentrations of dissolved magnesium, dissolved sulfate, dissolved solids, and pH of the water generally increase oceanward. Within the upper aquifer, continuous recharge maintains the dissolution of carbonate minerals, and calcium and bicarbonate remain the dominant ions in much of the aquifer.

Near the coast, saltwater underlies and mixes with freshwater in the upper aquifer. This mixing causes large concentrations of dissolved sodium, potassium, and chloride in the ground water. Sea spray carried inland by wind enters the aquifer, which further contributes to the increase of sodium and chloride ions. Mixing of saltwater and freshwater is the dominant chemical process in the upper aquifer near the coast, and, in some places, for a considerable distance inland. For example, water from a well completed in the upper aquifer at La Pollera (**fig. 108**), almost 5 miles from the coast, contains large concentrations of sodium and chloride (**fig. 111**). The lower aquifer, where it is present at the coast, is protected from the downward leakage of saltwater by the overlying confining unit. The hydraulic gradient in this aquifer also is upward where the aquifer is confined. The lower aquifer probably contains freshwater throughout its entire inland extent.

Excessive ground-water withdrawals and chemical spills on the land surface locally have caused changes in the quality of the water in the limestone aquifers. Various organic chemicals used as industrial solvents, degreasers, dry-cleaning agents, and other uses have been detected in water from wells. Many of these organic contaminants have found their way into the limestone aquifers and locally are present in concentrations as large as 770 micrograms per liter. The contaminants have forced the abandonment of 13 public water-supply wells; the wells had a combined production of 5.5 million gallons per day. In the Rio de la Plata to the Rio Espíritu Santo area, excessive ground-water withdrawals and dewatering accompanying urbanization have caused the migration of saltwater from the ocean into the limestone aquifers. As a result, continuously operated public-supply wells exist only near the Rio de la Plata; these wells have a sustained yield of less than 4 million gallons per day.



Concentrations in milligrams per liter, unless otherwise specified

Constituent	Range	Average	Number of samples	
pH (standard units)	7.2 to 8.0	- -	10	7.2
Calcium (Ca)	37 to 112	83.3	11	93
Magnesium (Mg)	1.7 to 18	7.8	11	29.0
Sodium (Na)	6.2 to 19	10.0	10	210
Potassium (K)	0.0 to 1.5	.6	10	11
Bicarbonate (HCO_3)	136 to 385	264		257
Sulfate (SO_4)	2.0 to 28	9.1	11	60
Chloride (Cl)	10 to 39	21.2	11	420
Silica (SiO_2)	3.6 to 21	7.9	11	7.1
Dissolved solids	205 to 523	318	10	1030

Figure 111. *The chemical quality of water in much of the aquifer system is suitable for most uses and is a calcium bicarbonate type. The water becomes more mineralized downgradient and becomes a sodium chloride type nearer the ocean.*

FRESH GROUND-WATER WITHDRAWALS

Total fresh ground-water withdrawals from the North Coast Limestone aquifer system during 1985 were about 66 million gallons per day (**fig. 112**). Withdrawals for public supply accounted for the majority of the water pumped from the aquifer system; 65.5 percent, or about 43 million gallons per day, was withdrawn for this use. Public supply use was concentrated in the principal cities of the north coast in the area west of the Río de la Plata. Self-supplied domestic and commercial withdrawals from the aquifer system were only about 3.3 percent of the total withdrawals during 1985, or 2.18 million gallons per day. The limited use of water for domestic and commercial purposes reflects the largely urban population along the north coast; most of the population was supplied from public rather than private systems. Agricultural use of water from the aquifer system was largely for irrigation at plant nurseries and for dairies along the coast. Agricultural withdrawals during 1985 amounted to 15.7 percent, or about 10 million gallons per day. Other agricultural uses of water, largely stock watering, were probably less than 5 percent of the total agricultural withdrawals. Industrial withdrawals accounted for 15.5 percent, or 10.2 million gallons per day. An estimated 5 million gallons per day was pumped from the lower aquifer for industrial use along the north coast, mainly in Barceloneta Municipio. Minimal ground-water withdrawals were reported for aggregate mining during 1985, and no withdrawals for thermoelectric power generation were reported.

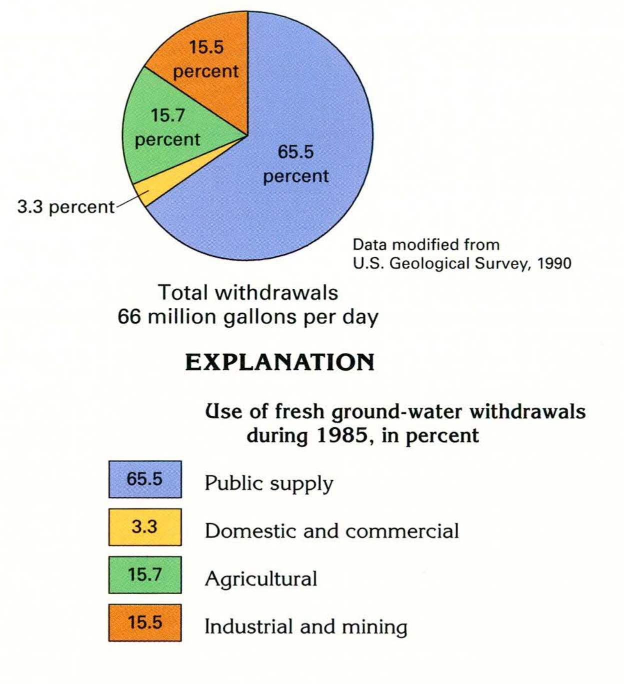


Figure 112. *Almost two-thirds of the fresh ground-water withdrawals from the aquifer system during 1985 were for public supply. Most of the remaining withdrawals were equally divided between agricultural and industrial and mining uses.*

Kingshill aquifer

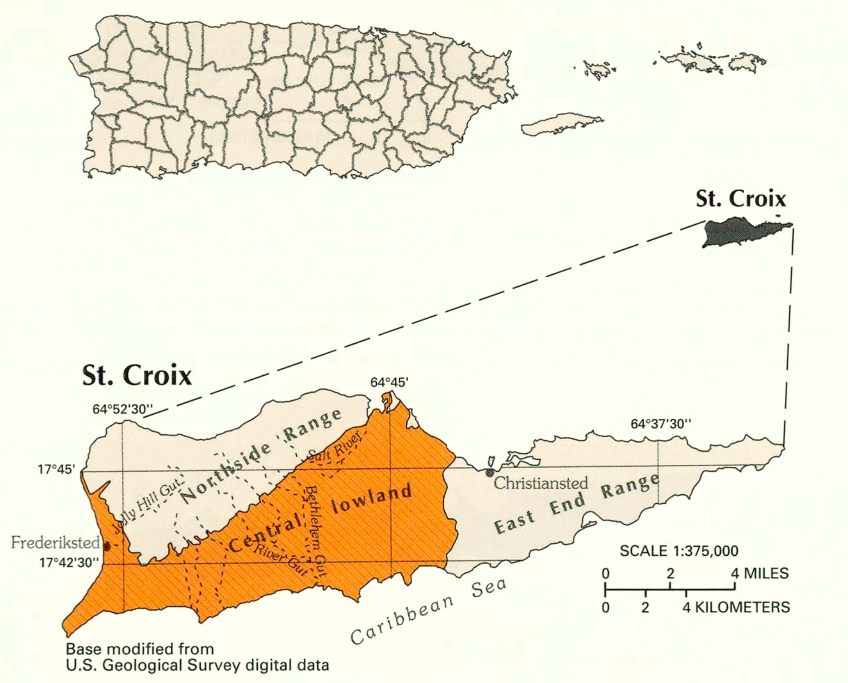


Figure 113. *The Kingshill aquifer is in the central and southwestern parts of the island of St. Croix in the U.S. Virgin Islands.*

EXPLANATION

Kingshill aquifer

INTRODUCTION

The Kingshill aquifer is located in the central to southwestern parts of the island of St. Croix in the Virgin Islands of the United States (**fig. 113**). The aquifer consists of limestone and marl that has a maximum saturated thickness of about 200 feet. Although the aquifer produces only small volumes of water of marginal chemical quality, it is the only significant aquifer in the U.S. Virgin Islands and supplies a large proportion of the water needed for public supply and industry on St. Croix. Water is scarce on St. Croix. Streamflow is meager and not reliable; aquifers are small and yield mineralized water, much of which is unfit for human use.

St. Croix has a total area of about 80 square miles and is dominated in the northwestern (Northside Range) and eastern (East End Range) parts by highland areas that rise to altitudes of 1,088 feet and 866 feet, respectively, and that are underlain chiefly by poorly permeable intrusive, volcanic, volcaniclastic, and sedimentary rocks. The Kingshill aquifer, which lies between these two ranges, is in a lowland that slopes from the south flank of the Northside Range southward to the sea. The surface of the limestone and marl that compose the aquifer has been deeply eroded, but about one-fourth of it is covered by a blanket of alluvium, alluvial fan, debris flow, and slope wash deposits as much as 80 feet thick, which moderates the dissected topography and forms a broad rolling plain through which low, rounded limestone hills are exposed.

St. Croix has four major streams that flow intermittently. All four rise in the Northside Range, and River Gut, the largest, flows southward across the Kingshill aquifer to the sea. The other three streams flow mostly across volcanic rocks to the west coast. The remainder of the streams on the island are very short and flow only after heavy rains.

Although average annual rainfall in St. Croix is abundant, ranging from 30 inches on the east to 50 inches in the mountains of the Northside Range, most of the rainfall is returned to the atmosphere by evapotranspiration, and not more than about 3 percent is available for recharge to aquifers.

HYDROGEOLOGIC UNITS

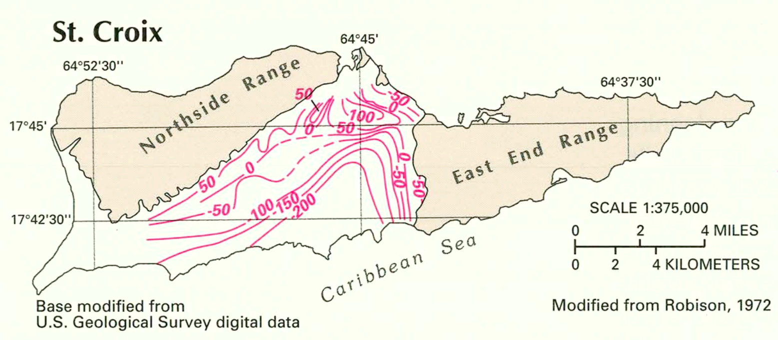
The island of St. Croix is roughly divided into thirds, both geologically and topographically. The mountainous northwestern and eastern parts are underlain by faulted and deformed volcaniclastic and sedimentary rocks of the Mount Eagle Group of Late Cretaceous age (**fig. 73; table 7**) that have been intruded by the Fountain Gabbro in the Northside Range and the Southgate Diorite in the East End Range. These two ranges are separated by a sediment-filled graben structure that has surface expression as a broad plain that occupies the central and southwestern one-third of the island. The northeastern part of the central plain is characterized by a hilly and dissected carbonate highland area. The plain slopes southeastward from about 400 feet above sea level where it adjoins the Northside Range to sea level on the southern coast.

The lower part of the graben is filled to an estimated depth of 6,000 feet with the Jealousy Formation of Miocene to Oligocene (?) age (**table 7**). The top of the Jealousy Formation is buried throughout its extent; its upper surface generally slopes southeastward from an elevation of about 100 feet above sea level in the north-central part of the island (**fig. 114**) to about 200 feet below sea level on the south coast. The formation, which is described as a blue clay by well drillers, is made up primarily of deep-water calcareous mud, marl, or limestone. The Jealousy Formation represents hydrologic basement due to the progressively poorer quality water with increasing depth.

Conformably overlying the Jealousy Formation is the Kingshill Limestone (**fig. 115; table 7**), which consists mostly of deep-water limestone and marl, calcareous clay, and some conglomerate. Recent work on St. Croix indicates that the contact of the Kingshill Limestone and the Jealousy Formation may represent only a color change due to oxidation of the Kingshill sediments by circulating ground water. Thus, the two formations may represent continuous deposition. It does appear, however, that the contact represents a hydrologic boundary and, therefore, the Jealousy Formation forms the bottom of the Kingshill aquifer.

Unconformably overlying the Kingshill Limestone in the southern and western parts of the central plain are unnamed post-Kingshill carbonate strata (**fig. 115; table 7**) that consist of shallow-water calcareous sediments of limestones and minor dolomite of Pliocene age with some silt, sand, and gravel. The Kingshill Limestone and unnamed post-Kingshill carbonate rocks compose the Kingshill aquifer; the rocks dip and thicken southeastward.

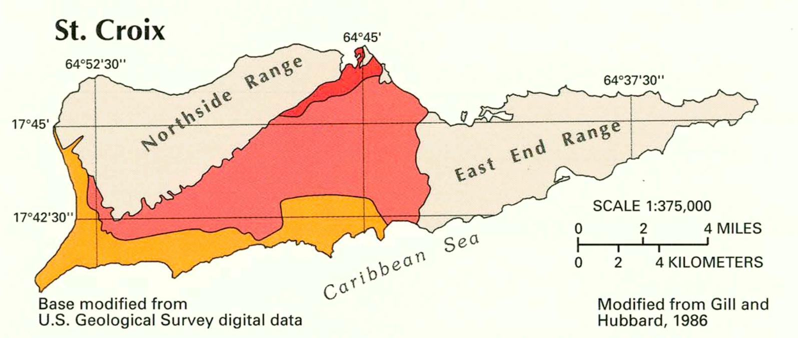
Alluvial material, including sandy to clayey river valley deposits, alluvial fan, debris flow, colluvial deposits, and beach terraces, overlies the Kingshill Limestone and unnamed post-Kingshill carbonate rocks. The alluvial material fills bedrock valleys and subdues the topography of the dissected surface of the Kingshill Limestone. The alluvial material thickens southward to a maximum of about 80 feet, whereas silt- and clay-rich alluvial fan and debris flow deposits are usually less than 30 feet in thickness.



EXPLANATION

—50— Structure contour—Line shows equal altitude of the top of the Jealousy Formation. Dashed where approximately located. Contour interval is 50 feet. Datum is sea level

Figure 114. *The top of the Jealousy Formation forms the base of the Kingshill aquifer and slopes southeastward from about 100 feet above sea level on the northeast to 200 feet or more below sea level at the southern coast.*



EXPLANATION

Post-Kingshill carbonate rocks

Reef and shelf limestone; some dolomite

Kingshill Limestone

Lithic conglomerate in marly matrix

Foraminiferal marl and limestone

Figure 115. *The lithology of the Kingshill Limestone and post-Kingshill carbonate rocks is variable.*

Table 7. *Rocks of St. Croix range from Cretaceous to Holocene in age. The rocks vary in lithology from intruded, faulted, and deformed volcaniclastic rocks to flat-lying limestone units to unconsolidated sand, gravel, and beach deposits. The water-yielding properties of the rocks vary according to rock type.*

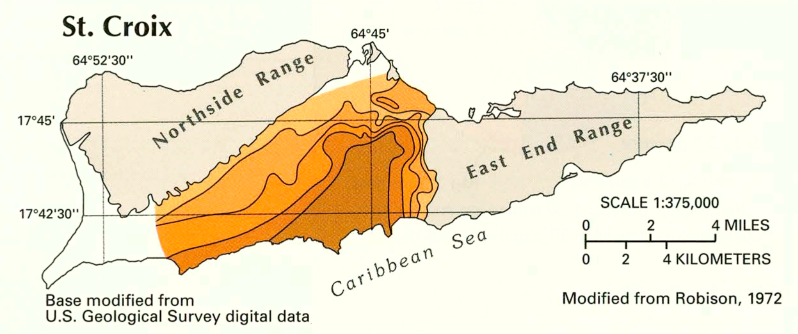
[Modified from Jordan, 1975]

Geologic age	Formation	General character and distribution	Water-bearing properties
Holocene and Pleistocene	Beach deposits	Unconsolidated calcareous sand; consolidated beach rock in intertidal zones. Present irregularly along shore, particularly as beaches in embayments.	Moderate permeability. Saturated below sea level, mostly with brackish water.
	Alluvium	Poorly sorted silt, clayey sand, and some gravel. Thin beds of sand and gravel usually in bedrock valleys, principally on south coast. Alluvium partly covers limestone in central part of island.	Low permeability in silt and clay deposits, but some sand and gravel beds have moderate permeability. Yields only small amounts of water to wells but often major source of water to underlying and adjacent rocks. Water is fresh, becoming brackish near shore.
Pliocene	Post-Kingshill carbonate rocks	A complex of fossiliferous reef and lagoonal limestone and dolomitic limestone.	Permeability of limestone generally moderate to high, but variable. Permeability enhanced by karstic solution voids that may promote seawater intrusion along the coast. Part of Kingshill aquifer.
Miocene	Kingshill Limestone	Foraminiferal marl and limestone with thin interbeds of terrigenous and carbonate turbidite deposits.	Commonly contains slightly brackish water, becoming more salty with depth. Permeability generally moderate to low. Principal part of Kingshill aquifer.
Miocene to Oligocene(?)	Jealousy Formation	Dark-gray to blue-green foraminiferal marl and limestone. Found only in subsurface underlying Kingshill Limestone.	Forms base of aquifer due to progressively poorer chemical quality of water with increasing depth.
Late Cretaceous	Fountain Gabbro and Southgate Diorite	Fractured and weathered to depths of 50 feet. Fountain Gabbro in Northside range; Southgate Diorite in East End Range.	Generally not an aquifer. Moderate to low permeability in weathered zones. Water brackish in coastal parts of Southgate Diorite.
Late Cretaceous	Mount Eagle Group	Tuffaceous sandstone, tuffaceous sandstone-mudstone, calcareous mudstone and siltstone, pebble conglomerate.	Permeability generally low. Porosity of rocks due to open fractures and joints. Water of good quality in central mountains, brackish in immediate coastal areas and eastern-most end of island. Well yields generally greatest where overlain by alluvial deposits.

AQUIFERS AND CONFINING UNITS

The post-Kingshill carbonate rocks are far more permeable than the carbonate rocks of the Kingshill aquifer. However, the two units act together as a single unconfined aquifer. Alluvial deposits, which are made up of clay, silt, sand, and gravel, mostly fill erosional valleys in the Kingshill Limestone and the post-Kingshill carbonate rocks and generally underlie existing drainage. The alluvial deposits serve principally as zones in which recharge from rainfall and streamflow is stored temporarily and then percolates downward to recharge the underlying Kingshill aquifer. Upland areas between streams have only a shallow, unsaturated soil that overlies the aquifer. The saturated thickness of the Kingshill aquifer ranges from less than 50 feet near the Northside Range to more than 200 feet near the coast in the south-central part of the island (**fig. 116**).

A band of clayey alluvial fan and debris flow deposits is present along the southern flank of the Northside Range (**fig. 117**). The clayey deposits are poorly sorted and generally yield less than 5 gallons per minute to wells. Elsewhere, the alluvium tends to be coarser grained and yields from 5 to 100 gallons per minute to wells.

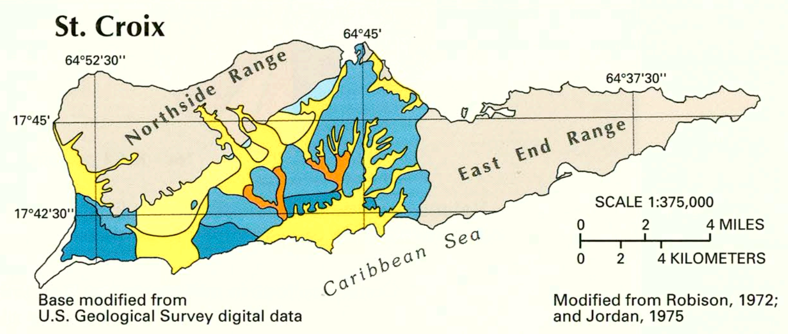


EXPLANATION

Saturated thickness of the Kingshill aquifer, in feet

50
100
150
200
Insufficient data

Figure 116. *The estimated saturated thickness of the Kingshill aquifer ranges from less than 50 feet near the Northside Range to over 200 feet in the east-central part of the aquifer.*



EXPLANATION

Probable yield of water to wells, in gallons per minute

Alluvial aquifer	Kingshill aquifer
Less than 5	Less than 5
5 to 30	5 to 20
30 to 100	20 to 100
Insufficient data	

Figure 117. *The probable yield of water to wells is greatest in gravelly sand deposits of the alluvial aquifer and in reef and shelf limestone of the Kingshill aquifer.*

HYDRAULIC PROPERTIES

The marl of the Kingshill Limestone generally has microscopic porosity and is permeable only where it is fractured. However, the fractures might be partially closed and poorly connected. Wells that encounter connected fractures in the marl yield about 5 to 20 gallons per minute. Wells completed in limestone beds of the Kingshill or in minor terrigenous deposits of the formation might yield larger amounts of water. The post-Kingshill carbonate rocks are more permeable because they contain well-defined fractures and solution cavities, as well as intergranular porosity. Yields to wells completed in the post-Kingshill carbonate rocks range from 20 to 100 gallons per minute, and the wells have specific capacities from about 0.5 to 50 gallons per minute per foot of drawdown.

The estimated transmissivity of the Kingshill aquifer (**fig. 118**) reflects the increased saturated thickness, as well as the higher permeability, where the post-Kingshill carbonate rocks occur along the southern part of the aquifer. Transmissivities are least in a wide band parallel to the south flank of the Northside Range. The aquifer dips and thickens southeastward toward the ocean and is thinnest in this wide band.

GROUND-WATER FLOW

Regional ground-water flow in the Kingshill aquifer is southeastward, approximately parallel to the dip of strata that compose the aquifer (**fig. 119**). Locally, movement is northeastward toward Salt River Bay in the north-central part of the island.

The principal recharge to the Kingshill aquifer is from infiltration of an estimated 3 percent of the precipitation that falls on the aquifer and is not lost to evapotranspiration. Some recharge also is from streams, especially during periods of storm runoff, when the altitude of the water in the stream is above that of the water table. Some water from runoff of the Northside Range may enter the aquifer at its contact with the volcaniclastic and sedimentary rocks. Water readily moves into the permeable alluvium and into fractures in the marl and limestone.

Ground water moves down the hydraulic gradient defined by contours on the water table (**fig. 119**). The broad spacing of the contours in the north-central part of the aquifer indicates a shallow gradient that changes to a steeper gradient (indicated by closer spacing) in the central part of the aquifer. A shallow gradient also is shown by the broad contour spacing along the south coast. The gradient changes probably reflect permeability changes in the aquifer related to fracturing, thickness of alluvium, and the presence of the more permeable post-Kingshill carbonate rocks along the south coast.

Discharge from the Kingshill aquifer is largely to wells and to the ocean, but some water also probably discharges to streams during high stages of the water table. Evapotranspiration also accounts for some discharge of water where the water table is less than 20 feet below land surface.

A freshwater-saltwater interface occurs where the aquifer meets the sea. The interface is in the form of a transition zone from freshwater to saltwater and slopes downward and landward from the coastline. Freshwater from the aquifer moves up this interface to discharge at the sea floor.

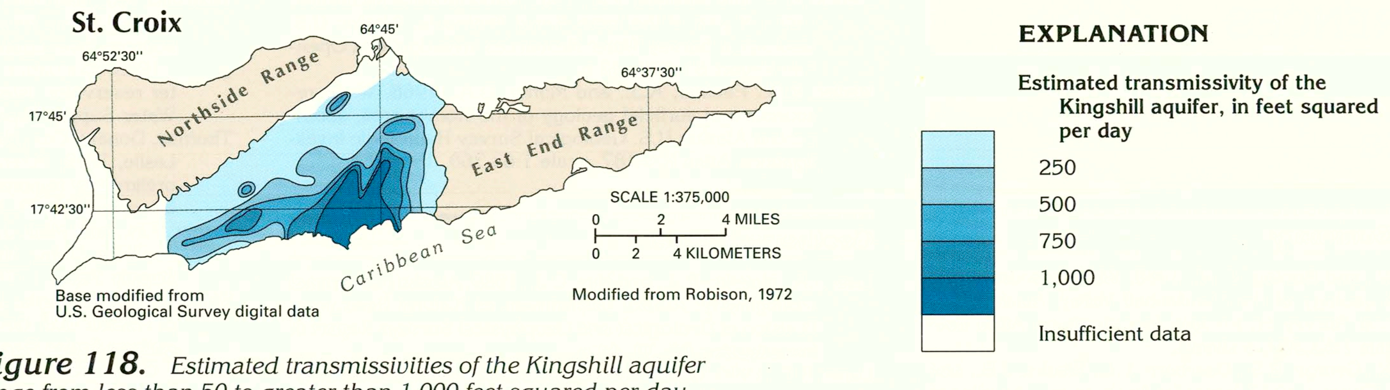


Figure 118. Estimated transmissivities of the Kingshill aquifer range from less than 50 to greater than 1,000 feet squared per day.

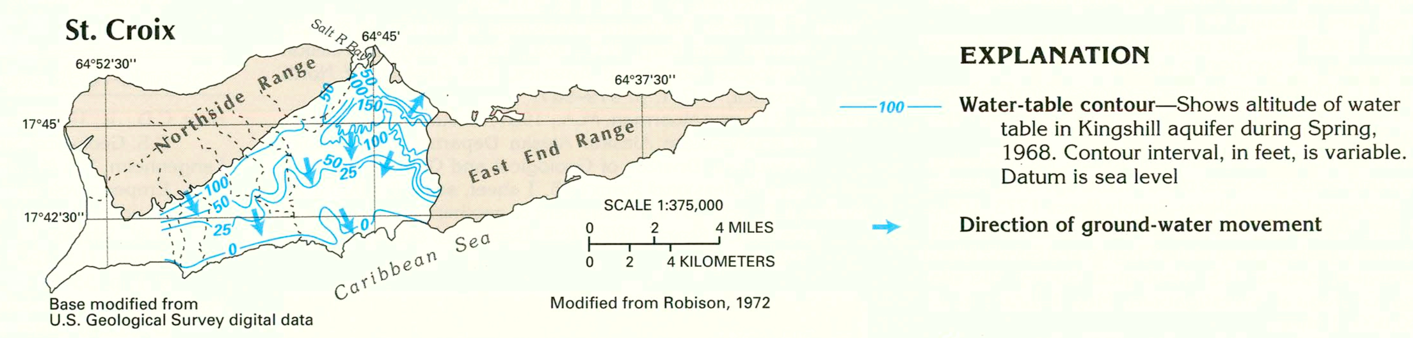
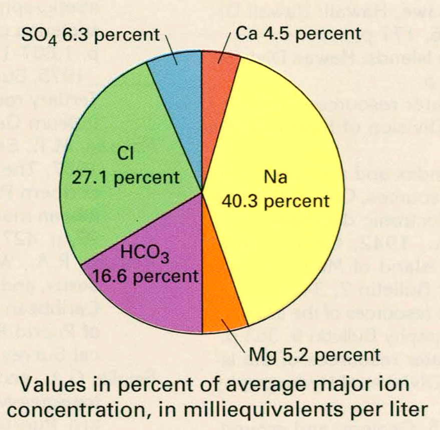


Figure 119. The water table in the Kingshill aquifer slopes southeastward and ranges in altitude from 150 feet on the north and slopes to sea level at the south coast. In the hilly terrain of the northeastern Central Lowland, the water table locally slopes to the northeast.

Concentration, in milligrams per liter

Constituent	Range	Average	Number of samples
Hardness($CaCO_3$)	22 to 1240	289	65
Calcium(Ca)	6 to 168	53	66
Magnesium(Mg)	1 to 126	37	66
Sodium(Na)	125 to 1090	536	65
Bicarbonate(HCO_3)	292 to 852	588	65
Sulfate(SO_4)	16 to 752	176	65
Chloride(Cl)	70 to 1680	556	66
Dissolved solids	738 to 3470	1610	65



Data from Robison, 1972

Figure 120. Analyses of water from the Kingshill aquifer indicate that the water is typically a sodium chloride type and that average dissolved-solids concentrations exceed 1,600 milligrams per liter.

GROUND-WATER QUALITY

The chemical quality of water in the Kingshill aquifer is marginal for human consumption and most other uses. A criterion on the island for use of water from the aquifer for drinking purposes is that the water contain chloride concentrations of less than 500 milligrams per liter; this is nearly twice the concentration of chloride recommended for drinking water by the U.S. Environmental Protection Agency. Dissolved-solids concentrations generally exceed 1,000 milligrams per liter, which is the definition of saline water used in this report. These values are for the part of the aquifer that contains the least mineralized water. Water quality deteriorates with depth and is highly saline in some areas.

The island environment of the Kingshill aquifer has an influence on ground-water quality. The source of ions in the water is not only from partial dissolution of aquifer minerals, but includes ions from seawater that is transported to the land surface by precipitation, waves, and sea spray and percolates downward to recharge the aquifer. Chloride in the ground water is largely from sea spray or residual salts in the aquifer matrix. Other ions are probably derived from dissolution of aquifer minerals, which include carbonate minerals as well as siliceous volcaniclastic material incorporated in the aquifer.

Analyses of water from the western and southern parts of the aquifer indicate that the water typically is a sodium chloride type and that average dissolved-solids concentrations exceed 1,600 milligrams per liter (**fig. 120**). Although water that contains dissolved-solids concentrations of 1,000 milligrams per liter is considered to be saline water in this report, on St. Croix water with concentrations of dissolved solids in the order of 2,000 to 5,000 milligrams per liter is used for many purposes because no less-mineralized water is available in most places.

Water in the Kingshill aquifer becomes highly mineralized with depth. The chloride concentration of the water increases rapidly with increasing depth below sea level (**fig. 121**). The distribution of dissolved-solids concentrations in water from the shallow part of the aquifer (**fig. 122**) indicates a general increase downgradient and toward the sea.

GROUND-WATER WITHDRAWALS

Total ground-water withdrawals from the Kingshill aquifer during 1985 were about 0.96 million gallons per day (**fig. 123**). The aquifer produced only small quantities of water, most of which was highly mineralized. About 81 percent of the water withdrawn, or about 0.78 million gallons per day, was used for domestic and commercial purposes. About 15 percent of the withdrawals, or about 0.14 million gallons per day, was used for public supply; only about 3 percent, or about 0.04 million gallons per day, was withdrawn for industrial, mining, and agricultural uses. No ground water was used for thermoelectric power production. Most of the water withdrawn is mixed with seawater and used to feed desalination plants for public supply. In many households not served by public supply systems, water from the Kingshill aquifer is supplemented with freshwater obtained from roof-top collection systems.

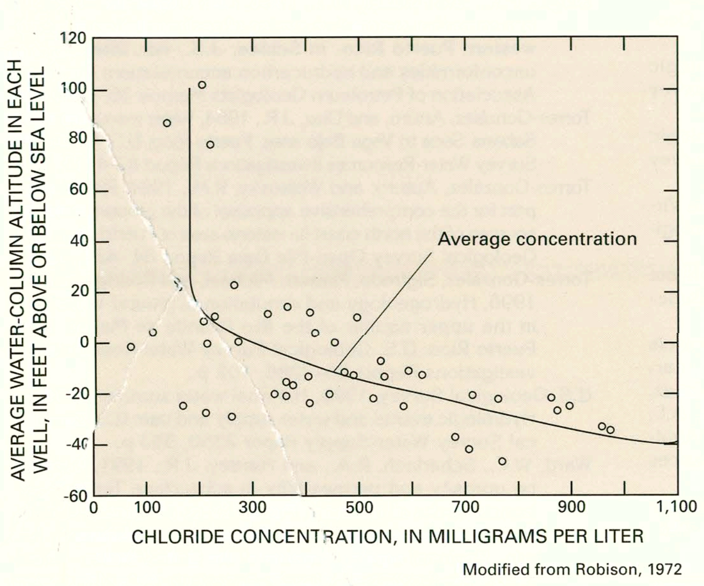


Figure 121. Water quality in the Kingshill aquifer deteriorates with depth and rapidly increases in mineralization below sea level.

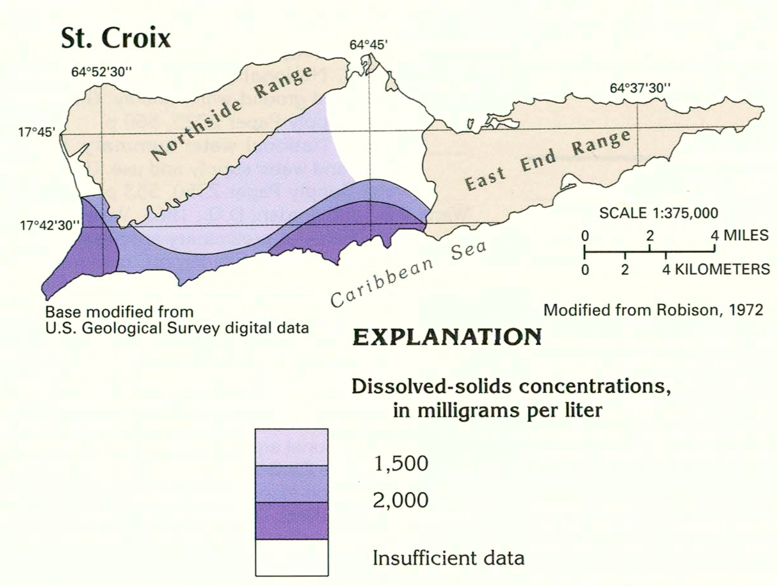


Figure 122. Dissolved-solids concentrations in ground water in the Kingshill aquifer generally increase downgradient toward the sea.

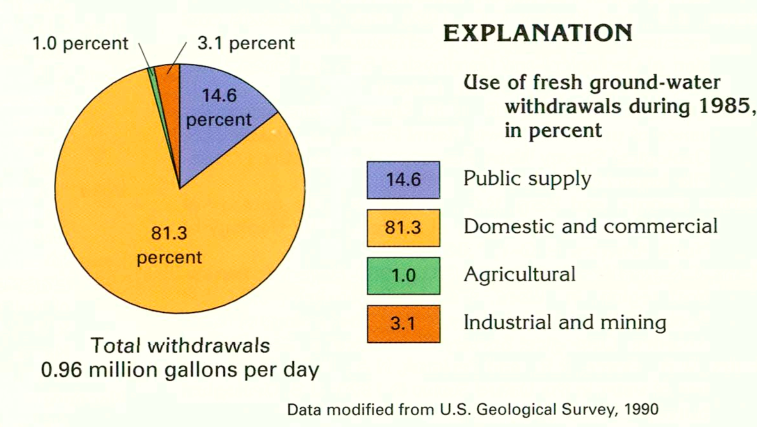


Figure 123. Most of the water withdrawn from the Kingshill aquifer in 1985 was used for domestic and commercial purposes.

Minor aquifers

INTRODUCTION

There is a large demand for water in Puerto Rico and the Virgin Islands; thus, even minor sources of ground water that can be developed for domestic, commercial, or other purposes are important locally. An atlas of the ground-water resources of these islands, therefore, would be incomplete without at least a synopsis of these minor aquifers.

Puerto Rico and the Virgin Islands each have a central core of faulted and folded volcaniclastic, igneous, and sedimentary rocks (**fig. 124**). Although these rocks have little or no intergranular porosity, some secondary permeability has developed as a result of weathering, faulting, and fracturing. These secondary openings transmit and store small volumes of water that can be recovered through wells.

Freshwater also is present in small alluvial deposits in coastal embayments of the Virgin Islands (**fig. 124**). These deposits are commonly exploited for small supplies of water.

VOLCANICLASTIC-, IGNEOUS-, AND SEDIMENTARY-ROCK AQUIFERS

The volcaniclastic-, igneous-, and sedimentary-rock aquifers consist of the upper 50 feet to a maximum of 300 feet of fractured and weathered volcaniclastic, plutonic, and sedimentary rocks that make up the core of each of the islands (**fig. 124**). Where exposed, these rocks store and transmit small quantities of water in fractures and overlying saprolite. The water can be recovered through domestic and small-diameter commercial wells that generally yield 5 to 10 gallons per minute or less. Although yields to individual wells are small, the area of the volcaniclastic-, igneous-, and sedimentary-rock aquifers comprises a large part of each of the islands, and the aquifers generally are the only source of ground water in those areas

Fresh ground-water withdrawals from these aquifers during 1985 amounted to about 11 million gallons per day in Puerto Rico and about 0.36 million gallons per day in the Virgin Islands. This constituted about 6 percent of the total ground-water withdrawals in Puerto Rico and about 25 percent of the total ground water withdrawn on the Virgin Islands.

Water in the volcaniclastic-, igneous-, and sedimentary-rock aquifers generally is very hard and locally contains large concentrations of sodium, chloride, bicarbonate, iron, and manganese.

COASTAL EMBAYMENT AQUIFERS

Coastal embayment aquifers in the Virgin Islands consist of alluvial valley-fill deposits that grade into beach sands as the bedrock valleys open onto coastal embayments (**fig. 124**). The alluvium, which commonly ranges in thickness from 30 to 50 feet, generally is fine grained and consists of clay, silt, and fine sand eroded primarily from volcanic rocks. Where they contain mostly fine-grained sediments, the aquifers yield only small amounts of water and are semiconfined. Locally, the alluvium is coarse sand and gravel, and the aquifer is unconfined. The alluvial deposits interfinger and grade into beach deposits that consist primarily of coarse coral sand. These deposits are permeable and yield only a few gallons per minute to wells. However, water in the coastal embayment aquifers is generally brackish to saline. Approximately 0.11 million gallons per day was withdrawn from the coastal embayment aquifers during 1985. The water is used primarily for domestic nondrinking purposes and as feed water to supply reverse osmosis desalination units.

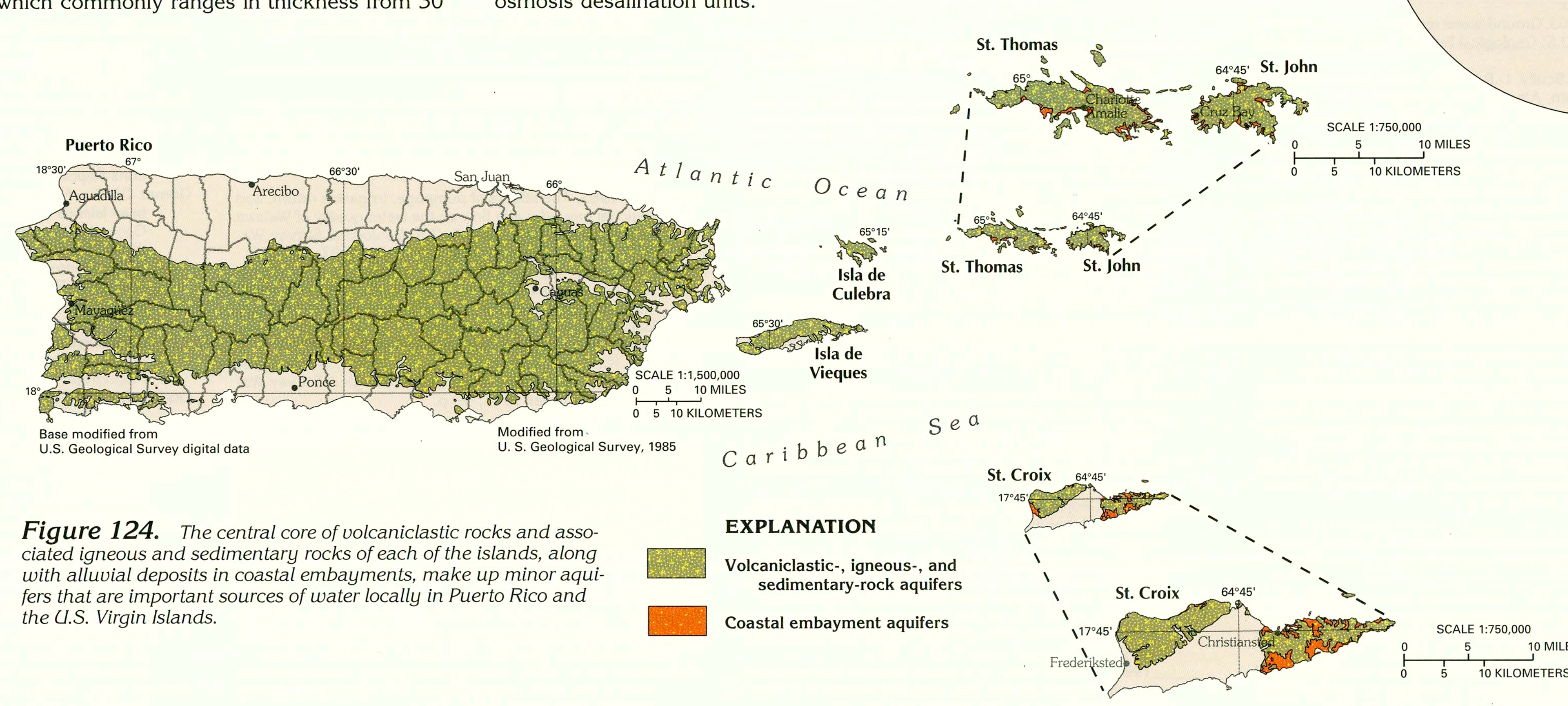


Figure 124. The central core of volcaniclastic rocks and associated igneous and sedimentary rocks of each of the islands, along with alluvial deposits in coastal embayments, make up minor aquifers that are important sources of water locally in Puerto Rico and the U.S. Virgin Islands.

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