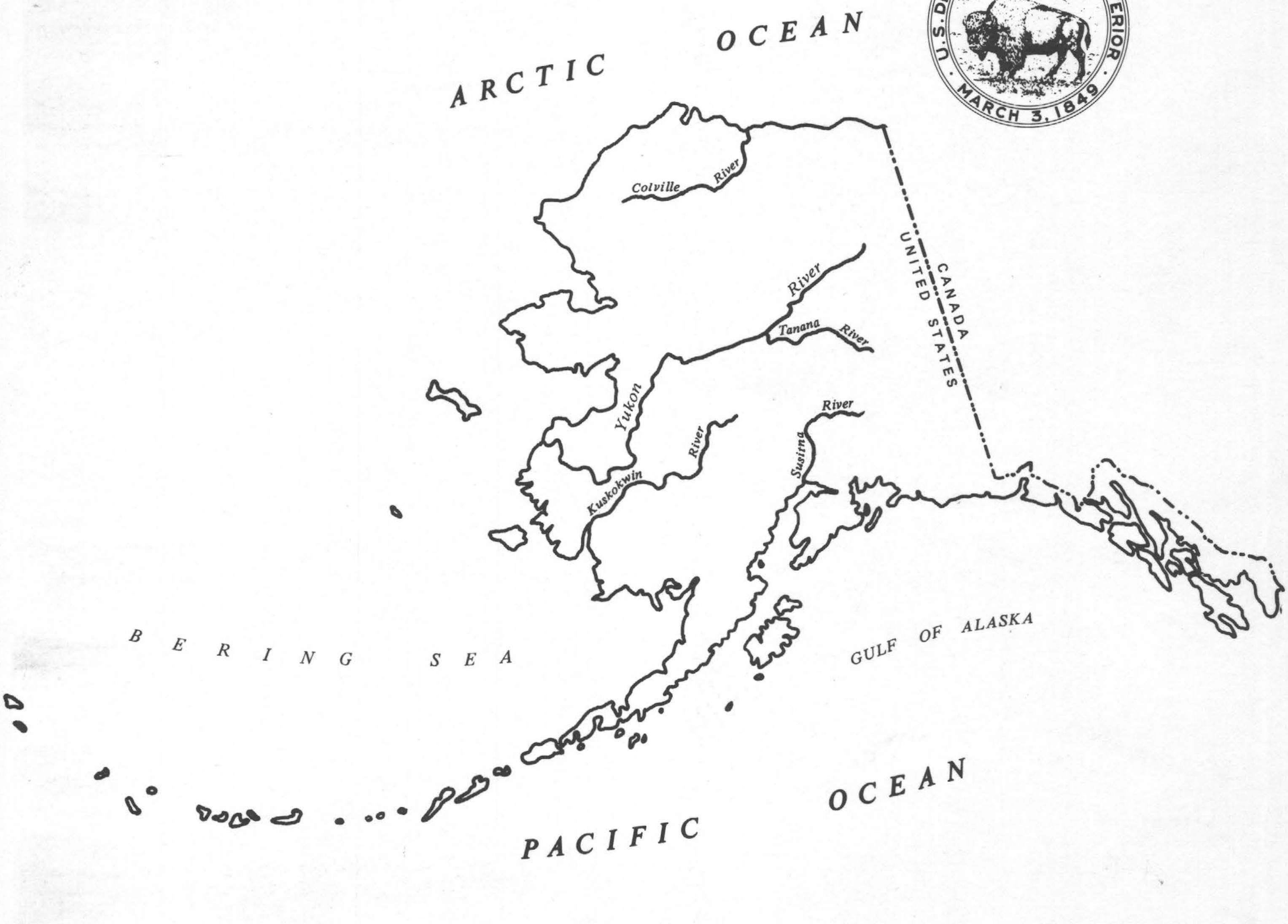
Summary Appraisals of the Nation's Ground-Water Resources— Alaska

GEOLOGICAL SURVEY PROFESSIONAL PAPER 813-P



Summary Appraisals of the Nation's Ground-Water Resources— Alaska

By CHESTER ZENONE *and* GARY S. ANDERSON

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A summary of the distribution and availability of ground water, the problems related to its development and use, and its significance in arctic and subarctic climatic zones

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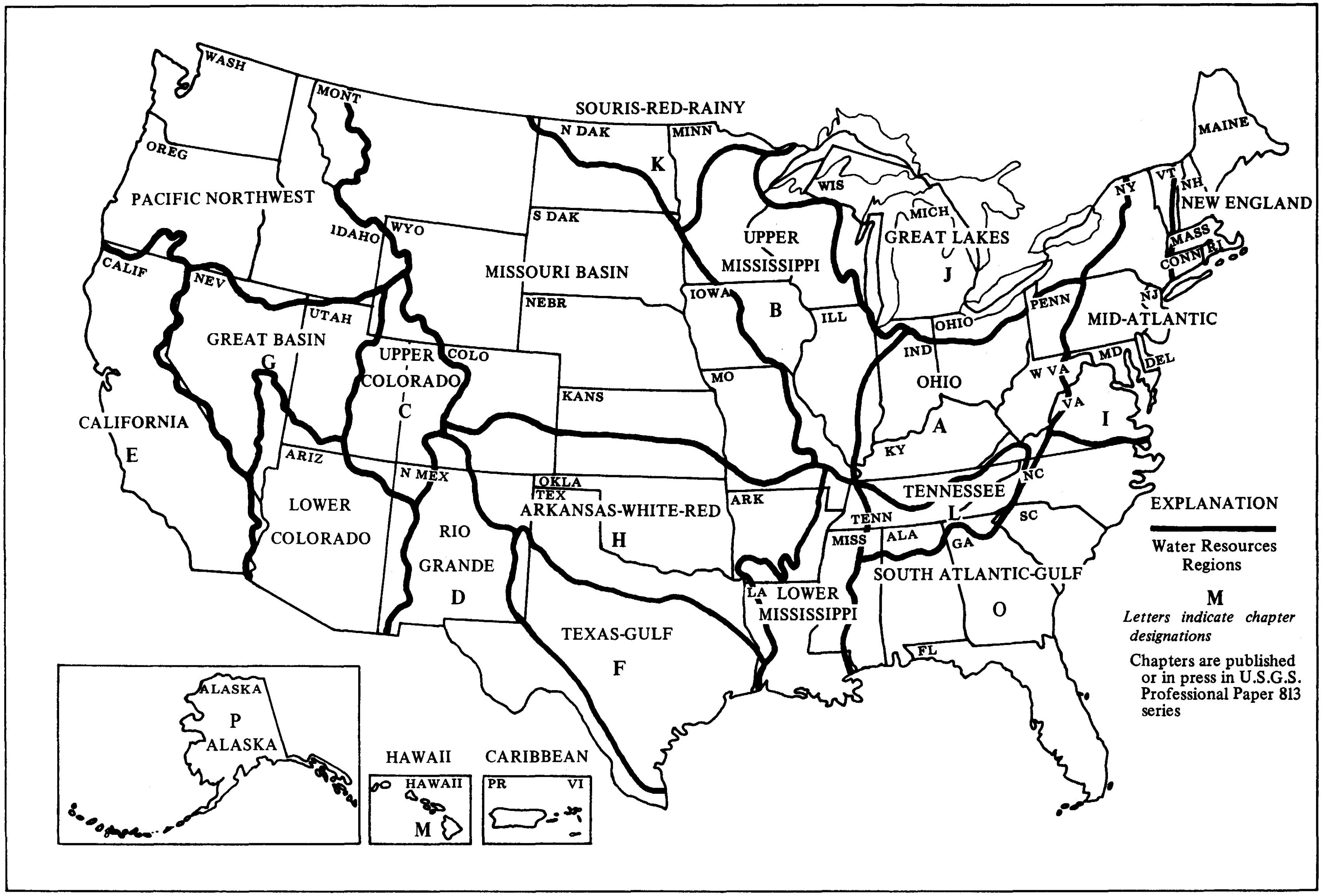

Geographic Index to the Series, U.S. Geological Survey Professional Paper 813, *Summary Appraisals of the Nations Ground-Water Resources.*

Boundaries shown are those established by the United States Water-Resources Council for Water-Resources Regions in the United States.

Water-resources regions in the United States

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U.S. CUSTOMARY-METRIC EQUIVALENTS

For those readers who may prefer to use metric units, the conversion factors for the U.S. Customary units used in this report are listed below:

Multiply U.S. Customary units	*by*	*to obtain metric units*
inch (in.)	25.4	millimeter (mm)
foot (ft)	3.048×10^{-1}	meter (m)
mile (mi)	1.609	kilometer (km)
square miles (mi^2)	2.59×10^{6}	square meters (m^2)
feet per day (ft/d)	3.53×10^{6}	meters per second (m/s)
cubic feet per second (ft^3/s)	2.832×10^{-2}	cubic meters per second (m^3/s)
gallons per minute (gal/min)	6.31×10^{-5}	cubic meters per second (m^3/s)
gallons per day (gal/d)	4.38×10^{-8}	cubic meters per second (m^3/s)
millions gallons per day (Mgal/d)	4.381×10^{-2}	cubic meters per second (m^3/s)

The conversion from temperature in degrees Fahrenheit (°F) to temperature in degrees Celsius (°C) is expressed by: °C = (5/9) (°F−32).

SUMMARY APPRAISALS OF THE NATION'S GROUND-WATER RESOURCES—ALASKA

By CHESTER ZENONE and GARY S. ANDERSON

ABSTRACT

Alaska has enormous surface-water resources, but many of the streams are frozen for most of the year and most contain glacial silt that makes them unacceptable for human use. These factors lend special significance to ground water as a water-supply source, even though perennially frozen ground (permafrost) profoundly modifies ground-water flow systems in much of Alaska north of the maritime southern coast and southeastern panhandle areas. Frozen ground is a virtually impermeable layer that restricts recharge, discharge, and movement of ground water, acts as a confining layer and limits the volume of unconsolidated deposits and bedrock in which water may be stored.

Ground water is an untested resource in most of Alaska, but in many areas potential development of ground water far exceeds current use. Alluvium of major river valleys, such as the Yukon, Tanana, Kuskokwim and Susitna Rivers, probably contains the most extensive aquifers in the State. Large amounts of ground water are also stored in glacial outwash aquifers that underlie coastal basins and valleys, such as those at Kenai and Anchorage in the Cook Inlet lowland. Individual wells yielding more than 1,000 gallons per minute have been developed in the Tanana River valley, Cook Inlet lowland, and the coastal valleys at Seward and Juneau. Comparable yields should be possible in other areas that have similar geohydrologic environments. No major aquifers have been identified in glacial and glaciolacustrine deposits of interior valleys or in deltaic deposits. Major bedrock aquifers have been identified only in carbonate rocks of the Brooks Range and on the north side of the Alaska Range. Springs issuing from the carbonate rocks of the Brooks Range have discharges as great as 16,000 gallons per minute.

Most ground-water recharge occurs beneath reaches of stream channels that are losing flow to the ground-water system. Most ground-water discharge also takes place along reaches of stream channels. This discharge augments streamflows during summer and maintains low flows during winter when there is no surface-water runoff. On the basis of a streamflow hydrograph separation technique and using the 60 percent flow-duration value as an indicator of ground-water discharge, it is estimated that 25 percent of the total volume of streamflow in Alaska (exclusive of coastal, maritime environments) is contributed by ground-water discharge.

The thawing of frozen ground in the permafrost regions of Alaska causes construction and engineering problems. Disturbance of the ground surface disrupts the natural thermal equilibrium and tends to thaw part of the permafrost. Thawing can cause loss of strength, a decrease in volume, and an increase in erosion potential, particularly if the frozen ground is fine grained and poorly drained.

Present deficiencies in the ground-water information base are obvious limiting factors to ground-water development in Alaska. There is a need to extend the ground-water data-collection network and to pursue special research into the quantitative aspects of ground-water hydrology in cold regions, particularly the continuous permafrost zone.

INTRODUCTION

An oft-repeated, probably overworked, but still true statement about Alaska is that it contains America's last remaining true wilderness areas—areas about which there are many unknowns. There are,however, enough "knowns" in Alaska to suggest the presence of vast reserves of mineral resources. The inevitable future development of Alaska's mineral wealth, and of its forestry, fishery, and agricultural potentials will create a great demand for water, itself a critical resource.

The early, sparse developments and settlements in Alaska created few water-resource problems. Demands for water and water-resource information began with hydraulic mining for placer gold in interior and western Alaska in the early 1900's and increased thereafter with the need for water power in the south-central region and water supply for the pulp and paper industry in southeastern Alaska (Waananen and Giles, 1964). The steady growth of population and development since World War II has created more critical water-supply needs and problems, particularly at Anchorage and Kenai. Detailed hydrologic studies have been made in and around these major population centers and at several of the larger settlements along the State's limited highway system, but there are still large areas where data are insufficient to allow more than a general evaluation of water-resource potentials.

Surface water is abundant in Alaska, but the presence of glacial silt in many streams and drastic reduction or even cessation of stream-flow caused by freezing of surface water during winter may make it an unacceptable or unreliable supply source. These factors lend special significance to ground water. At the present time, however, because of the sparse hydrologic data base, evaluations of local ground-water resources must be founded largely on basic principles of ground-water occurrence and a general knowledge of regional climatic effects on the hydrologic environment.

The purpose of this report is to present a regional assessment of Alaska's ground water, an important resource that should be considered in any water development plans. The assessment includes discussions of factors that influence the occurrence, movement, and availability of ground water, and of the problems that may accompany its development and use.

No new data were acquired specifically for this report, and the present authors have drawn extensively from summaries and compilations by earlier investigators of Alaska's water resources, most notably those by Cederstrom (1952), Hopkins and others (1955), Waananen and Giles (1964), Williams (1970a), Feulner, Childers, and Norman (1971) and Balding (1976). Figure 1 is an index map of the geographic locations mentioned in the text.

CLIMATE

Alaska has a great geographic extent, spanning lat 54° to 71° N. and long 130° to 172° W.; consequently it has a large range in climate. The State is divided into four climatic zones—arctic, continental, transition, and maritime—on the basis of temperature and precipitation (Watson, 1959, and fig. 2). Mean annual temperatures range from 10°F in the arctic zone to 45°F in the maritime zone; extremes range from a high of 100°F to a low of −80°F, both of which occur in the continental zone. Recorded annual precipitation ranges from about 5 in. (inches) in the arctic zone to 300 in. along the southeast coast within the maritime zone. Heavy precipitation and relatively low temperatures in the coastal mountains of the southeastern and south-central parts of the State favor the existence of glaciers and icefields. Nearly 30 ft (feet) of snow, the deepest winter snowpack ever reported for an established long-term measurement site, has been measured at the 4,430-foot level of a small glacier near the west side of Prince William Sound (L. R. Mayo and D. C. Trabant, U.S. Geol. Survey, written commun., 1977). Perennial ice now covers 28,100 square miles (mi^2) of Alaska and is an integral part of the hydrologic regimen where it occurs.

PERMAFROST

Permafrost, or perennially frozen ground, is present throughout the State except for a narrow strip along the southern and southeastern coasts. Permafrost is the result of both the present climate and colder climates that occurred intermittently in the past (Williams, 1970a). Permafrost is discontinuous or occurs as isolated masses in the southern and interior parts of the State and is continuous further north on the northern Seward Peninsula, in the Brooks Range, the Arctic Foothills, and the Arctic Coastal Plain (fig. 3). However, even in the continuous permafrost areas, unfrozen zones generally are present under deep lakes and in the alluvium adjacent to major rivers.

THE HYDROLOGIC REGIMEN

The principles of movement of water through the hydrologic cycle, via precipitation, surface runoff, infiltration, ground-water flow, and evapotranspiration, are as valid in Alaska as in more temperate regions, but the rate of occurrence of transient hydrologic events and their distribution in time may differ greatly. Therefore, although the progression of events is not unique to subarctic and arctic regions, a flurry of hydrologic activity is concentrated in a short summer period after many months of hydrologic dormancy (Brandon, 1964).

Except in the maritime zones of south-central and southeastern Alaska, subfreezing air temperatures cause precipitation to fall as snow for 6–9 months of the year and even year-round in the high mountain regions. The water content of that snow is stored on the surface for several months until Alaska's spring melt or "breakup" period begins, rather than being immediately available as runoff to streams and as recharge to the ground-water body. This seasonal storage of snow gives to hydrographs of streamflow in interior and northern areas of Alaska a characteristic prolonged winter recession followed by a rapid rise when snowmelt begins in the spring. In those areas where only a thin snow cover accumulates, the ground may freeze to a depth of many feet during winter. This frozen layer acts as a relatively impermeable barrier that temporarily restricts ground-water recharge and promotes rapid runoff of snowmelt. As soon as melt runoff begins, rapid downward thawing occurs in the ground beneath meltwater channels, and ground-water recharge can then take place (Cederstrom, 1963, p. 25).

Water is stored for long periods of time in glaciers and icefields. The melting of snow and ice in glaciated areas, therefore, provides a water source not directly related in time to local precipitation. For example, the net long-term melting of glacier ice may contribute 5 percent of the total water yield in the Tanana River basin in central Alaska (Anderson, 1970). The meltwater has a regulatory or moderating effect on streamflow variability and, in turn, on ground-water recharge and discharge along alluviated glacial valleys. Given similar basin characteristics such as size, configuration, topography, and geology, streamflow variability is generally greater for nonglacial streams than for glacier-fed streams (fig. 4).

The presence of permafrost on Alaska's Arctic Coastal Plain results in a hydrologic paradox in that the area is semiarid, having less than 10 in. annual precipitation, but it contains a myriad of lakes. A study of the hydrology of a drainage basin near Barrow, Alaska, showed that summer precipitation was ap-

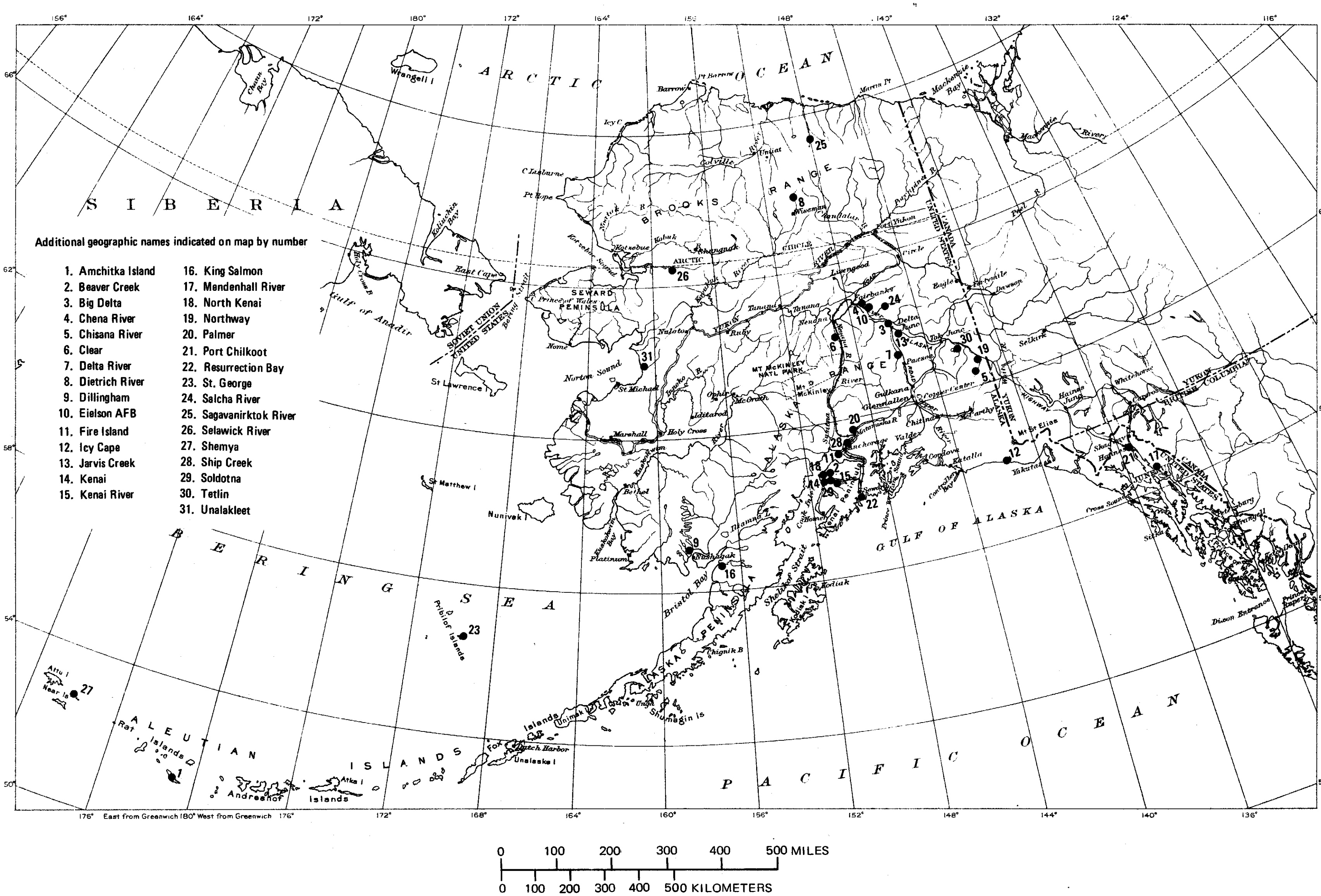


FIGURE 1.—Geographic locations mentioned in text.

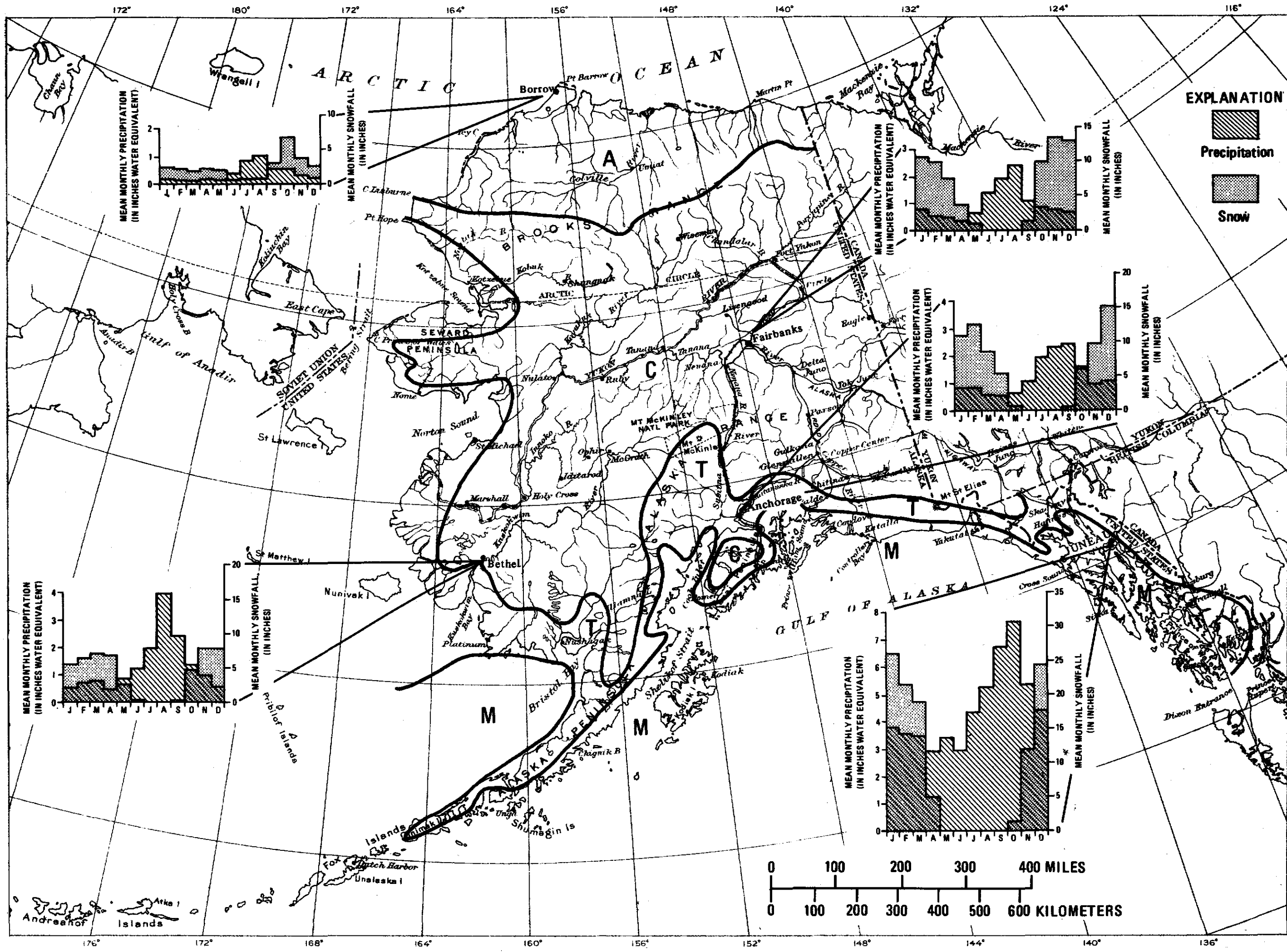


FIGURE 2.—Climatic zones of Alaska. A represents Arctic; C, continental; T, transition, and M, maritime.

proximately balanced by evapotranspiration, and that evaporation from lake surfaces was two to three times precipitation during the short (60–90 days) summer thaw season (Brown and others, 1968). However, runoff from melting ice and snow stored for the remainder of the year compensates for this summer deficit. Seasonal thawing of saturated frozen ground, the active layer, may be an important factor in maintaining summer lake levels (Marsh and Woo, 1977); presumably this release of water is also a source of surface runoff. The low permeability of frozen ground beneath the active layer restricts recharge and effectively isolates the near-surface ground-water system from the regional subpermafrost layer.

In summary, the special characteristics of the hydrologic environment in Alaska, as well as in other arctic and subarctic areas, result from the influence of climatic conditions on the physical state (solid or liquid) of water and its rate of movement through the hydrologic system.

ASSESSMENT OF THE GROUND-WATER RESOURCE

REGIONAL OCCURRENCE

The occurrence of ground water in Alaska is allied to the geologic and physiographic framework and is influenced by the distribution of permafrost in all but the south coastal regions. The effects of permafrost on ground-water systems decrease progressively from the continuous permafrost zone of northern Alaska to the southern limit of permafrost. In the continuous permafrost zone, the sediments are almost entirely frozen to depths as great as 2,000 ft (Howitt and Clegg, 1970). Ground water is usually present below the base of the permafrost, or locally, above permafrost at places where convective heatflow from surface-water bodies lowers the upper surface of permafrost (the permafrost table) below the depth of seasonal freezing (fig.5). In the discontinuous permafrost zone, the fro-

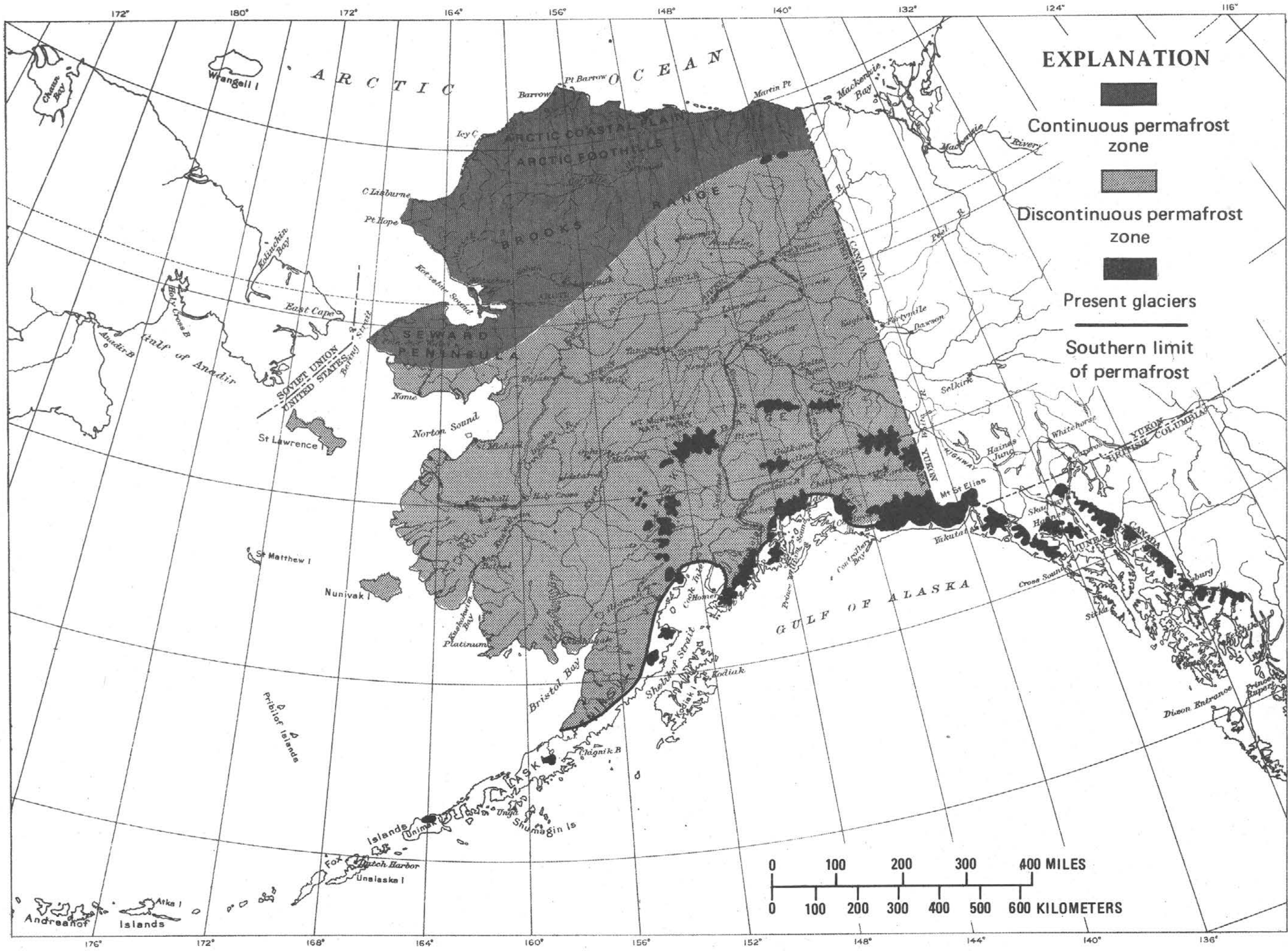


FIGURE 3.—Permafrost zones (Williams, 1970a) and location of present glaciers.

zen ground is warmer than in the continuous permafrost zone, and larger, interconnected or areally extensive unfrozen areas are present. However, even within this zone of "warm" permafrost, its local distribution is determined largely by subsurface drainage and surface insulation (Hopkins and others, 1955, p. 117), which are in turn controlled by such factors as slope, geologic materials, and vegetation cover. For example, in the Fairbanks area (fig. 6*A*) deposits of silt are extensively frozen and effectively confine ground water in the principal aquifers. However, in the Big Delta area (fig. 6*B*), which has a climate similar to that of Fairbanks, the deposits generally consist of coarse sand and gravel, and permafrost is present as isolated bodies which have little effect on the occurrence of ground water.

Alaska's geologic framework has been compared to that of western Canada and the western United States (fig. 7, insert). Major landforms include three great mountain ranges: the Brooks, Alaskan, and Coastal; a broad interior lowland drained by large rivers and containing scattered highlands and plateaus; and large coastal plains, valleys, and river deltas (fig. 7). Covering the rocks of the mountain ranges and those of smaller mountains and uplands is the drift of glaciers that occupied these highlands during the Pleistocene Epoch. Outwash deposits derived from and extending beyond the limits of existing and former glaciers and materials originally of alluvial rather than glacial origin occupy the interior valleys and mantle the older rocks in large areas of the interior lowland.

Four generalized geohydrologic environments are recognized in Alaska (Williams, 1970a, p. 5): (1) alluvium of river valleys, including the flood plains, terraces, and alluvial fans of both major valleys and upland and mountain valleys, (2) glacial and glaciolacustrine deposits of the interior valleys, (3) coastal-lowland deposits, and (4) bedrock of the uplands and mountains (fig. 8).

ALLUVIUM OF RIVER VALLEYS

Of the major geohydrologic environments in Alaska, alluvium of river valleys, including the flood plains, terraces, and alluvial fans of both major valleys and smaller mountain and upland valleys, contains the greatest volume of ground water in storage. Alluvial deposits also have the greatest recharge potential because they are hydraulically connected to the extensive surface-water drainage system. The Yukon, Tanana, Kuskokwim, Kobuk, and Susitna River basins are the major ground- and surface-water systems. In the lower Tanana basin, for example, the maximum known thickness of alluvium is 2,000 ft (Anderson, 1970). In the lower coastal reaches of large river valleys such as the Susitna, the alluvial deposits, perhaps only a few tens of feet thick, are interbedded with thick lacustrine, glacial, and glaciomarine deposits.

In the continuous permafrost region, all the deposits may be frozen except those adjacent to river channels and large lakes. Williams (1970b) refers to subsurface data from two wells near the Colville River at Umiat and cites Black (1955, p. 119) to suggest that unfrozen zones (perforating taliks) may extend completely through the permafrost along the major rivers north of the Brooks Range. Williams (1970b, and written commun., 1977) also suggests that a more or less continuous unfrozen zone is present beneath the Colville River. Data from recent Geological Survey test borings do not refute the concept of perforating taliks, but they indicate that such unfrozen zones are isolated under deeper parts of the stream channel and do not form a continuous unfrozen conduit for ground water beneath the river (C.E. Sloan, oral commun., 1977). Even if such streambed aquifers are present in the continuous permafrost zone, frozen ground severely reduces the storage capacity of the aquifers in the zone as a whole.

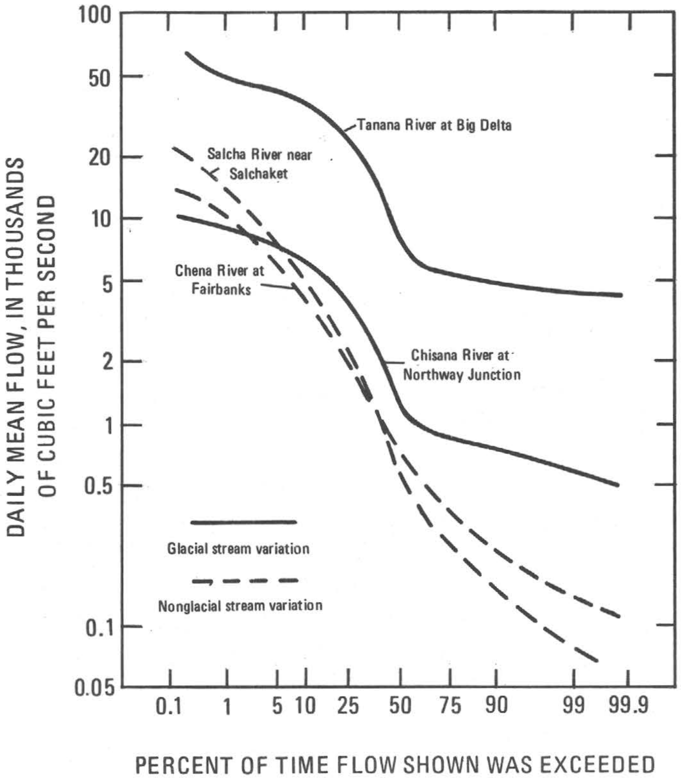


FIGURE 4.—Variability of flow in glacial versus nonglacial streams (modified from Anderson, 1970). 1. Tanana River at Big Delta, 2. Salcha River near Salchaket, 3. Chena River at Fairbanks, and 4. Chisana River at Northway Junction.

In the discontinuous permafrost zone, the volume of frozen ground does not significantly reduce the storage capacity of alluvial aquifers along the major rivers—the Yukon, Tanana, and Kuskokwim—because the thickness of permafrost is generally small relative to the total thickness of unconsolidated deposits. Alluvium along smaller tributary valleys may be mostly frozen, however, and there are areas within the major valleys, such as the Yukon Flats and the vicinity of Northway-Tetlin in the Upper Tanana River valley where frozen ground does greatly reduce ground-water storage capacity (Williams, 1970a, and written commun., 1977).

The major ground-water bodies lie beneath the base of permafrost in the discontinuous permafrost zone. At Fairbanks, productive water-bearing deposits are present beneath permafrost that varies widely and irregularly in thickness and has a maximum reported thickness of 265 ft (Anderson, 1970). Recharge and discharge of these alluvial aquifers takes place chiefly along stream channels and through lake beds and other thawed zones that perforate the permafrost.

GLACIAL AND GLACIOLACUSTRINE DEPOSITS OF INTERIOR VALLEYS

Glacial deposits consist largely of till laid down during the Pleistocene epoch as the glaciers advanced from major mountain ranges into the interior plains and lowlands (fig. 7). During the retreat of glaciers, the till was covered by permeable water-worked deposits, some of which were buried by till of later glacier advances. Where the glaciers advanced into proglacial lakes, beds and lenses of clay, silt, sand, gravel, and stony clay or silt are interbedded with the till. The sediments are predominantly fine grained and are frozen in northern Alaska and at the higher altitudes of the south-central part of the State. The largest deposits of glacial and glaciolacustrine sediments are in the Copper River lowland. Glacial deposits of smaller extent occur in valleys of the southern Brooks Range and the Alaska Range. Although these deposits are

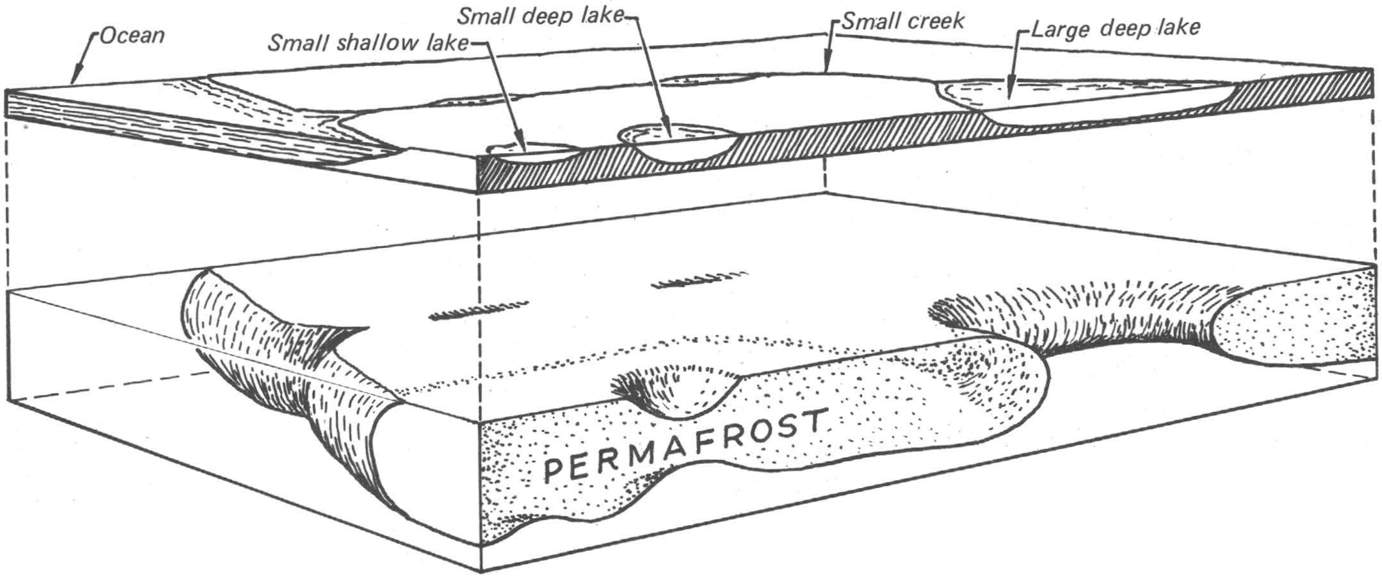


FIGURE 5.—Schematic representation of the effect of bodies of water on the configuration of permafrost in the continuous permafrost zone (Williams, 1970a, modified from Lachenbruch and others, 1962).

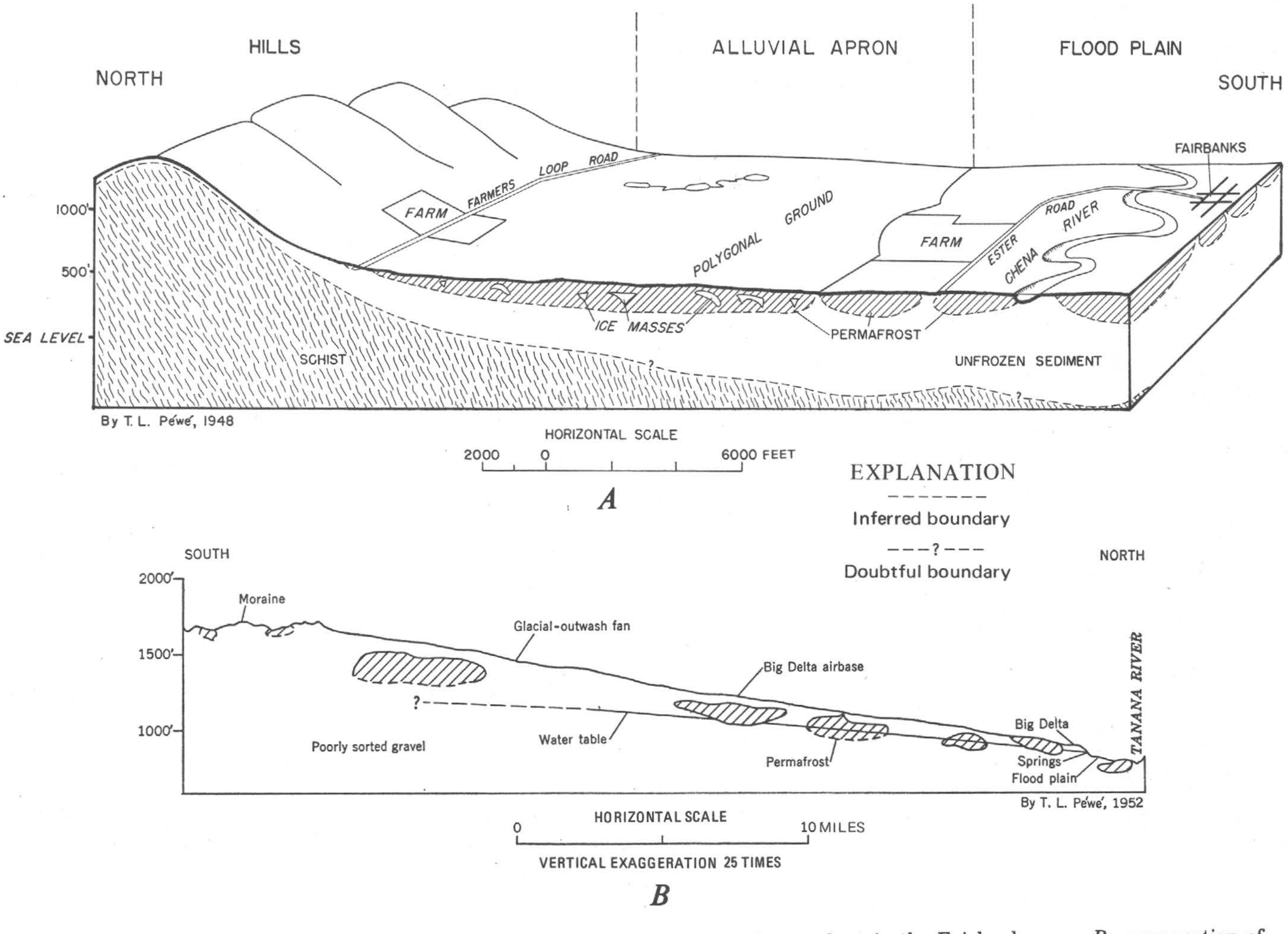


FIGURE 6.—Diagrammatic sketches showing: *A*, character and distribution of permafrost in the Fairbanks area; *B*, cross section of permafrost and ground water in the Big Delta area (from Hopkins and others, 1955).

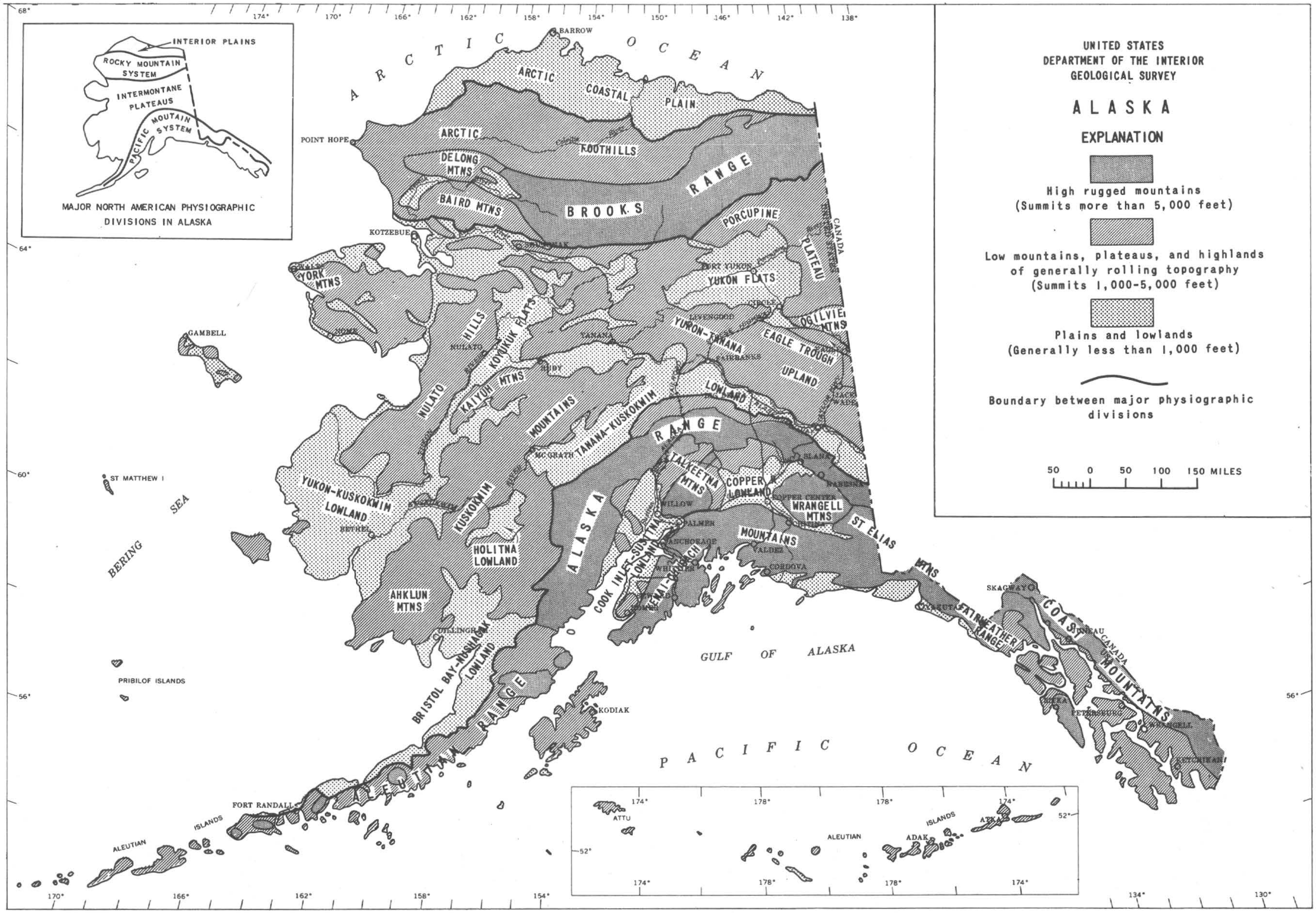
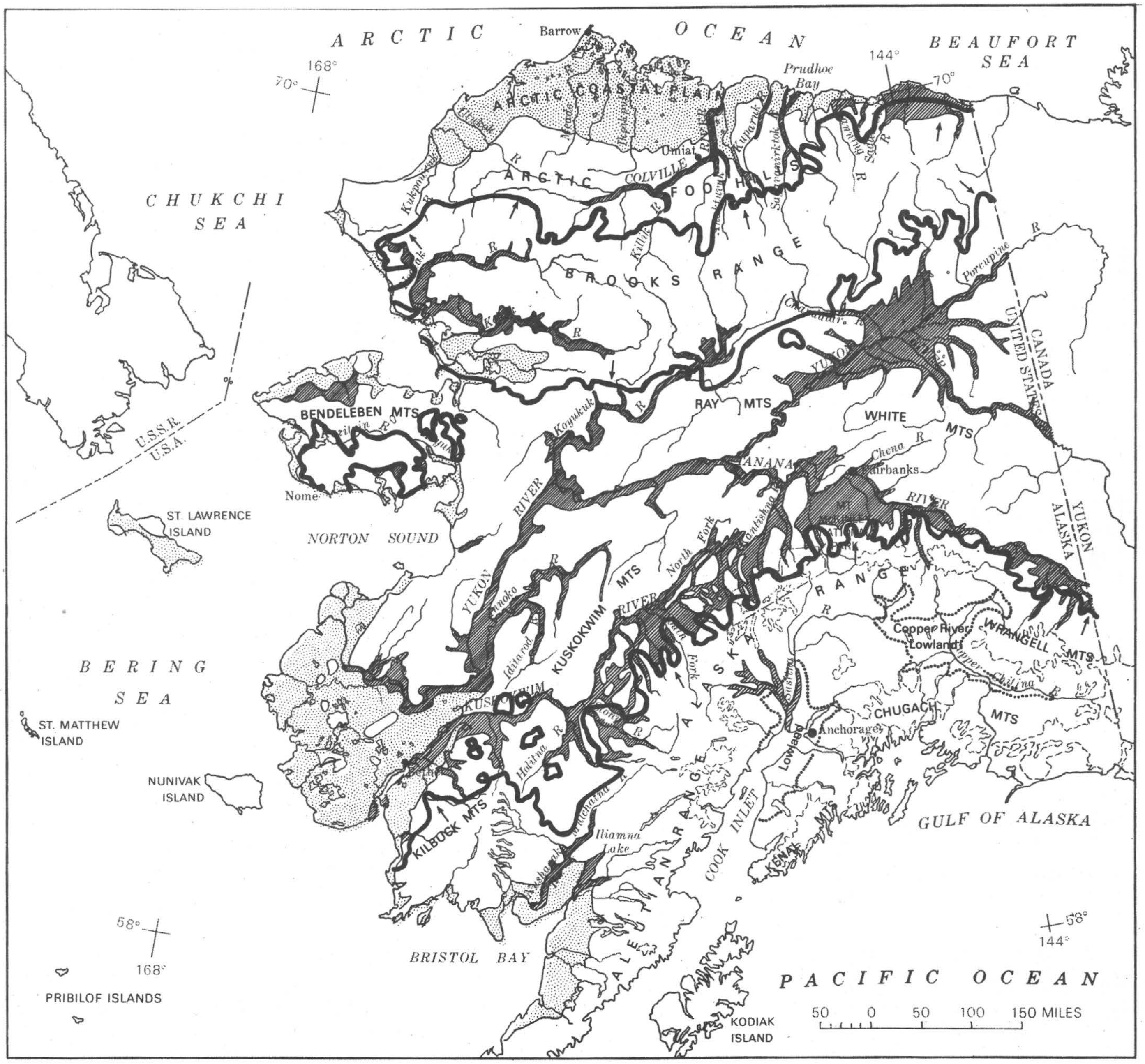


FIGURE 7.—Physiographic provinces of Alaska (Wahrhaftig, 1965).



EXPLANATION

Alluvium of major valleys
Sand, gravel, and silt of flood plains, low terraces, and alluvial fans

Coastal-lowland deposits
Chiefly silt and sand, and subordinate amounts of gravel; includes sand and gravel of bars, beaches and spits, and sand, silt, and gravel of deltas. Within limits of Pleistocene glaciation, include till, glaciomarine, and glacioestuarine deposits

Bedrock of mountains and uplands
Chiefly bedrock mantled locally by weathered bedrock rubble reworked by frost action, alluvium, and eolian deposits, and, within limit of Pleistocene glaciation, by glacial deposits

Limit of Pleistocene glaciation
Unconsolidated deposits within this limit may include till, sand and gravel, and silt and clay of glacial, glaciolacustrine, glaciomarine, or glacioestuarine origin. (Coulter and others, 1965)

Cook Inlet and Copper River Lowlands
Approximate upper limit of lacustrine silt, clay, sand, gravel. and stony silt and clay of extensive glacial lakes in Copper River Lowland and of glaciolacustrine, glacioestuarine, and glaciomarine deposits in the Cook Inlet lowland

Major glaciers and ice fields

Contact

FIGURE 8.—Geology and major geohydrologic environments of Alaska (Williams, 1970a; modified from Coulter and others, 1965; and Karlstrom and others, 1964). Note: Southeastern Alaska, the Alaska Peninsula and the Aleutian Islands fall virtually entirely within the category "Bedrock of mountains and uplands."

widely distributed, they have not been extensively explored for ground water and probably do not contain major aquifers except in southern Alaska, where permafrost either is absent or occurs only as small isolated masses.

COASTAL LOWLAND DEPOSITS

The coastal lowland deposits of Alaska reflect various combinations of several depositional environments. They can be generalized to include: (1) constructional shoreline features formed on land or in shallow water, including coastal plains, deltas, bars, spits, and beaches, and (2) coastal basins and valleys whose basic configuration was produced chiefly by structural or erosional forces and which subsequently were filled by sediments from both marine and nonmarine (glacial and alluvial) sources.

CONSTRUCTIONAL SHORELINE DEPOSITS

Coastal plains.—The Arctic Coastal Plain is the largest coastal lowland deposit in Alaska; it is underlain by as much as 200 ft of unconsolidated silt, sand, and gravel (Black, 1964). Permafrost generally extends from the land surface through the entire thickness of the unconsolidated sediments and into the underlying bedrock. In the Prudhoe Bay area, the permafrost is approximately 2,000 ft thick (Howitt and Clegg, 1970). Permafrost restricts ground water to local, discontinuous thawed zones under deep lakes and river and to places where springs issuing from bedrock maintain a thawed conduit. The water from bedrock beneath permafrost is generally brackish to saline. To the southwest, the coastal-plain deposits at Nome have been extensively explored during placer gold-mining operations. Some ground water is present there, but its movement and storage are restricted by permafrost. A narrow, discontinuous coastal plain borders the Gulf of Alaska from the Copper River southeast to Icy Cape. Exploratory drilling for oil and gas in this area revealed that alluvial, glacial, marine, and beach sediments overlie great thicknesses of sedimentary rocks (Plafker, 1967; Miller, 1971), but the hydrologic characteristics of the deposits were not reported. Farther southeast at the city of Yakutat, which is on a glacial moraine, one water well was drilled through 335 ft of unconsolidated, predominantly fine-grained glacial sediments that included 60 ft of coarse-grained sand and gravel. Petroleum-exploration wells on this coastal plain are reported to have reached bedrock at depths of less than 500 ft. Because of the high precipitation and lack of permafrost in this area, recharge rates are assumed to be high. However, freshwater aquifers are probably quite thin because of the low relief and proximity to the Gulf of Alaska.

Deltas.—Deltas of the Colville, Noatak, Kobuk, and Selawik Rivers and the compound delta of the Yukon and Kuskokwim Rivers form a large part of the coastal lowlands of northern and western Alaska. Smaller deltas are formed by several other rivers in south-central and south-eastern Alaska; the largest of these is the Copper River delta. Subsurface data are available only from the Yukon-Kuskokwim and Copper River deltas. Sediments of the deltas consist of sand, silt, and thin beds of gravel. Yukon-Kuskokwim deltaic sediments are nearly 1,000 ft thick at the site of an exploratory oil well near Bethel (Williams, 1970a). The base of deltaic sediments near the mouth of the Copper River was not reached in a 200-ft-deep well east of Cordova. Permafrost is widespread in the upper part of the deposits of the Yukon-Kuskokwim delta. It extends from near the surface to a maximum known depth of 603 ft near Bethel. However, a comparison of river stage and ground-water levels at Bethel (Waller, 1957) suggests an hydraulic connection between the river and ground-water system, and thus a lack of permafrost beneath the river. If the sediments of major deltas are in hydraulic connection with their associated rivers, the potential for induced ground-water recharge from streamflow is enormous. Ground-water availability in the deltas is limited, then, by predominantly fine-grained sediments and to a greater extent by permafrost in northern and northwestern Alaska. Additionally, the thickness of the freshwater aquifer is determined by the position of the freshwater-saltwater interface, which is probably very shallow near the distal edge of the deltas.

Bars, spits, and beaches.—These depositional forms border the entire coastline of Alaska. They may contain only a small amount of ground water, but its presence is significant at many Native villages and military sites which require an economical but not necessarily large source. The distribution and availability of fresh ground water in these deposits depends on several factors. Along the Arctic Ocean coastline, ground water is perched on permafrost and the thickness of the water body depends on the rate of recharge from rainfall and snowmelt, the depth to the permafrost, and the time since storm waves last inundated the area. In areas without permafrost, the presence of fresh ground water depends on the rate of recharge and discharge and consequently the depth to the freshwater-saltwater interface. Along the Gulf of Alaska coastline, abundant recharge from precipitation, freshwater lagoons, and streamflow create conditions favorable for the occurrence of shallow ground water in permeable coastal sediments.

DEPOSITS OF THE COASTAL BASINS AND VALLEYS

Deposits of the coastal basins and valleys consist of till interbedded with sand, silt, clay, and gravel of fluvial and marine origin. The largest and best-known ground-water system of this type is that of the Cook Inlet lowland, particularly in the Kenai and Anchorage areas. Petroleum-exploration records indicate that unconsolidated sediments reach a maximum thickness of more than 4,000 ft in the Cook Inlet lowland, but in most wells the thickness is less than 1,000 ft. The sediments are predominantly interbedded glacial till, fine-grained glaciolacustrine deposits and more permeable water-worked deposits of sand and gravel. Throughout the Cook Inlet lowland, small quantities of ground water occur under unconfined conditions near the surface or are confined in thin water-bearing lenses within the till or glaciolacustrine deposits. Greater volumes of recoverable ground water are found in coarse-grained alluvial deposits, ranging in thickness from 10 to 100 ft, such as those forming the confined glacial-outwash aquifers at Anchorage. These deposits may be of limited areal extent, however, and their location is unpredictable without exhaustive subsurface exploration. Ground-water conditions in the Bristol Bay lowland are inferred to be similar to those in the Cook Inlet lowland, except for the effects of more extensive and thicker permafrost. Permafrost is present in the Bristol Bay lowland in approximately one-fourth of 600 wells and borings for which records are available; the maximum reported thickness of frozen ground is 175 ft (Williams, 1970a). The potential for recharge of the ground-water system by induced infiltration of streamflow through unfrozen, permeable channel and floodplain sediments could be realized by ground-water development efforts near the active stream channel. Away from the central part of the river valleys of the Cook Inlet and Bristol Bay lowlands, recharge takes place principally by infiltration of rainfall and snowmelt, and recharge rates are highly variable because of the complex stratigraphy and wide range of permeability of glacial sediments.

Ground-water supplies can be developed from alluvial fills at the heads of fiords along the Gulf of Alaska. In the Seward area at the head of Resurrection Bay, unconsolidated sediments have been penetrated by drill holes to a depth of 480 ft and are estimated from geophysical surveys to be more than 1,000 ft thick. The sediments consist of glacial till, glaciofluvial sand and gravel, marine deposits of fine sand and silt, and stream-deposited sand and gravel. Recharge rates to these deposits are assumed to be high because streams crossing the alluvial fans that border the basin lose a large part of their flow to the ground-water system. The volume of fresh water within the deposits is not known, but fresh water was present several hundred feet below sea level in wells drilled near the coastline. The freshwater aquifers are confined beneath marine silt and clay. At Valdez, where ground-water conditions are assumed to be similar to those at Seward, unconsolidated sediments have been penetrated to a depth of 250 ft and may be as much as 600 ft thick (Coulter and Migliaccio, 1966).

Alluvium-filled coastal valleys in mountainous southeastern Alaska are generally smaller than those of the Gulf of Alaska coast. However, Barnwell and Boning (1968) reported the presence of a fresh ground-water reservoir as thick as 700 ft in the Mendenhall River valley near Juneau.

BEDROCK

In approximately 75 percent of Alaska, glacial and alluvial deposits are thin, poorly permeable, or absent. In such areas, appreciable amounts of ground water occur only in aquifers consisting of consolidated rocks. The occurrence of ground water in bedrock is described here under four general rock types: carbonate rocks, sandstone, volcanic rocks, and metamorphic and intrusive igneous rocks.

CARBONATE ROCKS

Although carbonate rocks are quite extensive in southeastern Alaska, they have not been explored and utilized there as a water source. The Brooks Range area, which lies entirely in the continuous permafrost zone, also contains extensive carbonate-rock deposits. Ground-water movement in these rocks apparently has developed solution cavities and conduits through which the water flows to the surface. Conclusions concerning the occurrence and movement of ground water in carbonate rocks of the Brooks Range are inferred from measurements and observations of spring flow in both the eastern Brooks Range (Childers and others, 1973, 1977) and the Baird and DeLong Mountains area in the western Brooks Range (C. E. Sloan, U.S. Geol. Survey, written commun., 1976). The hydrology of springs in the latter area was described by Waller (1966) and by Piper (1966). Craig and McCart (1974) studied both the northern and southern flanks of the Brooks Range and reported the existence of approximately 25 springs which emerge from carbonate rocks. Some springs in the Brooks Range have discharges as great as 16,000 gal/min.

SANDSTONE

Sandstone and alternating strata of indurated sand, silt, and clay are widespread throughout the State.

Although these deposits have been extensively explored for oil, gas, and coal, few hydrologic data have been reported. Such deposits have been explored for ground water in the western Kenai Peninsula, where they are poor aquifers because of low permeability.

VOLCANIC ROCKS

Volcanic rocks are widespread in Alaska, but they are especially prevalent in some areas in the western part of the State, on the Aleutian Chain, Alaska Peninsula, the Seward Peninsula, and in the Wrangell Mountains. The occurrence of ground water in volcanic rocks is highly variable, and only a few wells are known to produce water from them. On Shemya Island near the west end of the Aleutian Chain, the volcanic rocks are dense and unfractured; consequently they are poor aquifers (Feulner and others, 1976). By comparison, the volcanic rocks on St. George Island have much greater permeability because of layering of flows, interbeds of gravel or scoria, and cooling fractures within the rocks (Anderson, 1976). Yet the occurrence of fresh ground water on St. George Island is limited, not because the rocks do not have the capacity to receive and store water, but rather because they are so permeable that the ground water drains rapidly to the sea. The presence of many springs suggests that basaltic lava flows in the mountains and uplands of the northern Seward Peninsula are promising sources of ground water (Hopkins and others, 1955, p. 122).

METAMORPHIC AND IGNEOUS ROCKS

These rocks make up the cores of the principal ranges of Alaska. Ground water occurs chiefly in faults and fractures within these rocks. Some areas of fractured slate on Kodiak Island yield a modest amount [50–100 gal/min (gallons per minute)] of water (S. H. Jones, Chester Zenone, and R. J. Madison, U.S. Geol. Survey, written commun., 1977). Elsewhere, wells in such rocks generally produce less than 10 gal/min. Probably the most intensive development of bedrock aquifers is in the uplands near Fairbanks (fractured schist), Anchorage (slate and metagreywacke), and a few places on the Kenai Peninsula and southeastern Alaska. Ground water is generally present only in weathered zones at the bedrock surface and in fractures. The probability of penetrating zones of secondary porosity below a depth of 300–500 ft diminishes rapidly, and many deep wells are reported to be dry.

GROUND-WATER STORAGE AND AVAILABILITY

It is estimated that 1.5×10^{14} cubic feet of ground water, with a dissolved-solids concentration of less than 3,000 mg/L (milligrams per liter), is stored in aquifers in Alaska (A. J. Feulner, written commun., 1975). Estimates of the amount of ground water in storage are academic, however, if they cannot be related to the quantity that can be transmitted by the aquifer and economically developed. Aquifer transmissivity, or water-transmission property, which varies greatly in Alaska and is strongly influenced by permafrost, exerts the major control on the availability of ground water that is present. For example, the porosity of predominantly fine-grained glacial and glaciolacustrine sediments is large, and a great volume of water is stored in the sediments. However, the amount of water that can be efficiently recovered is limited by low permeability of the fine-grained sediments themselves and by the limited extent of coarser, more permeable horizons within those sediments. In permafrost zones, even the coarse-grained potential aquifers may be frozen.

There have been attempts at ground-water development in most areas of the State. However, only at Anchorage and perhaps at Fairbanks, Kenai, and Juneau is the basic framework of the ground-water system reasonably well known. Elsewhere, data are too scarce to describe the areal extent, thickness, and hydraulic boundaries of the aquifers. In the areas for which data are scarce, ground-water availability is deduced from reports of the few wells that have been drilled and from what is known of the lithology, permafrost distribution, potential recharge, and base flow of streams, which reflects ground-water discharge (see later section). This paucity of data, combined with the known complexity and wide range of geologic and hydrologic conditions in Alaska, permits preparation of only a very generalized map of ground-water availability on a regional basis. Potential yields of properly constructed (screened and adequately developed) wells are indicated in figure 9. Exceptions to the indicated yields can and do occur; the map is intended to represent average conditions only.

Individual yields greater than 1,000 gal/min have been obtained from wells in alluvial deposits in the Tanana valley (at Fairbanks, Eielson AFB, Big Delta, and Clear), Cook Inlet lowland (Anchorage and Kenai), and in the glacier-carved coastal valleys at Juneau and Seward. Development of comparable well yields should be possible in other areas that have similar geohydrologic environments and comparable permafrost conditions, that is, the major alluvial valleys, large alluvial fans, coastal valleys and basins, and perhaps in some volcanic rocks of the Seward and Alaska Peninsulas. Attempts to develop ground water in the carbonate rocks of the Brooks Range have been largely unsuccessful because of thick (600–800 ft)

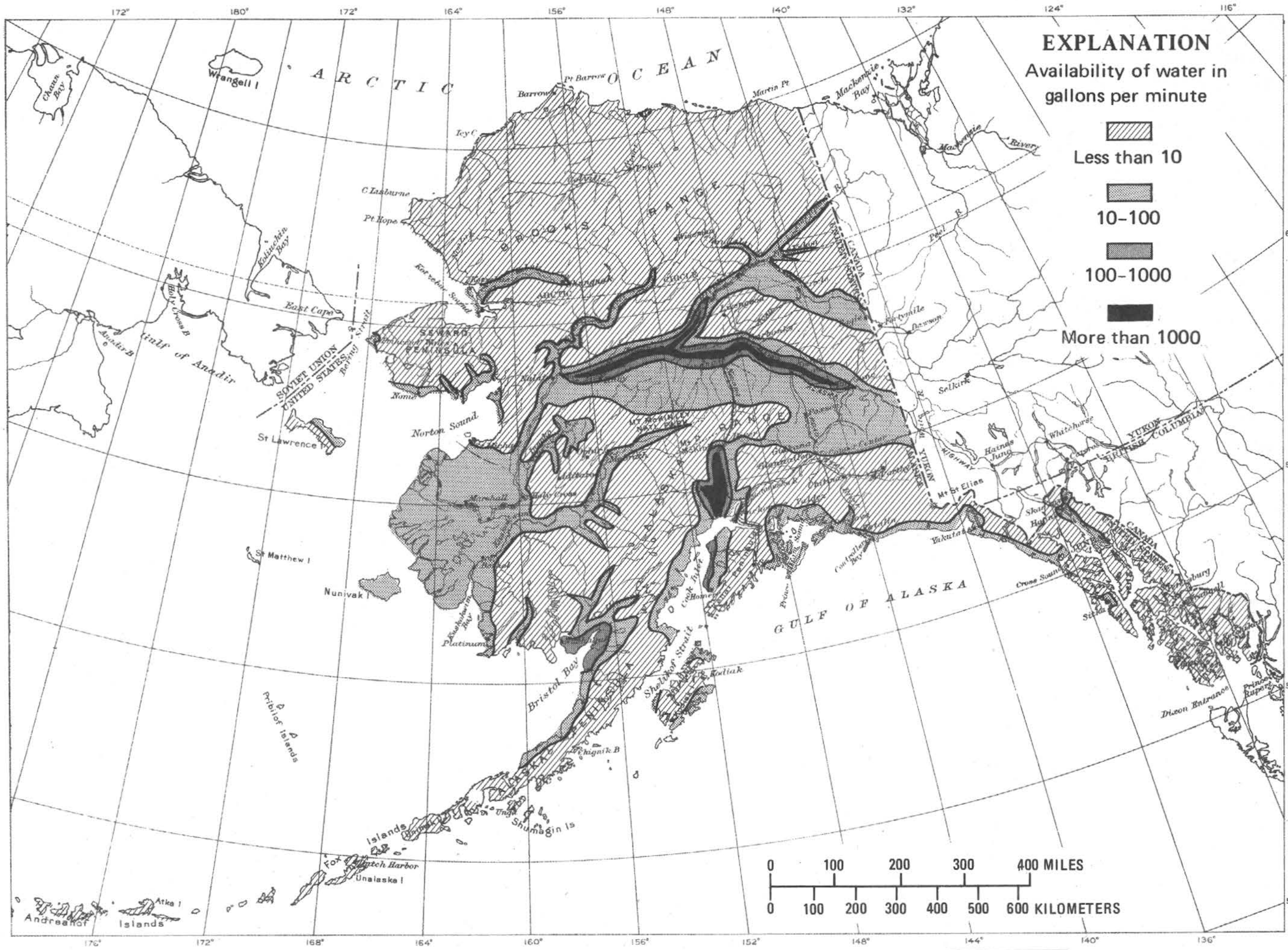


FIGURE 9.—Generalized availability of ground water (Feulner and others, 1971).

permafrost (J. R. Williams, U.S. Geol. Survey, written commun., 1977), but flows ranging from 500 to as much as 16,000 gal/min have been measured at springs issuing from those rocks. Yields of 100–150 gal/min have been reported from deltaic sediments of the Yukon-Kuskokwim Rivers. Larger yields should be recoverable from permeable sand and gravel zones within the several hundred feet of unfrozen material beneath the base of permafrost. Well yields of less than 10 to as much as 20 gal/min are common for most areas of igneous or metamorphic bedrock, glacial and glaciolacustrine deposits (Copper River lowland), and in the permafrost regions of nothern and northwestern Alaska.

GROUND-WATER RECHARGE

Ground water is considered to be a renewable resource because practically all usable supplies are ultimately derived from precipitation. Total volumes of water available for recharge on an annual basis depend in part on, and thus vary with, annual amounts of precipitation. Ground-water reservoirs are replenished either by direct infiltration of precipitation or by percolation from surface-water bodies. Recharge rates also vary with surficial geologic conditions. A perennial supply of ground water is generally assumed to be available if the amount discharged from the aquifers does not exceed the rate of replenishment.

The highest ground-water recharge rates in Alaska occur beneath alluvial stream channels that are losing flow to the ground-water system. Infiltration through the permeable sediments in these channels and adjacent flood plains probably accounts for most of the total volume of recharge. Direct recharge from precipitation is not significant in the uplands of Alaska. Precipitation is not abundant except in the coastal areas and in the higher mountains of the interior (fig. 2). The winter precipitation in the mountains is temporarily stored as snow or ice and there is only minor surface-water loss to evapotranspiration or ground-water infiltration. Snowmelt and icemelt from the mountains, as well as most of the surface-water runoff from bedrock and permafrost areas, is eventually concentrated in the major alluvial valleys.

The relationship between ground water and surface water in Ship Creek near Anchorage was discussed by Weeks (1970) (fig. 10). Stream-channel losses for Ship Creek have been calculated, on the basis of seepage investigations, to be approximately 4 ft^3/s (cubic feet per second) per mile of channel; this is equivalent to a vertical infiltration rate of 1.0 to 1.5 ft/d (feet per day) within the wetted perimeter of the channel. At Jarvis Creek near Big Delta, Anderson (1970) reported streamflow losses of 10 ft^3/s per mile of channel, for a vertical infiltration rate of 1.5–4 ft/d. These infiltration rates are comparable to those measured in artificial recharge experiments on the Ship Creek alluvial fan near Anchorage (Anderson, 1977) where a rate of 1.4 ft/d was measured in one basin and a rate as great as 6 ft/d was estimated for a second basin.

Ground-water recharge from the infiltration of precipitation and snowmelt in the Anchorage area is estimated, from analog- and digital-model results, to be 5–9 in/yr (inches per year) or about 30–50 percent of the mean annual precipitation (R. S. George, U.S. Geol. Survey, oral commun., 1976). Such infiltration along the Chugach Mountains front is considered to be a significant source of recharge for the confined ground-water system at Anchorage. In the Beaver Creek valley near Kenai, where the drainage basin has low relief and the surficial deposits consist of generally fine-grained glacial outwash, the estimated mean annual ground-water recharge from precipitation is 4 in/yr or about 25 percent of the mean annual precipitation. This estimate for Beaver Creek basin

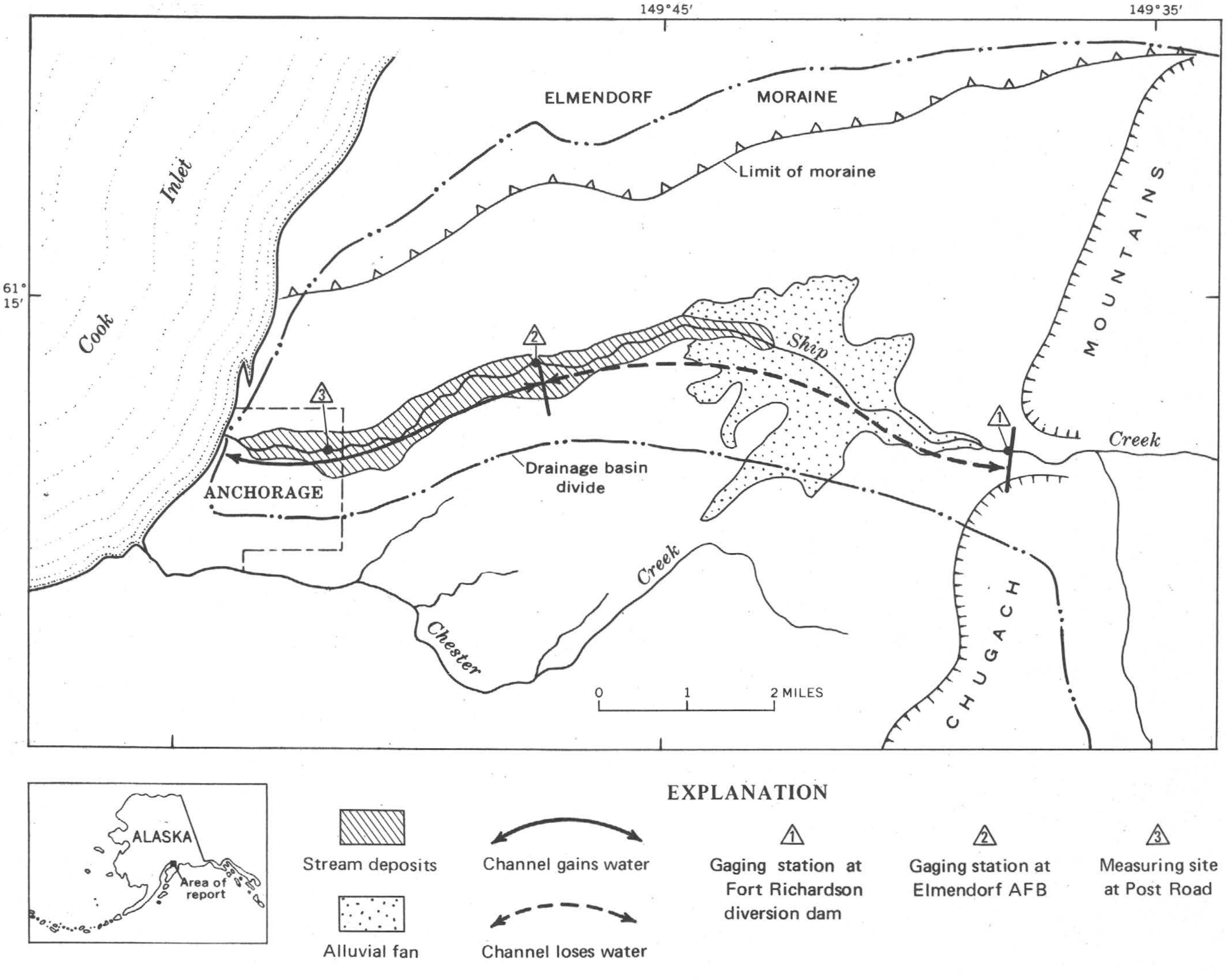


FIGURE 10.—Lower part of Ship Creek basin showing gaining and losing reaches of the stream channel (Weeks, 1970).

was derived from a streamflow hydrograph separation (Anderson and Jones, 1972). In digital-model simulations of the North Kenai area (Dames and Moore, 1976), it was estimated that about 40 percent of annual precipitation, or 7–9 in/yr, ultimately becomes part of the ground-water body. In North Kenai, the surficial deposits are coarser and better drained than those of Beaver Creek valley and there is virtually no surface-water runoff.

Over most of the land area of Alaska, either permafrost or poorly permeable bedrock is present at or near the surface, and there is very little infiltration from precipitation.

GROUND-WATER DISCHARGE

Ground water is discharged both naturally and artificially. It is discharged naturally from water-table aquifers as seeps or springs, as ground-water runoff to streams whose channels have cut below the water table, and by evaporation and transpiration. Natural discharge from artesian aquifers occurs by vertical leakage through confining beds or at springs where the aquifers crop out. Both types of aquifers also discharge freshwater along coastlines. The winter flow of many Alaskan streams is maintained by discharge of ground water. In interior and northern regions, this discharge is most conspicuously displayed by the annual formation of extensive icings[1] along stream channels and flood plains (Sloan and others, 1976). Artificial discharge of aquifers is accomplished principally by pumping from wells. Shallow, unconfined ground water is sometimes discharged along ditches excavated to drain water-logged areas.

A great quantity of ground-water discharge in Alaska occurs naturally as inflow to streams. Because little information is available on aquifer lithology and ground-water hydraulics, probably the best quantitative estimate of regional ground-water budgets in Alaska can be made from analyses of streamflow records that are available for most areas of the State. Separation of the ground-water component (base flow) of a streamflow hydrograph is a technique commonly used to estimate ground-water discharge (Linsley and others, 1975, p. 230 and fig. 8–7). Under natural conditions, a long-term equilibrium exists between ground water entering and leaving an aquifer system. Ground-water discharge estimated from streamflow data should thus approach the long-term average ground-water recharge in the area contributing to streamflow.

Base flows of Alaskan streams, estimated from simple hydrograph-separation techniques, correspond to points on the flow-duration (cumulative flow-frequency) curve within a range of streamflows that are exceeded 50–75 percent of the time. For this report, the streamflow equalled or exceeded 60 percent of the time is taken as an indicator or index of natural ground-water discharge. Stated another way, 40 percent of the time streamflow is supported entirely by ground-water discharge. Actual ground-water discharge to many Alaskan streams may be greater than that indicated by the 60 percent flow parameter, however, because there is virtually no direct surface-water runoff during about half the year in most of the State.

The regional distribution of ground-water unit runoff and the total ground-water discharge for hydrologic subregions of the State, estimated on the basis of the 60-percent duration of flow at gaging stations, are shown in figure 11 and table 1, respectively. These estimates (exclusive of Bristol Bay drainage and the maritime areas) were made by comparing relationships between mean annual and 60-percent duration flows within hydrologically similar regions and then estimating the 60-percent flows for the corresponding mean annual basin runoffs reported by Balding (1976). The estimate of ground-water discharge for the Kotzebue Sound subregion seems anomalously high for an area underlain by permafrost. This value was based on analysis of streamflow data for the Kobuk River, which may not be representative of the entire subregion. However, the headwaters of the Kobuk River basin contain many springs that discharge ground water from limestone rocks of the Brooks Range.

In the Bristol Bay subregion, the 60-percent flow duration estimating techniques gave a ground-water discharge rate of 47,000 ft^3/sec, or unit base flow of 15.9 in. This estimate was not considered to be representative of ground-water discharge because all gaged basins in the subregion contain considerable lake storage that augments winter streamflow. For this subregion, then, a ground-water discharge value equal to 25 percent of streamflow, which is the average value for the State if Bristol Bay and the maritime areas are excluded, was selected as a first approximation.

Reliable estimates of ground-water discharge based on streamflow data cannot be made for southeastern Alaska and the Gulf of Alaska coast, where large amounts of precipitation fall (see fig. 2) and most streams receive snowmelt throughout the year. These

[1]An icing is a buildup of surface ice formed by freezing of water that discharges to the surface from seeps and springs, or from streams whose channel flow is constricted by freezing and forced to flow above the original "normal" winter ice cover. The summer flow of several large rivers in northeastern Alaska is augmented by the melting of very large icings.

areas are characterized by steep, mountainous and (or) glaciated terrain underlain by igneous and metamorphic rocks that have low permeability. In most places only a thin mantle of glacial and alluvial deposits is present. Ground-water discharge from these areas probably would not increase the total estimated ground-water discharge for the remainder of Alaska by more than 20 percent. Excluding estimates for the Bristol Bay, southern coastal and southeastern Alaska areas for the reasons noted above, total ground-water discharge (equal to recharge) for the remainder of the State is estimated to be 159,200 ft³/s, or 100,000 Mgal/day.

WATER QUALITY

A data base adequate to describe areal variations in the chemical quality of ground water is available for only a few places, such as Juneau, Kenai, Anchorage, and Fairbanks, and data is virtually nonexistent for large areas of the State. Known dissolved-solids concentrations range from less than 25 mg/L in shallow ground-water in stream channel alluvium, to as much as 64,000 mg/L in saline waters in shallow coastal wells, but most of the sampled ground water contains less than 400 mg/L dissolved solids (table 2) and is acceptable for most uses. In inland areas, calcium bicarbonate- or calcium magnesium bicarbonate-type water is most common. Water of sodium bicarbonate or sodium chloride type is present in coastal areas.

The quality of ground water causes problems, however, such as those related to saline waters in coastal areas and in springs and deep artesian wells in the Copper River lowland, relatively high mineralization of subpermafrost water in some areas, and magnesium sulfate bicarbonate-type waters from bedrock in the Tanana River valley. Iron is present in objectionable concentrations in a large proportion of shallow wells in most areas of the State. Undesirable concentrations of other constituents also occur in ground water in Alaska. Chemical analyses (U.S. Geol. Sur-

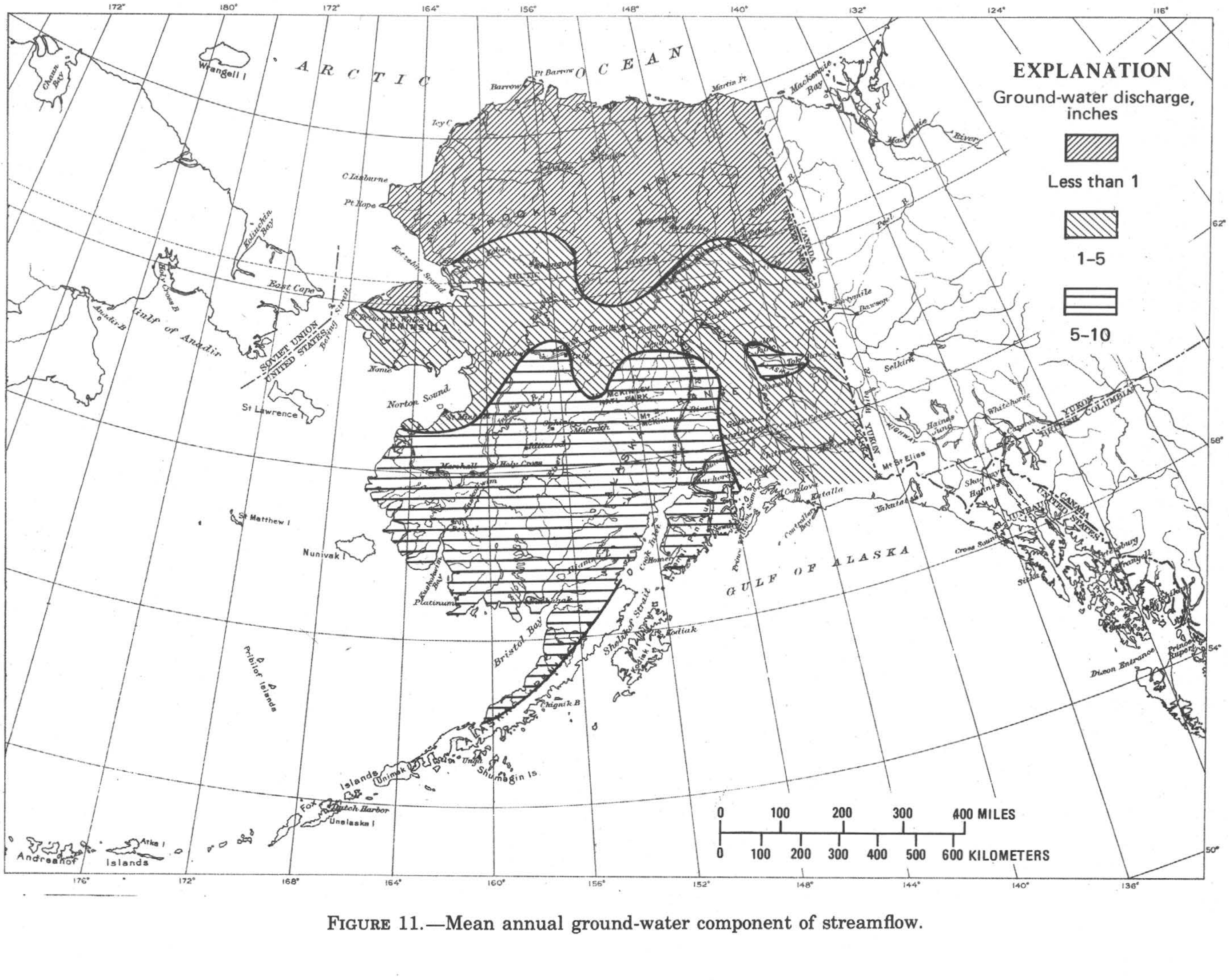


FIGURE 11.—Mean annual ground-water component of streamflow.

TABLE 1.—*Summary of surface-water and ground-water discharge by hydrologic subregions and subareas of Alaska*

[Mean annual surface-water runoff estimated following method by Balding (1976). Estimated ground-water discharge determined using flow exceeded 60 percent of the time (from flow duration curves) as an index, except for values in parentheses, which are approximations discussed in text]

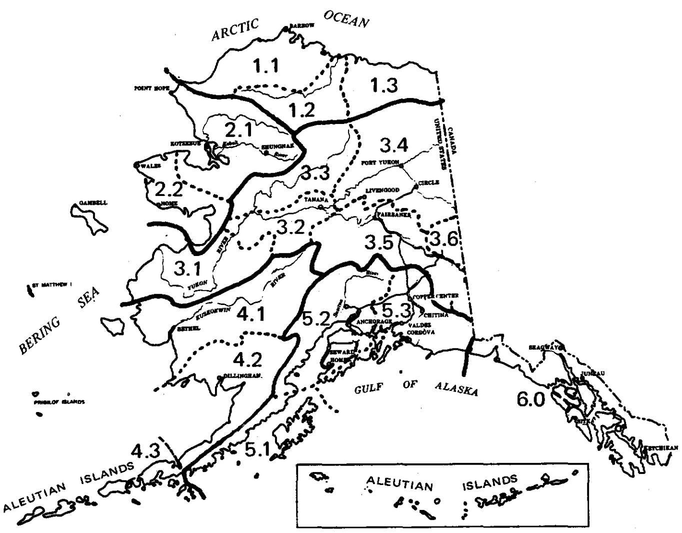
Subregions and subareas	Area (mi²)	Mean annual surface-water runoff		Estimated ground-water discharge	
		From within unit	Including upstream inflow	Total ft³/s	Inches of water per unit area
1. Arctic:					
1:1 West Arctic	31,000	14,800	—	200	0.1
1:2 Colville	24,000	14,000	—	200	.1
1:3 East Arctic	26,000	15,200	—	200	.1
2. Northwest:					
2:1 Kotzebue Sound	41,000	59,100	—	10,600	3.5
2:2 Norton Sound	26,000	18,500	—	1,900	1.0
3. Yukon:					
3:1 Lower Yukon	38,000	43,000	262,000	18,200	6.5
3:2 Central Yukon	19,000	28,300	219,000	11,000	7.9
3:3 Koyukuk	33,000	23,100	—	2,000	.8
3:4 Upper Yukon	60,000	34,700	128,000	7,000	1.6
3:5 Tanana	45,000	39,200	39,600	12,600	3.8
3:6 Upper Yukon—Canada	9,000	6,140	—	1,700	2.6
4. Southwest:					
4:1 Kuskokwin Bay	58,000	71,200	—	31,200	7.3
4:2 Bristol Bay	40,000	120,000	—	(30,000)	(10.0)
4:3 Aleutian	11,000	22,400	—	no estimate	—
5. Southcentral:					
5:1 Kodiak-Shelikof	11,000	54,200	—	no estimate	—
5:2 Cook Inlet	38,000	91,300	—	19,600	7.0
5:3 Gulf of Alaska	34,000	61,800	—	12,800	5.1
6. Southeast	42,000	388,500	458,000	no estimate	—
Totals		1,105,000		[1]159,200	

[1]Equivalent to 10 × 10⁴ million gallons per day.

TABLE 2.—*Summary of DS (dissolved-solids) concentrations data in ground waters of Alaska*

[Normal range is defined as ± one standard deviation of the mean; approximately 68 percent of all values would fall within this range]

Area	Number of DS values	Average DS (mg/L)	Normal range of DS (mg/L)
Juneau (McConaghy, 1969)	141	199	26– 372
Haines-Port Chilkoot (McConaghy, 1970)	14	209	66– 352
Copper River lowland (U.S. Geol. Survey, unpub. data)			
Wells less than 100 ft deep	11	535	55–1015
Wells greater than 100 ft deep	13	1936	382–3490
King Salmon (Feulner, 1963)	16	158	94– 222
Bethel (Waller, 1957, and U.S. Geol. Survey, unpub. data)	36	157	124– 190
Homer (Waller, 1963)	27	314	139– 489
Kenai-Soldotna (Anderson and Jones, 1971)	140	209	50– 368
Anchorage (Donaldson, and others, 1975)	567	159	93– 225
Fairbanks (U.S. Geol. Survey, unpub. data)	502	227	112– 342
Nome (Waller and Mathur, 1962)	8	354	188– 520



vey, unpub. data) show undesirably high concentrations of mercury in the ground water in the Yukon-Kuskokwim delta area, and high concentrations of nitrate are reported in occur locally in the Palmer and Fairbanks areas. Other examples are: organic materials in ground water of alluvial stream channels and flood plains, and arsenic in ground water in the bedrock hills north of Fairbanks (Hawkins, 1976) and in glaciolacustrine clay at Anchorage and Kenai.

The role of permafrost in directly imparting a particular type of mineralization to ground water is probably minor. Reduction of the rate of ground-water movement by permafrost provides a longer residence time for reactions between the water and the enclosing rocks than in regions without permafrost (Williams and van Everdingen, 1973). Chemical reaction rates and saturation concentrations of some constituents are also affected by low water temperatures in permafrost areas. Ground water beneath permafrost is usually of nearly constant quality at a particular site, although it may differ in composition from one area to another. Ground water above permafrost is subject to variation in quality due to seasonal reduction in recharge and possibly also because of fractionation due to freezing of part of the aquifer. Feulner and Schupp (1963) found such a seasonal variation in ground water developed by infiltration gallery at Cape Lisburne in northwestern Alaska.

Streams that receive ground-water inflow show a seasonal variation in concentration of dissolved minerals because of the changing proportions of ground water and surface water that contribute to streamflow (Brandon, 1964). Thus surface-water quality data, particularly during low-flow (or base-flow) periods, can be used as an indication of regional ground-water quality. Because ground water is generally more highly mineralized than surface water, the highest concentrations of dissolved solids occur during low-flow periods. Dissolved-solids concentration of a stream can be still further increased during low-flow periods in winter as freezing causes rejection of impurities from the ice phase into the remaining water (Osterkamp and others, 1975). This phenomenon can cause the winter flow of streams to have an even higher concentration of dissolved minerals than the inflowing ground water.

Dissolved-solids concentration is considered to be a useful index of overall water quality, but available data do not provide representative coverage for winter streamflow in Alaska. However, specific conductance, which is dependent on dissolved-solids content, is a characteristic commonly measured in field water-quality determinations. Ranges in specific conductance values measured during base-flow periods, November through April, for streams in the various hydrologic subregions of Alaska are given in table 3.

CURRENT DEVELOPMENT AND USE

Water use in Alaska in 1975, exclusive of large nonconsumptive uses by fish hatcheries, pulp mills, and by hydroelectric power-generating facilities, was estimated to be about 100 Mgal/d (million gallons per day) (A. J. Feulner, written commun., 1976, and table 4). Nearly half of that total was ground water. Ground water supplies an even higher proportion of total demand in some public-supply systems (50–60 percent at Anchorage) and is the only source in others (Fairbanks and Juneau). Most private domestic supply in the Anchorage and Fairbanks areas is from ground water.

TABLE 3.—*Summary of specific conductance values for base flow of streams in Alaska*

[Base-flow period November 1 to April 30 when little or no surface runoff is occurring]

Hydrologic subregion and subarea	Range of specific conductance (μmhos/cm^2) of base flow
Arctic	225–350
Northwest	150–250
Yukon:	
Lower and Central Yukon	250–300
Koyukuk	350–400
Upper Yukon and Tanana	250–400
Southwest:	
Kuskokwim Bay	100–240
Bristol Bay	[1]50–100
South-central:	
Cook Inlet	100–300
Gulf of Alaska	100–250
Copper River Lowland	300–500
Southeast	(Base flow not defined)

[1]Influenced by significant volume of lake storage.

TABLE 4.—*Water use in Alaska in 1975*

[Does not include 80 Mgal/d nonconsumptive pulpmill use or 907 Mgal/d nonwithdrawal hydroelectric power use. Table based on revision of data compiled by A. J. Feulner, U.S. Geological Survey. Values in Mgal/d (millions of gallons per day)]

Use category	Ground water	Surface water	Total
Public supply	35	21	[1]56
Rural use:			
Domestic	6.2	3.0	9.2
Livestock	.03	.08	.11
Irrigation	—	.02	.02
Electric powerplant cooling	2.20	19	21
Industrial	5.0	10	15
Total	48	53	101

[1]Includes unspecified industrial uses in Fairbanks, Anchorage, Juneau, and other smaller communities.

Surface water provides most of the supply to the small population of the Arctic Slope and Northwest regions of the State (see index map on table 1). Wells supply distribution systems, chiefly for domestic use, at some small villages and at the larger communities of Nome and Unalakleet. A military installation at Cape Lisburne formerly used about 5,000 gal/d (gallons per day); this water was provided mainly by infiltration galleries installed in the alluvium of stream valleys or in fractured bedrock. Galleries have also been used to develop small ground-water supplies from streambed and flood-plain alluvium at several sites along the trans-Alaska oil pipeline route.

Ground water is the principal source of supply in the Yukon subregion. Virtually all the population, and thus most of the water use, is within the Tanana and Delta River basins; Fairbanks and nearby military installations use approximately 11–12 Mgal/d. Springs, especially thermal springs, have been used locally for many years for small farming operations and as summer resorts.

In Alaska's Southwest region, ground water provides part of the community water supply at Dillingham, and wells have been drilled at many small villages. Springs, wells, and galleries are used for water supply at military installations on Shemya and Amchitka Islands in the Aleutians.

The largest concentration of population in Alaska, and consequently the greatest development and use of water, is in the South-central region. Ground water provides about 150,000 gal/d at Palmer and about one-half of the 40 Mgal/d of water used in the Anchorage area for domestic, industrial, and commercial purposes. At Anchorage, the largest municipal wells yield up to 2,000 gal/min. There has been considerable development of ground water in the Kenai-North Kenai industrial area. Public supply systems and private, domestic water demands at Kenai and nearby Soldotna are also exclusively served by ground water. Total ground-water withdrawal in the Kenai and Soldotna areas is about 4 Mgal/d.

Ground water is the principal source of domestic, commercial, and industrial supply at Juneau, Sitka, Skagway, and at several other major communities in southeastern Alaska. The large water needs of the wood pulp processing industry in that region, however, are met almost exclusively by surface water.

PROBLEMS IN THE DEVELOPMENT AND USE OF GROUND WATER

Man impinges on the domain of ground water when he drills and pumps wells, uses aquifers as waste-disposal sites whether intentionally or accidentally, and in Arctic and subArctic areas, when he constructs buildings, roads, and pipelines on and across zones of ice-rich permafrost. The development of mineral and fuel deposits and of geothermal resources usually involves ground water. These activities, along with the development and use of ground water itself, may lead to the types of problems described below.

DECLINE OF WATER LEVELS

Pumping from a well or closely-spaced group of wells creates a cone of depression in the water level of an unconfined aquifer or in the potentiometric surface of a confined aquifer. The decline in water level or potentiometric surface may be small and temporary. However, if ground-water withdrawal exceeds recharge, the decline will become progressively greater and will result in increasingly greater pumping lifts, higher pumping costs, and ultimately, depletion of the resource.

In Anchorage, a significant cone of depression has formed in the potentiometric surface of the artesian aquifer near the Municipal well field, where withdrawal in 1975 averaged 4.2 Mgal/d. The potentiometric surface has not been permanently lowered, but fluctuates in response to pumping rates (fig. 12). Water-level data collected during a short, nonpumping period in 1969 indicate that if all ground-water withdrawal from the confined aquifer were to cease, the potentiometric surface would recover to within a few feet of the 1955 pre-pumping levels within a few months. Production of additional ground water from confined sand and gravel aquifers in the Anchorage area is currently limited by drawdown of water levels near existing wells (Barnwell and others, 1972) rather than by available resources of the aquifers.

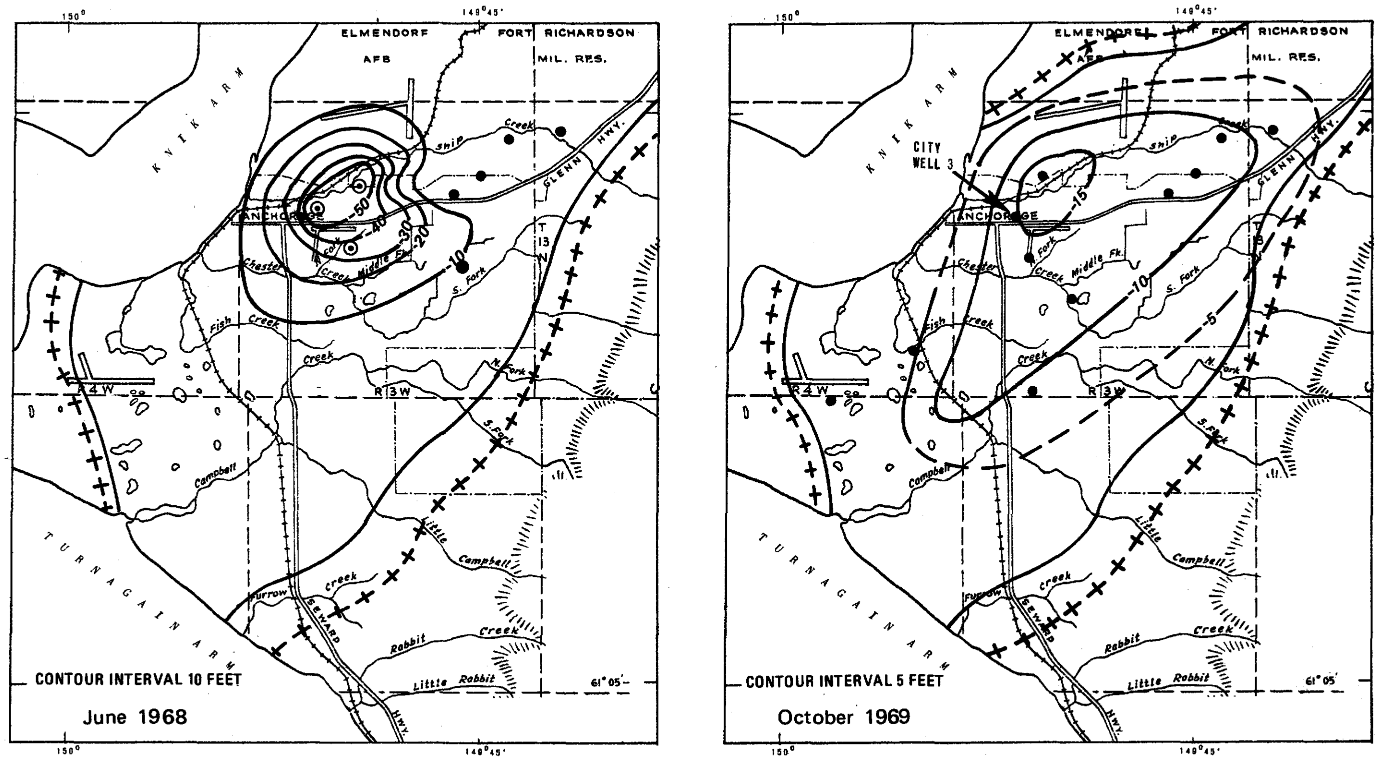
Other areas in Alaska where artesian pressure reductions are caused by the pumping of high-yield municipal or industrial wells include North Kenai, Kanai, Soldotna, and Cordova. In the North Kenai area, a decline of lake levels is also thought to be caused at least partly by the lowering of the potentiometric surface in the confined aquifer, with consequent leakage of unconfined water downward to the confined system. Anderson and Jones (1972) reported maximum declines of 6 ft at three lakes near North Kenai industrial plants that pump large volumes (3 Mgal/d) of ground water.

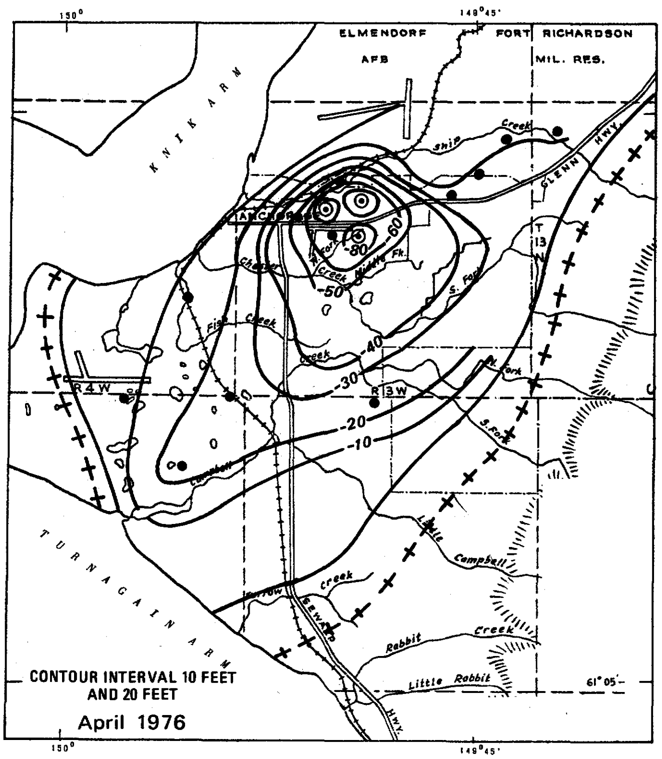
Declines in ground-water levels have been observed in the upland area north of Fairbanks where low-yielding wells produce water from fractures and small perched zones in bedrock (G. L. Nelson, U.S. Geol. Survey, written commun., 1976). In this area the aquifers are unconfined and the water-level declines represent a reduction in storage. This loss of storage may be due partly to a decrease in natural recharge caused by below-average precipitation in Fairbanks over the past 4 years, but pumping from an increasing number of privately owned wells apparently is having some effect. Locally, well owners have reported water-level declines of 20–35 ft since 1973; a decline of 7 ft in a recent 17-month period was recorded at a U.S. Geological Survey observation wells in the area.

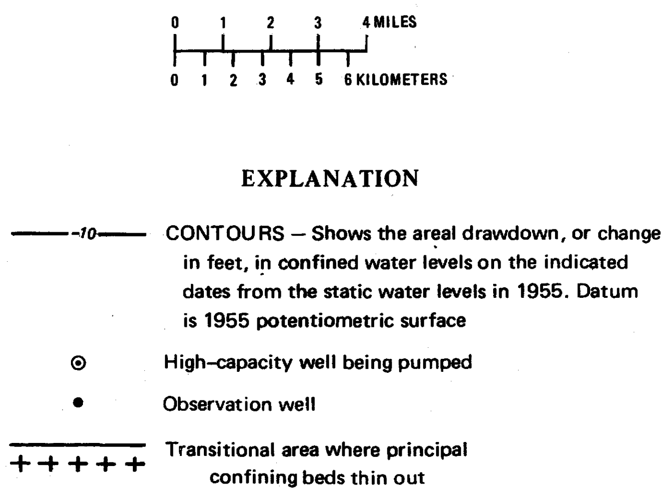
DEPLETION OF STREAMFLOW

In areas where streams are hydraulically connected to the ground-water reservoir, pumping water from nearby wells may cause interception of potential streamflow or diversion of water from the stream. In Alaska this interconnection of surface and ground waters may have significant effects on streamflow, particularly in winter when no surface runoff is occurring.

Some communities and individuals utilize water from shallow wells drilled in stream-valley alluvium, but there are few quantitative data relating to streamflow depletion caused by these ground-water withdrawals. Infiltration galleries near streams provide water supplies at some military installations in Alaska (Feulner, 1964; Feulner and Williams, 1967). Galleries or shallow (20 ft or less) wells near active stream channels were used for water supply at former construction camps along the Dietrich and Sagavanirktok River sections of the trans-Alaska oil pipeline route (Sherman, 1973; J. R. Williams and C. E. Sloan, oral commun., 1976). These ground-water







ESTIMATED GROUND-WATER WITHDRAWALS

Date	Well-field area	Total areal pumping rate
1955	none	1 Mgal/d
June, 1968	4.7 Mgal/d	11 Mgal/d
October, 1969	none	4.5 Mgal/d
April, 1976	5.2 Mgal/d	18-20 Mgal/d

FIGURE 12.—Changes in water levels caused by pumping from artesian aquifers at the Anchorage Municipal well field (modified from Barnwell and others, 1972).

developments rely amost exclusively on recharge from the nearby surface-water source; consequently, some streamflow depletion inevitably occurs. This depletion can be significant in winter when no surface runoff is occurring and all water is pumped from storage in deep pools or from alluvium under the pools.

The relationship of surface water and ground water along the channel of Ship Creek near Anchorage was discussed earlier (p. 14). Water required for the proposed expansion of fish-rearing facilities along lower Ship Creek would rely chiefly on ground water recovered from shallow wells and infiltration galleries in streamside alluvium (Freethey, 1976). Hypothetical streamflow depletion curves, derived by L. D. Patrick and others (U.S. Geol. Survey, unpub. data 1976–77), show that the proposed development would ultimately reduce streamflow by an amount nearly equal to the ground-water withdrawal. The streamflow could be totally depleted during winter low-flow periods.

POLLUTION OF THE GROUND-WATER RESERVOIR

Deterioration of water quality caused by man's own activities is commonly termed pollution or contamination. The cone of depression and resulting change in gradient of the water table or potentiometric surface caused by pumping from wells can induce the movement of pollutants already in the aquifer toward the pumping center. If this occurs, wells may have to be abandoned and new water sources sought. The slow movement of ground water and the slow process of natural dilution make the effects of water pollution long-lasting, even though pumping or the discharge of pollutants to the ground water stops.

Pollution may be caused by actions or land-use practices not directly involving ground-water withdrawal. The concentration of people and activities that accompanies urbanization promotes the generation of large amounts of waste materials. In some cases, the wastes are disposed of or stored at sites where there is a potential for ground-water pollution. Ground water has been polluted locally in the Anchorage area by solid-waste disposal directly into lakes which are hydraulically connected to the ground-water body or by surface disposal at places where the water table is at very shallow depth (Zenone and others, 1975). Solid-waste disposal in frozen ground in the Fairbanks area is in effect a storage of material from which a contaminating leachate could be produced if the frozen mass of waste and adjacent permafrost were to be naturally or artificially thawed (Straughn, 1972).

Local pollution of ground water has been caused by septic tank effluent in unsewered areas of Anchorage (Dearborn and Barnwell, 1975) and at Fairbanks (G. L. Nelson, oral commun., 1976). The present problem area at Anchorage is the mountain slope environment east of the city where bedrock is mantled by only a thin, poorly permeable layer of unconsolidated glacial materials. The quality of water of some private water supplies has also been impaired by drainage of surface water into wells that were either improperly constructed or had damaged casing at the ground surface. Other potential sources of ground-water pollution in heavily urbanized areas are leakage of sanitary sewers and infiltration of runoff from streets (deicing chemicals) and lawns (fertilizers). The disposal of primary-treated sewage effluent, either through injection wells or by surface spreading and infiltration, is being considered as an alternative to the present ocean outfall at Anchorage's sewage-treatment plant. Such practices create yet another potential for ground-water pollution, even though they have been tested elsewhere and shown to be at least partly successful methods of purifying and recycling wastewater (Bouwer, Lance and Riggs, 1974; Bouwer, Rice and Escarcega, 1974; Satterwhite and others, 1976).

The practice of using lagoons for wastewater disposal and treatment at remote construction camps and villages throughout Alaska is a potential source of pollution for ground-water supplies. Some of these lagoons are too close to shallow water-supply wells and galleries. Successful operation of the wells and galleries may depend on the permeability and porosity of the same small body of unfrozen material as that being recharged by the lagoons. Accidental oil or fuel spills that inevitably occur during major construction projects, and disposal of petrochemical wastes, oil-field brines, and drilling muds are other potential sources of pollution of ground water.

SALINE WATER INTRUSION

In coastal areas, aquifers that contain fresh water may be hydraulically connected to the ocean or other saline water body. Under natural conditions the hydraulic gradient or direction of ground-water flow is generally toward the coast (fig. 13a). If ground-water withdrawal lowers the water table or potentiometric surface so that the natural gradient is reversed, saline water will begin to invade the freshwater aquifer (fig. 13b). The potential for saltwater intrusion at Anchorage has been discussed by Barnwell and others (1972, p. 45), but the probability of its occurrence due to

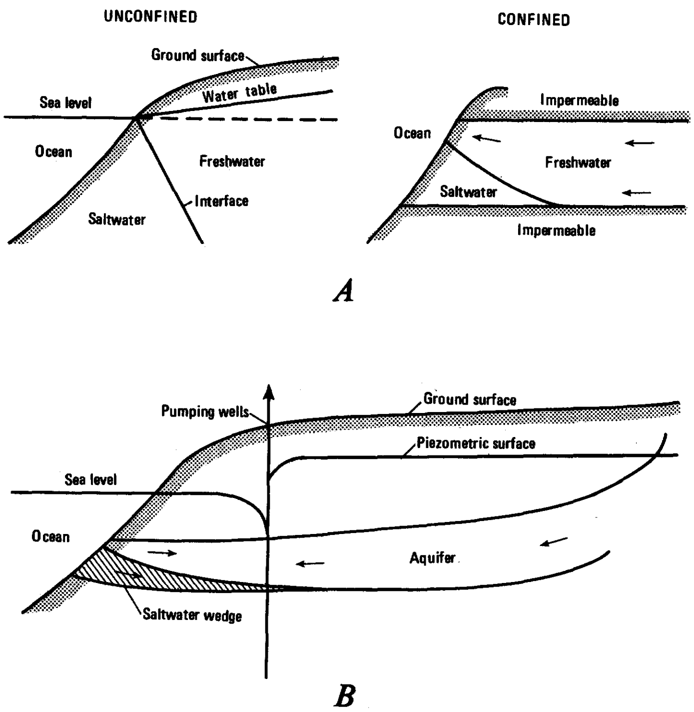


FIGURE 13.—Aquifers that contain fresh water may be hydraulically connected to a saline water body and may be intruded by saltwater. *A*. Idealized sketch of freshwater and saltwater distributions in coastal aquifers illustrates Ghyben-Herzberg relation. *B*. Effect of pumping on saltwater wedge movement into a coastal confined aquifer.

ground-water withdrawals at present (1978) pumping sites and rates is considered remote. Existing wells are already being pumped at the maximum rate allowed by well construction and drawdown limitations. The center of the cone of depression at the Municipal well field is several miles inland and artesian water levels near the coast were 20–30 ft above sea level in 1976 (fig. 12). The two major public water suppliers in the Anchorage area are aware that the potential for saltwater intrusion must be considered in selecting new well locations.

In island settings and on offshore bars and spits, fresh ground water generally occurs as an unconfined, lens-shaped body floating on sea water. The Ghyben-Herzberg principle (see Todd, 1959, p. 278) states that there is a 40-ft-thick zone of freshwater below sea level per foot of water-table altitude above sea level. This situation exists at St. George Island, in the Pribilof Islands in the Bering Sea (Anderson, 1976) and at Fire Island near Anchorage (A. J. Feulner, U.S. Geol. Survey, written commun., 1964). Other areas where ground water probably occurs only as thin lenses are at locations such as Unalakleet, Kotzebue, and the lowermost fringes of the Yukon and Kuskokwim River deltas in the coastal areas of western Alaska. Under natural or equilibrium conditions, a transition zone of brackish water separates the freshwater from the saltwater below.

The withdrawal of ground water from the fresh lens and the resulting lowering of the water table may disturb the natural balance and induce movement of saltwater into the freshwater-bearing formations. For example, saltwater intrusion has apparently occurred because of pumping from bedrock wells near the coast on Kodiak Island (F. and S. Ogden, drilling contractors at Kodiak, written commun., 1976). It follows from the Ghyben-Herzberg principle that each foot of lowering of the water table in the freshwater lens will induce a rise of 40 ft in the top of the underlying saltwater body. Successful development of ground water under such conditions depends largely upon control of pumping to avoid creating excessive drawdown.

All major population centers except Fairbanks are in coastal areas. Imminent development of Alaska's offshore petroleum and other resources will insure that future growth, including an increasing demand for water, will be concentrated in coastal areas, in part because of the need for transportation bases from which those resources will be shipped outside the State. Any development of ground-water supplies in those areas will require consideration of the potential for saltwater intrusion.

In the Copper River basin area, saline water is pumped from wells and issues from several springs and mud cones. The connate origin of the saline water (Grantz and others, 1962) has been confirmed by exploratory drill holes for oil (Williams, 1970a). Barnes (1970) believes the water to be a product of low-grade metamorphism of marine sediments. Relatively impermeable glaciolacustrine sediments confine the saline aquifers and separate them from overlying potable-water aquifers (Williams, 1970a). Dissolved-solids concentrations of the waters range from 760 to 35,000 mg/L. Dissolved-solids concentration generally increases with the depth of the well. The potential exists for degradation of the shallow, fresh (or at least less saline) water should excessive pumping cause up-coning of the deeper, highly saline water or leakage through the confining beds.

CONSTRUCTION AND ENGINEERING PROBLEMS RELATED TO THE PRESENCE OF GROUND WATER

Construction or installation of roadways, foundations, and pipelines is generally more difficult, more costly, and more time consuming if saturated soil must be dealt with. The soil may have to be dewatered temporarily during construction, though permanent drainage may be required for some structures. Rapid urban development during dry years in areas that normally have a high water table (such as parts of Anchorage) could result in flooding of basements and failure of foundations when water levels return to normal. Similar problems could result from recovery of a water table that was temporarily lowered because of ground-water withdrawal or high infiltration rates to sewer and storm-drainage lines.

The strength of unconsolidated materials such as sand and silt is reduced when they are saturated. Damage to and even collapse of foundations at Fairbanks during the disastrous 1967 flood was caused by a decrease in bearing capacity of the soil as the water table rose (Childers and others, 1972). A rising ground-water table that accompanies a rise in river stage can damage foundations on flood-plain deposits even though the river is below flood stage.

Landslides may be triggered by imposition of loads of buildings on slopes or bluff areas, or by seismic shaking of liquifiable deposits in earthquake-prone areas such as south-central Alaska. Liquifaction of saturated sand and silt lenses in the Bootlegger Cove clay was considered to be a major factor in causing landslides at Anchorage during the 1964 earthquake (Shannon and Wilson, 1964). Severe damage by submarine landsliding and ground displacement at Valdez was also attributed to spontaneous liquifaction of saturated sand (Coulter and Migliaccio, 1966).

Normal construction and maintenance problems in saturated ground are magnified if the ground is frozen, as it is in the permafrost zones of Alaska.[2] Permafrost is generally in a natural state of thermal equilibrium with the present climate, even though it may be a relic of former, colder periods. Disruption of this equilibrium caused by disturbance of the ground surface or vegetation cover by vehicular movement, construction and maintenance activities, and by heat produced within structures or by operation of facilities tends either to raise the mean annual ground-surface temperature or to increase the amplitude of seasonal variations in ground temperature. Either result will degrade or thaw part of the permafrost. A discussion of the specific engineering problems caused by the melting of permafrost is beyond the scope of this paper. Those problems are discussed in detail by Ferrians, Kachadoorian and Greene (1969), Lachenbruch (1970), and by Linell (1973). The development and application of unique engineering practice in permafrost is described by Ferrians and others (1969); Linell and Johnston (1973); and by Sanger (1969).

[2]This discussion is included under the assumption that ice-rich permafrost can be considered to be "frozen ground water" when in fact some subsurface ice may have formed as hoarfrost or buried icings that were never actually ground water. Meinzer (1923, p. 22) specifically excluded subsurface ice as a type of ground water.

CONSIDERATIONS IN RESOURCE DEVELOPMENT

The environmental effects of ground-water development are not always known or anticipated, even in areas where ground-water use is most intensive. In the Anchorage area, artesian flow to the surface at many private wells was reduced or eliminated coincident with initiation of large-scale Municipal pumping in the late 1950's. Effects such as these are obvious and measurable; the more subtle or long-term effects are not completely understood. These might be, for example, the potential effect of land-drainage activities or ground-water pumpage on lake levels, wetlands, and the base flow of streams that are hydraulically connected to the producing aquifer. Development of ground water invariably produces some changes in other elements of the hydrologic system. However, the amount of change that will be tolerated must be defined if conflicts of use are to be held to acceptable limits. Paraphrasing Anderson and Jones (1972, p. 74, 75), who drew principally from a discussion by Lohman (1972, p. 62): To determine whether moderate quantities of water can be withdrawn from a given ground-water reservoir is generally not difficult. But to determine the maximum amount of water that can be withdrawn without producing an undesirable result requires detailed knowledge of the geologic framework of the hydrologic system and planning decisions as to the extent that undesirable results can be tolerated. This is difficult to do because normally the potential of a hydrologic basin cannot be determined in advance of development. However, the hydrologic information that is available concerning the geohydrologic system and the cause-effect relationships of ground-water withdrawals can be used to construct models that will predict aquifer response. Even after a model of the aquifer has been constructed and shown to be reliable for predicting hydrologic responses to pumping, the optimum yield cannot be estimated until the water planners or users define precisely the undesirable results that are to be avoided.

Some questions that are relevant to water-resources development (specifically ground-water withdrawal) in Alaska include:

1. What is a tolerable water-level drawdown, and over what areal extent can it occur?
2. What is the relative value of swamp lands? Should they be preserved as natural habitat areas, or should the lowering of water levels be allowed in order to make the land more suitable for construction or agriculture?
3. Can changes in lake levels be tolerated; if so, to what extent?
4. Can the reduction of natural ground-water discharge be tolerated, and what will be the ef-

fect on streamflow maintained by the reduced discharge? Will such a reduction affect instream flow requirements of salmon migration, degrade spawning habitat, or cause movement of the freshwater-saltwater interface in coastal areas?

5. Should temporary overdraft (pumpage in excess of recharge) of the hydrologic basin be permitted, provided the effects are not catastrophic, if use of ground water contributes to development of an economic base that would later be able to support a more expensive, integrated surface-water/ground-water system?

As a basis for management decision, it may be assumed that optimum yield of ground water will be achieved when the average recharge is balanced by the average discharge and when the discharge for nonbeneficial purposes has been reduced to a minimum. In most years, however, such a balance will not be achieved. During dry years, ground water is drawn from storage, water levels decline, and recharge from lakes and streams may increase. During wet years, lakes are filled, streams flow above normal discharge, and the ground-water reservoir is replenished. Maximum use of ground-water reservoirs cannot be achieved by holding the storage constant; it is achieved by drawing on storage during dry years, but only to the extent that the storage can be replenished during wet years.

Superimposed on the natural hydrologic factors which must guide the decisions of the water-resource manager are the legal aspects of water appropriation and use. All the waters of Alaska, both surface and subsurface, are considered to be the property of the public and thus subject to appropriation. The doctrine of prior appropriation was applied to early territorial decisions in order to settle water-use conflicts between competing users of the available water supply. The principles of the appropriation system were carried forward in the State Constitution and the water rights code which was adopted in 1966 (Dewsnup and others, 1973). The code is now (1977) being reviewed and will probably be revised and updated to meet the changing needs of a rapidly developing area. Although the State presently claims public ownership of all the waters of Alaska, there remain conflicts of ownership and rights to water use that will have to be considered as part of the final implementation of the Alaska Native Settlement Act of 1971. Disputes have already arisen over established water uses on lands now being claimed by the various Native corporations (Robert Bursiel, Alaska Division of Lands, oral commun., 1976). The adjudication of water rights and management of the resource will also have to be accomplished within a checkerboard pattern of projected land uses and political subdivisions that does not correspond with either surface-water or ground-water drainage divides.

SIGNIFICANCE OF THE GROUND-WATER RESOURCE

Advantages of ground water over surface water are common to both arctic and temperate regions. Ground water is widely if not evenly distributed, has less annual variation in temperature and chemical quality, and is less subject to pollution than is surface water. In addition, the subsurface environment provides a vast storage reservoir which is not as subject as surface water to changes in the volume of storage caused by short-term extremes in climate. It is this storage factor that enhances the importance of ground water in Alaska, where seasonal freezing reduces and in some cases eliminates the availability of surface water.

Alaska's ground-water resource has been virtually untouched over vast areas. Permafrost severely restricts the availability of ground water in northern Alaska, but for the remainder of the State potential development far exceeds current use. Probably the greatest potential for development of ground water is in the Tanana River valley and to a lesser extent in the Yukon and Kuskokwim valleys and their major tributaries.

CONJUNCTIVE USE OF GROUND WATER AND SURFACE WATER

Conjunctive use of ground water and surface water should be considered in water-supply development in Alaska. In some areas use of these dual sources has been a necessity rather than a consciously applied principle of management. Surface-water flows in the Arctic are drastically reduced in early winter and may even cease during mid- to late winter. If a stream does maintain year-round flow, domestic, commercial, or industrial water needs that outgrow the supply will require a search for supplemental sources. Ground water may be able to provide the storage necessary to carry the community over the low-flow period of its surface-water source.

An excellent example of conjunctive use of ground and surface sources is the Municipal water supply at Anchorage. Direct withdrawal from Ship Creek, from nearby springs, and from an infiltration gallery in the gravels beneath the channel of lower Ship Creek provided Anchorage's first water supply. About 1946 a reservoir was built on the upper reaches of Ship

Creek, and for a time the city was supplied entirely by surface water. By 1956 the capacity of the reservoir was taxed by the demand from growing civilian and military populations, and development of a well field near the city center was begun to increase the water supply. Since that time all additional development has been from ground water, which now provides about one-half of the total Municipal water utility's demand of 16 Mgal/d. An added benefit from the use of dual sources at Anchorage has been a significant reduction in the incidence of freezing water mains, a common winter occurrence when surface water alone supplied the city (Nyman, 1958).

Locations favorable for large-yield (1–2 Mgal/d) wells are nearly exhausted in the Anchorage area, and various plans have been proposed recently for more complete utilization of excess summer flows of Ship Creek. Among these plans are the use of off-stream storage basins, diversion and treatment of water near the mouth of the creek (U.S. Army Corps of Engineers, 1976), and artificial recharge of the Ship Creek alluvial fan deposits (Barnwell and others, 1972, p. 46; Anderson, 1977).

NEED FOR ADDITIONAL INFORMATION ON GROUND-WATER RESOURCES

The deficiency of the ground-water data base has been referred to throughout this report. That deficiency is an obvious limiting factor for ground-water development in Alaska. The potential of the resource and the advantages of its utilization can best be realized if investigations are made in anticipation of future water demands. Important ground-water information needs in Alaska may be placed in two broad categories.

BASIC DATA

Several government agencies, private organizations, and individuals collect and compile ground-water data in Alaska. Such studies usually are made within a limited area in order to analyze or resolve a specific problem of water availability or water quality for a community or industrial venture; consequently, there remain large gaps in the ground-water data network for Alaska. Collection of hydrologic data in remote areas is time consuming and expensive and there may be neither present nor anticipated demand for the data. Collection of some data has been possible through Federal and State government funding made available to analyze environmental impacts of proposed development. Additional subsurface hydrologic information is available from activities such as pipeline trenching, and exploratory, foundation, and seismic shot-hole drilling. These records are not generally recognized as being valuable to the hydrologist and are not collected systematically, nor are they generally available to the scientific community.

There is a critical need, on a Statewide basis to (a) identify the sources and types of ground-water data being collected, (b) design a system and schedule to collect and process the data and make them accessible to interested parties, and (c) evaluate the adequacy of the data base on a continuing basis in order to recommend the collection of new information where deficiencies exist. Efforts to meet this ground-water data need were initiated in 1977 as part of a cooperative water-resources study between the Alaska Department of Natural Resources and the U.S. Geological Survey.

HYDROLOGIC STUDY AND RESEARCH

Alaska's generally unexplored and undeveloped ground-water resource has been the subject of several descriptive reviews, including this one. More important than simple description and data collection, however, is the need to understand the physical role of ground water in the hydrologic cycle of arctic and subarctic areas. Quantitative investigations of the hydrology of cold regions, particularly in the continuous permafrost zones, will help to explain the important "hydrological linkage" between surface and ground waters (Guymon, 1973). Suggested study and research areas include the following:

1. Field studies of evapotranspiration and soil moisture relations. Few such studies have been conducted in Alaska, and most empirical formulas, developed for temperate climates, do not apply in high-latitude locations.
2. Studies of the hydrology of springs and icings, and the identification of areas for aquifer recharge and discharge through unfrozen zones in permafrost. These studies could provide important information and methods for predicting locations of water-supply sources, the potential occurrence of icings, and the effect of permafrost on base flow of streams (Williams, 1970a). Resistivity and seismic-refraction methods could be used to supplement existing data in determining the configuration of permafrost, particularly adjacent to surface-water bodies (Hoekstra and McNeill, 1973).
3. Studies of the hydraulics of flow through porous media at subfreezing temperatures. Results of aquifer tests should be considered in terms of boundaries imposed by permafrost

as well as those related to lithology and rock structure. The validity of the common assumptions that permafrost contains water only in the solid state and that it is impermeable and thus prevents ground-water movement has been questioned (Williams and van Everdingen, 1973). Quantitative studies could resolve many uncertainties and permit better prediction of aquifer response in permafrost regions.

4. Continuation of geothermal studies of the type pioneered by Lachenbruch, Brewer, Greene, and Marshall (1962) in order to refine understanding of the thermal regimen and its effect on the formation, stability, and degradation of permafrost. Results of such studies could be applied in creating aquifers by thawing frozen ground as was attempted in the alluvium of Selin Creek at Cape Lisburne (Feulner and Williams, 1967).
5. Investigations of the chemistry of ground ice and unfrozen brines, and the seasonal variation and selective concentration of chemical constituents in ground water associated with permafrost. Information gained could be helpful in the solution or avoidance of water-quality or pollution problems. Reports of fresh potable water encountered during drilling for petroleum at offshore sites in Cook Inlet emphasize the need to evaluate the effects of brine injection for secondary recovery on potential water-supply aquifers.

SUMMARY AND CONCLUSIONS

Alaska's ground water is a large resource, but one that is virtually unexplored and undeveloped. Estimated average annual ground-water discharge, which is assumed to approximate recharge on a long-term basis, is 100,000 Mgal/d. In 1975, ground-water use in Alaska amounted to only 50 Mgal/d.

Probably only a small fraction of the total ground-water discharge can ever be captured for man's use, but this fraction represents a renewable resource which can play a significant role in the future development of the State. Alaska's population, currently less than one-half million, will inevitably increase as the demand for and development of the State's vast mineral and petroleum reserves increase. Much of that development, particularly for petroleum and natural gas, will take place in the Arctic Foothills and Arctic Coastal Plain. The occurrence of ground water in those areas is severely limited by continuous permafrost. However, the major population centers and greatest demand for water will remain in the southern half of Alaska where the influence of frozen ground on the occurrence and availability of ground water is comparatively minor and where potential ground-water development is many times greater than current use.

In the southern half of Alaska, conditions favorable for ground-water development occur over large areas. Wells in the major river valleys, alluvial fans, and some coastal valleys and basins commonly yield as much as 1,000 gal/min, and similar yields are possible from wells in volcanic rocks at some locations. At many places in these areas, annual ground-water recharge is sufficient to sustain high rates of continuous withdrawal, and, at these places, the ground-water resource is adequate for present and future needs. At other places, available ground water may be insufficient to meet needs but, in conjunction with surface water, may permit optimal development of the total water resource.

The development of additional supplies of ground water will circumvent many of the problems currently associated with the use of surface water, such as extreme seasonal variability of supply, the need for impoundment reservoirs, and the presence of objectionable amounts of glacial silt in many streams. The use of ground water, however, also entails some problems. Local water-level declines, depletion of streamflow, saltwater intrusion into aquifers, and natural or man-caused pollution of ground-water reservoirs are all significant problems at some places in Alaska and are potential problems at other places.

The ground-water resource of Alaska thus presents both challenge and opportunity. Through the acquisition of new information from field studies and the application of new and existing data in analytical models and interpretive reports, the information needed for effective management can be made available, and ground water can take on a vital role in the overall water-resource planning and management for Alaska.

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