Overview of Environmental and Hydrogeologic Conditions at Barrow, Alaska

By Kathleen A. McCarthy

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
millimeter (mm)	0.03937	inch
centimeter (cm)	0.3937	inch
meter (m)	0.3048	foot
kilometer (km)	0.6214	mile
hectare (ha)	2.471	acre
square kilometer (km^2)	0.3861	square mile
liter (L)	0.2642	gallon
liter per day (L/d)	0.2642	gallon per day
cubic meter per second (m^3/s)	35.31	cubic foot per second
degree Celsius (°C)	°F = 1.8 x °C + 32	degree Fahrenheit (°F)

Sea level:

In this report "sea level" refers to the National Geodetic Vertical Datum of 1929--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

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Abstract

To assist the Federal Aviation Administration (FAA) in evaluating the potential effects of environmental contamination at their facility in Barrow, Alaska, a general assessment was made of the hydrologic system in the vicinity of the installation. The City of Barrow is located approximately 16 kilometers southwest of Point Barrow, the northernmost point in Alaska, and therefore lies within the region of continuous permafrost. Migration of surface or shallow-subsurface chemical releases in this environment would be largely restricted by near-surface permafrost to surface water and the upper, suprapermafrost zone of the subsurface. In the arctic climate and tundra terrain of the Barrow area, this shallow environment has a limited capacity to attenuate the effects of either physical disturbances or chemical contamination and is therefore highly susceptible to degradation.

Esatkuat Lagoon, the present drinking water supply for the City of Barrow, is located approximately 2 kilometers from the FAA facility. This lagoon is the only practical source of drinking water available to the City of Barrow because alternative sources of water in the area are (1) frozen throughout most of the year, (2) insufficient in volume, (3) of poor quality, or (4) too costly to develop and distribute.

INTRODUCTION

The Federal Aviation Administration (FAA) operates airway support and navigational facilities throughout Alaska, and is currently conducting investigations at many of these sites to evaluate suspected releases to the environment of potentially harmful substances. Once released, the effects of such substances on the environment are often influenced strongly by transport in either surface water or ground water. Therefore, in order to accurately assess the effects of such releases and select the most appropriate remediation measures when such action becomes necessary, an understanding of the geohydrology in the vicinity of each site is critical. This report, the product of compilation, review, and summary of existing hydrogeologic data by the U.S. Geological Survey in cooperation with the FAA, provides an understanding of the geohydrologic system in the vicinity of the Barrow FAA facility.

The City of Barrow has a population of approximately 3,700 (Christy Miller, Alaska Department of Community and Regional Affairs, written commun., 1993), and is the largest community in the North Slope Borough. Air travel is the only year-round means of transportation to or from the city. In 1963, the Wiley Post-Will Rogers Memorial Airport, located immediately south of the city, was constructed. Since that time, the FAA has operated an attended flight service station at the airport. The FAA station consists of approximately 38 ha of noncontiguous land leased from the Alaska Department of Transportation and the Ukpeagvik Inupiat Corporation (Ecology and Environment, Inc., 1992). A recent environmental compliance investigation was done for the Barrow FAA station by Ecology and Environment, Inc. (1992), and a detailed description of the facility and suspected sources of potential contamination can be found in their report.

PHYSICAL SETTING

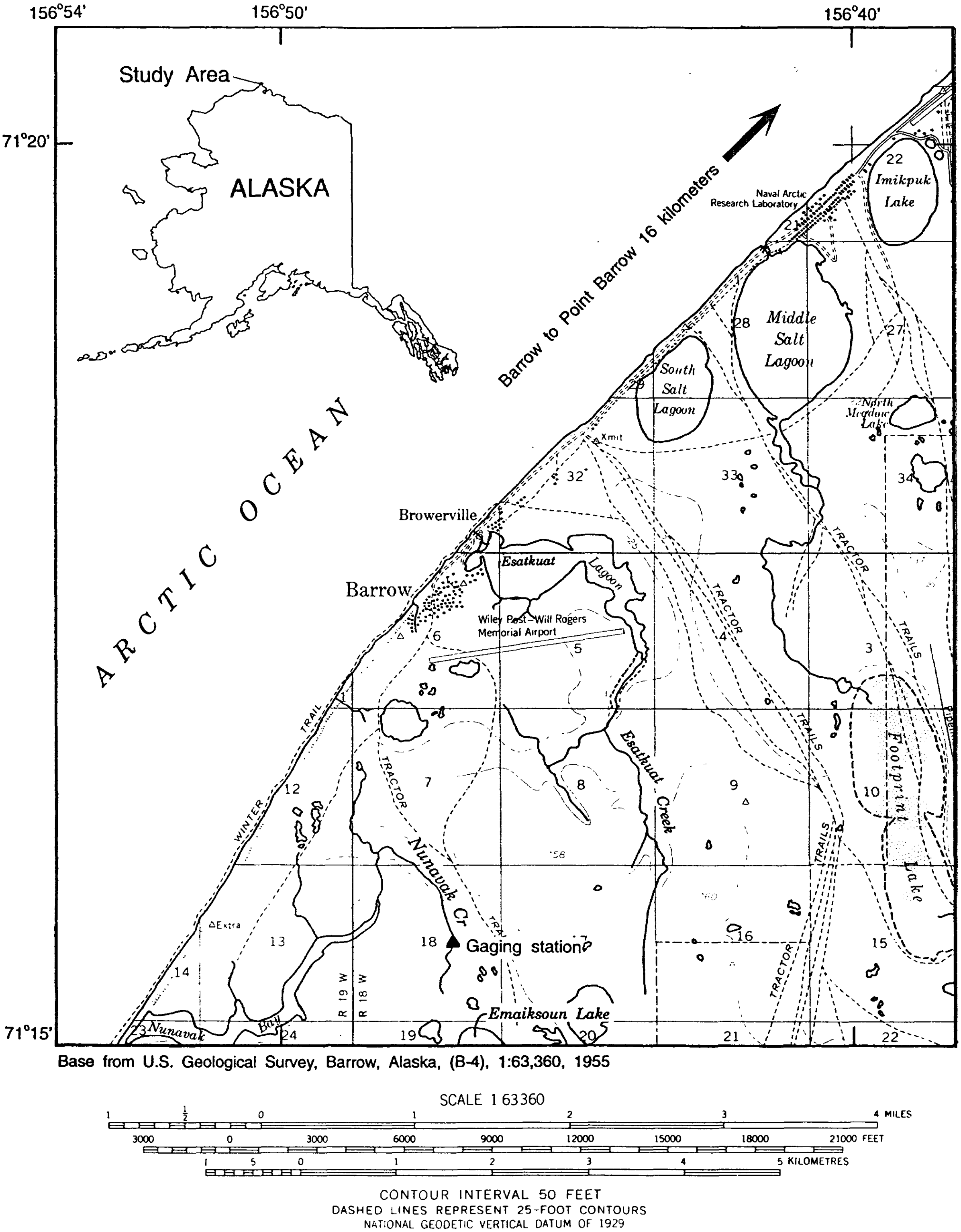
Barrow (fig. 1) is located at latitude 71°18' N, longitude 156°47' W, approximately 530 km north of the Arctic Circle and within the region of continuous permafrost. The Chukchi Sea of the Arctic Ocean borders the city to the northwest, and Point Barrow, the northernmost point in Alaska, is 16 km to the northeast.

Climate

The climate of the Barrow area is characterized by long cold winters, short cool summers, and persistent wind. The effects of the nearby Arctic Ocean cause summers to be generally cooler, more breezy, and more moist than at more inland locations. Average monthly temperatures range from approximately 4° C in July to -28° C in February and typically climb above freezing only during the months of June, July, and August (table 1).

The average annual precipitation at the National Weather Service station in Barrow is reported to be 119 mm (table 1). However, numerous observations indicate that actual precipitation on the Arctic Coastal Plain exceeds that recorded by standard National Weather Service gages. Accurate measurement of summer precipitation is difficult, due to the large proportion that occurs as fog and trace amounts of rainfall. Brown and others (1968) suggest that thaw-season precipitation recorded by standard gages averages approximately 90 percent of actual precipitation, but that the discrepancy between actual and measured rainfall varies considerably from year to year. During the winter, gage undercatch of snow is attributed primarily to persistent high winds. Actual snowfall in the Barrow area has been estimated to be from two to four times that recorded by standard gages (Black, 1954; Dingman and others, 1980; Benson, 1982). Benson's data (1982) also indicate that gage efficiency tends to be inversely related to the amount of precipitation with the smallest errors occurring during years of high precipitation.

More than 50 percent of the annual precipitation typically falls during the months of July, August, and September (table 1). Although most precipitation in July and August occurs as rain or fog, snow can occur during any month and is the predominant form of precipitation from September through June.



Base from U.S. Geological Survey, Barrow, Alaska, (B-4), 1:63,360, 1955

Figure 1. Location of Barrow.

Table 1. Mean monthly temperature, precipitation and snow data for Barrow, Alaska, for the period 1949-87 (Leslie, 1989)

[°C, degree Celsius; mm, millimeter]

Month	Mean temperature (°C)	Mean total precipitation (mm)	Mean total snowfall (mm)
January	-25.4	5.1	58
February	-28.4	4.6	56
March	-26.3	3.8	46
April	-19.0	5.1	61
May	-7.3	4.1	48
June	0.9	9.1	18
July	3.9	22.1	10
August	3.3	24.6	18
September	-0.8	16.3	99
October	-9.7	13.0	160
November	-18.2	6.9	86
December	-24.3	4.3	53
YEAR	**-12.6**	**118.6**	**716**

Surficial Geology

The Barrow peninsula is the northernmost extremity of the Arctic Coastal Plain, which extends from the foothills of the Brooks Range in the south to the Arctic Ocean in the north (Wahrhaftig, 1965). The area is characterized by low relief; numerous lakes, ponds, and drained thaw-lake basins; and areally continuous permafrost. Permafrost is rock or soil that has remained continuously below 0° C for two or more years. In the Barrow area, permafrost extends to depths of up to 300 m (Collins, 1961). The layer above the permafrost that thaws each summer and refreezes each winter is referred to as the "active layer." The maximum depth of the active layer is typically less than 0.5 m in areas where the vegetation and soil of the tundra surface are undisturbed (Brown and others, 1968; Dingman and others, 1980; U.S. Geological Survey, unpub. data). In areas of unvegetated gravels, the seasonal thaw extends to greater depths, but is generally limited to less than 2 m (DOWL Engineers and Crowley Environmental Services, Inc., 1986; Tryck, Nyman, & Hayes and Shannon & Wilson, Inc., 1987; U.S. Geological Survey, unpub. data). Beneath heated buildings, other artificial structures, and lakes that are more than approximately 2 m in depth, a zone of permanently thawed ground is commonly present. Such zones, referred to as thaw bulbs or thermal taliks, may extend to considerable depths. For example, Brewer (1958) reported measurable warming of the permafrost at a depth of 15 m beneath a 12-by-30 m building near Barrow. Beneath Imikpuk Lake, a small freshwater lake (approximately 750 m in diameter) located 8 km northeast of Barrow, Brewer (1958) found the depth to permafrost to be more than 50 m. Although such aberrations in the permafrost are common, especially in developed areas where the ground surface has been disturbed, they are generally limited in areal extent.

The geology of the Arctic Coastal Plain is relatively well characterized, due in part to the extensive exploration for petroleum that has occurred in the region over the past several decades. Detailed geologic information may be found in reports by Black (1964), Carlson and others (1958), Collins (1961), Dinter and others (1990), Gryc (1988), Wahrhaftig (1965), and Williams and Carter (1984). As discussed in the later section on hydrology, surface water and shallow ground water in the region are generally isolated from deeper ground water by permafrost. Therefore, the discussion here will be limited to the shallow subsurface environment.

Bedrock in the region forms a broad, low-relief surface known as the North Beringian Marine Abrasion Platform (Dinter and others, 1990). The uppermost bedrock unit in the Barrow area, which consists primarily of shale, is not exposed on the surface, but is commonly found in boreholes at depths ranging from 10 to 30 m (Collins, 1961; Black, 1964; M.C. Brewer, U.S. Geological Survey, oral commun., 1994). The bedrock is overlain by unconsolidated marine, eolian, and lacustrine-lagoonal deposits of late Tertiary and Quaternary age. These deposits are a mixture of sand, silt, gravel, and clay, and shallow ground water in the Barrow area generally occurs entirely within the uppermost materials. In coastal areas, deposits include sand dunes and beach gravels. The Barrow airport facility was constructed on one of these dunes (Alaska Transportation Consultants, Inc., 1983).

Soils

Soils in the Barrow area are classified as wet, loamy, histic pergelic cryaquepts (Rieger and others, 1979). These soils are included in the order Inceptisol and are generally characterized by thick accumulations of organic matter at the surface, persistent cold temperatures, shallow permafrost, and very high moisture contents. The considerable organic content of these soils is due largely to the persistent cold temperatures, which restrict biodegradation and thus promote the accumulation of organic material from vegetation. Because organic material has a lower thermal conductivity than mineral soils, it serves to insulate the underlying permafrost. As a result, the permafrost table is typically within 0.5 m of the surface in such soils, provided the surface has not been disturbed.

Physical churning of the soils above the permafrost results from cyclic freezing and thawing. Because of this churning, distinct soil layers are often absent and organic material from plants at the surface is commonly distributed downward. Cyclic freezing of the soils also causes contraction cracks to form. Such cracks may fill with water, which subsequently freezes and cracks. As this cycle repeats, the fissures grow. Extensive networks of interconnected cracks, referred to as patterned ground or ice-wedge polygons, are common in the Barrow area. A more detailed discussion of the formation of ice-wedge polygons is provided by Carter and others (1987).

The soils throughout the area generally have a very fine-grained texture and are characterized by high porosity and low permeability. However, gravelly soils also occur in the area, particularly near the beach. The permeabilities of soils in the area thus span several orders of magnitude. All soils, however, have a substantially reduced permeability to water once their temperature drops below freezing. As a result, hydraulic conductivities are extremely low for most of the year, and vertical movement of water is restricted year round by the presence of near-surface permafrost.

Vegetation and Wildlife

The diversity of plant and animal species is more limited in the Arctic than in more temperate regions. As a result of the cooling influence of the Arctic Ocean on the summer climate, the number of plant species in coastal areas, such as Barrow, is further reduced relative to the interior of the Arctic Coastal Plain.

Brown and others (1980) report 124 species of vascular plants (sedges, grasses, rushes, and a limited number of low-stature shrubs), 177 species of mosses, and 49 species of hepatics (liverworts) identified in the Barrow area. Lichens are also indigenous to the coastal tundra. All of these plant species are particularly adapted to the arctic climate and tundra terrain of the region and the niches within which many flourish are highly specific. Two factors that control the local distribution of plants are the moisture content and pH characteristics of the soils. These factors, particularly moisture content, can vary considerably over small distances. Gersper and others (1980) described meadows, ice-wedge polygon troughs, rims and basins of low-centered polygons, and centers of high-centered polygons as five microtopographic units of the coastal tundra. Soil-moisture content often differs considerably among these units. As a result, the vegetation patterns in areas of ice-wedge polygons often vary substantially over short distances (Brown and others, 1980).

The terrestrial vertebrate species found in the Barrow area are limited to homoiothermic (warm-blooded) birds and mammals; no reptiles or amphibians are indigenous to the region. Brown and others (1980) report 28 species of birds and 10 species of terrestrial mammals in the area. The considerable bird population includes loons, ducks, geese, shorebirds, passerines, owls, ptarmigan, and eagles, and the terrestrial mammals include caribou, arctic and red fox, and collared and brown lemmings. Numerous marine mammal and fish species are also indigenous to the Barrow area. Marine mammals of the area include polar bear, walrus, both toothed and baleen whales, and several species of seals; fish species include whitefish, arctic grayling, burbot, and trout. Many of these species, particularly whales, fish, caribou, and waterfowl, play a critical role in the subsistence lifestyle of local residents.

Environmental Susceptibility

The tundra environment in the Barrow area is much more susceptible to damage by human activity than environments typical of more temperate regions. For example, disturbances resulting from vehicle traffic or construction activities can cause long-term or even permanent changes to the tundra. Such changes are often the result of damage to vegetation, compaction of the surface organic mat and underlying soils, or a combination of these factors. Vegetation and the surface organic mat help to insulate underlying permafrost. If this insulating layer is damaged or destroyed, the thermal regime in the soil will be altered and the depth of seasonal thaw may increase substantially. Thawing of ice-rich permafrost may lead to considerable subsidence of the local land surface. In the flat terrain of the Barrow area, even small changes in land-surface elevation can have large effects on drainage patterns, and the formation of new lakes where surface disturbances have occurred is common. Once a lake has formed, the thermal regime of the underlying permafrost is further disturbed by heat from the water. Thawing of permafrost beneath the lake may thus occur, resulting in further subsidence of the lake bed and gradual expansion of the lake. This process is similar to the natural cycle of lake formation, expansion, and drainage—referred to as the thaw-lake cycle—which occurs commonly on the Arctic Coastal Plain (Billings and Peterson, 1980; Edwards and Brigham-Grette, 1990; Harry and French, 1983; Kidd, 1988).

Lakes in the Barrow area are also highly susceptible to degradation. One reason for this susceptibility is the process of concentration by freezing. As the surface freezes, impurities in the water tend to be excluded from the ice and are thus concentrated in the remaining unfrozen water. Because of this phenomenon, water quality in lakes and lagoons generally decreases throughout the winter and spring as the ice cover grows and the volume of unfrozen water decreases. In lakes and lagoons that remain partially unfrozen year round, water quality is generally poorest just prior to the thaw season, when the volume of unfrozen water is smallest. Water-quality problems in the Arctic are further exacerbated by the limited availability of water. Annual runoff on the Arctic Coastal Plain averages approximately 110 mm (Dingman and other, 1980) and a large part of this limited runoff occurs during the brief snowmelt period, typically no more than 2 weeks in duration. A considerable portion of this snowmelt runoff occurs while lakes and lagoons are still covered with ice. As a result, a portion of the annual inflow to surface-water bodies commonly flows over the ice cover and leaves through the outlet of the lake without mixing with the water beneath the ice. Dilution of the water remaining beneath the ice with fresh snowmelt water is thus reduced.

The arctic environment also has a limited capacity to attenuate contaminants in soil and active-layer water. Low soil temperatures restrict the activity of microorganisms and thus reduce rates of biodegradation. The presence of near-surface permafrost also decreases the ability of the environment to attenuate contamination by restricting the downward flow of water, thereby reducing the dilution of contaminants by dispersion.

The environment in the Barrow area is clearly sensitive to both physical disturbances and chemical contamination resulting from human activity. Potential damage to the environment from such activities is of particular interest to the community because the subsistence lifestyle of many residents makes them highly dependent on the environment for their livelihood.

HYDROLOGY

The proximity of permafrost to the surface and the great depths to which it extends largely control hydrology in the Barrow area. Permafrost is much less permeable than unfrozen ground and thus acts as a hydrologic confining layer, limiting the vertical movement of water. The presence of this shallow confining layer greatly impedes infiltration and, as a result, water remains at the surface or within the shallow subsurface. The permafrost thus isolates the near-surface flow system, including surface water and ground water within the active layer, from the deeper, regional flow system. Beneath the ocean and deep lakes, however, thermal taliks (thaw bulbs) may penetrate the entire thickness of the permafrost. Chemical taliks—subsurface zones that remain unfrozen because of the chemical composition of the water—also occur in the Barrow area as a result of saline ground water. High-salinity ground water is common throughout the region, particularly beneath the active layer. In some cases, therefore, thermal or chemical taliks may form conduits between the active layer and deeper ground water. Flow through such conduits will be negligible, however, because salinity, and therefore density, generally increase with depth. Relatively fresh shallow ground water and deeper saline ground water will thus tend to remain stratified.

In addition to the presence of permafrost, the limited relief of the tundra contributes to the unique hydrology of the Barrow area. This limited relief greatly impedes drainage and, as a result, lakes and ponds are ubiquitous, and few well-developed stream channels exist. The flat terrain also affects the configuration of drainage basins. Because even slight topographic highs often serve as drainage divides in this region, relatively small changes in the surface, such as soil cracks and the formation of ice-wedge polygon troughs, can breach these divides and significantly alter areal drainage patterns. Unmelted snow drifts and plugging of streams, polygon troughs, or culverts by ice can also result in temporary changes in surface drainage patterns. Although such surface-drainage phenomena are more evident, formation of polygon troughs and differential thawing of the active layer may lead to analogous changes in subsurface drainage patterns and, hence, ground-water flow directions. Furthermore, as a result of the limited vertical thickness of the active layer, distinct ground-water flow regimes in this shallow system are likely to exist at scales ranging from centimeters to tens of meters rather than at more extensive, regional scales. For example, the depth of thaw within ice-wedge polygons may not extend below the level of the polygon troughs. In such cases, no areally continuous ground-water flow system will exist and ground water within each polygon will discharge into the adjacent polygon trough.

Sublimation, evaporation, and transpiration are also significant to hydrologic budgets of the Arctic Coastal Plain. Average annual recorded precipitation of less than 120 mm (table 1) qualifies the Barrow area as a desert (Skinner and Porter, 1987). Average annual runoff for the nearby Nunavak Creek basin (fig. 1) is 119 mm (U.S. Geological Survey, 1993). Relative to these values for annual precipitation and runoff[1], estimates of annual evaporation, transpiration, and sublimation, though they vary considerably among sources, are high. Dingman and others (1980) report estimates ranging from 60 mm per thaw season to 210 mm per year, on the basis of data from Brown and others (1968), Weller and Holmgren (1974), and Stewart and Rouse (1976). Evaporation, transpiration, and sublimation are thus substantial components of the annual hydrologic budget in the Barrow area.

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[1] The similarity between average annual recorded precipitation and average annual runoff values reflects the fact that precipitation data do not account for the gage inefficiencies discussed in the "Climate" section.

Annual Hydrologic Cycle

Arctic Coastal Plain hydrology is largely controlled by the region's climate and the presence of near-surface permafrost. The annual pattern of mean air temperature in the area (table 1) results in an annual hydrologic cycle that can be described in terms of four periods: winter, snowmelt, summer, and freeze-up. Each period is characterized by distinct hydrologic processes.

Winter

The winter season in the Barrow area typically begins during late September and lasts through early to mid-June. During the winter, streams do not flow, freshwater lakes less than approximately 2 m in depth freeze to the bottom, and the subsurface is frozen from land surface to depths of up to 300 m (Collins, 1961). Nonetheless, three important hydrologic processes occur during this season: the accumulation of snow, sublimation from the snowpack, and redistribution of soil moisture.

Although the snow cover of the Arctic Coastal Plain is generally shallow (less than 0.5 m except in wind drifts), winter snowfall often accounts for more than half of the annual precipitation recorded for the Barrow area. Considerable moisture is lost from the snowpack, however, as a result of sublimation and evaporation. These high loss rates are caused by strong temperature gradients and air convection within the snowpack and shallow soil, which produce a substantial upward flux of water vapor. In addition to depleting the snowpack, the upward movement of moisture desiccates the shallow soil and surface vegetative mat. (This desiccation may result in the formation of salt crystals at the ground surface.)

Snowmelt Period

The snowmelt period, which marks the transition from winter to summer in the Arctic, generally begins during early to mid-June. A considerable part of the snowpack dissipates within the first few days, and except for isolated, sheltered patches, snow is usually completely gone within approximately 2 weeks. Streamflow during this brief period is considerable in arctic basins, and may constitute as much as 90 percent of the annual runoff (Church, 1988). A typical hydrograph for Nunavak Creek (fig. 2A) illustrates this phenomenon. Although runoff is high during this period, a substantial part of the snowpack is lost to the atmosphere through evaporation and sublimation. These processes are complex during the snowmelt period, especially after the snow cover becomes discontinuous. Large variations in surface albedo, and hence temperature, occur between the remaining snow cover and exposed ground surface and these variations result in complex spatial patterns of evaporation and condensation.

Infiltration during the snowmelt period is limited. Although the upper layer of soil is desiccated as a result of the upward migration of soil moisture during the winter, only shallow thawing of the active layer occurs during the snowmelt period. Meltwater penetrating the soil surface thus freezes, which initially limits infiltration. However, cracks in the soil, including ice-wedge polygon troughs, and other local depressions in the land surface can retain substantial quantities of water. Once the snowpack becomes discontinuous, radiative heating of the exposed darker surface promotes thawing of the active layer, allowing available water to infiltrate. After the existing soil-moisture deficit has been satisfied, excess infiltration provides recharge to the active layer ground-water system.

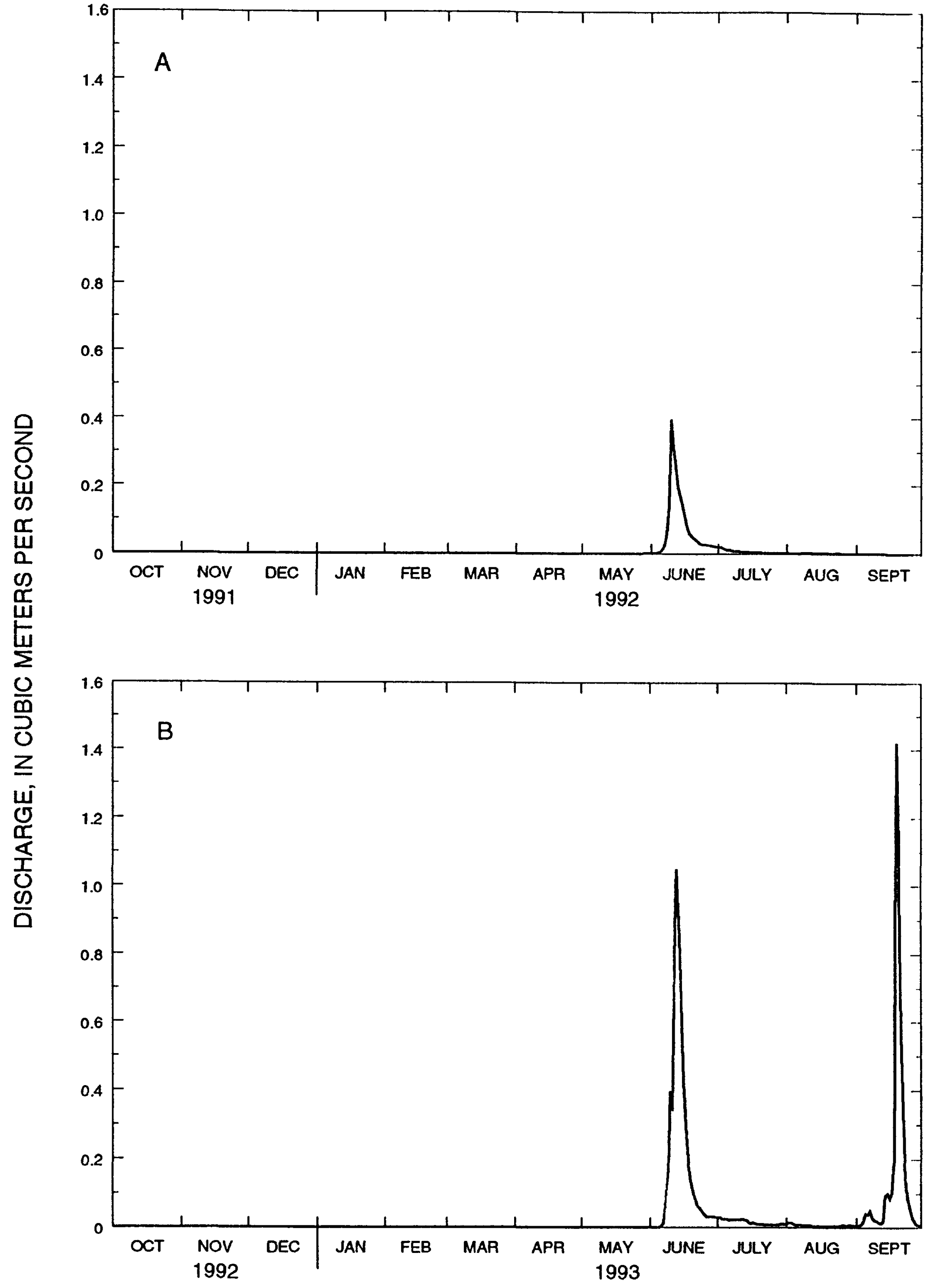

Figure 2. Discharge for Nunavak Creek, water years 1992 and 1993.

In contrast to the snowpack, only part of the ice covering lakes and lagoons melts during this period. During the early part of the snowmelt period, water surfaces remain covered by ice, and snowmelt runoff into lakes and lagoons occurs on top of the ice. Ice is generally thinnest at the shallow edges of surface-water bodies. As thawing progresses, these edges of the ice cover disintegrate most quickly, producing a thawed moat around a frozen interior. When the entire circumference of the frozen surface has thawed, the remaining ice floats free and rises to the surface. This initially massive ice block typically requires several ~~more weeks~~ to melt completely. During this period, winds continually shift the ice, resulting in substantial lake turbulence and shore erosion.

Summer

The short summer season in the Barrow area begins at the end of the snowmelt period (usually during mid- to late June) and typically extends through late August or early September. Important hydrologic processes that occur during the summer season include evapotranspiration; delayed movement of snowmelt water that has been temporarily stored in lakes, small ponds, or the subsurface; and development of the subsurface active layer.

As during the snowmelt period, the rate of water loss to the atmosphere continues to be high throughout the summer, and a number of studies in the Barrow area indicate that evapotranspiration and precipitation are approximately equal during this period (Brown and others, 1968; Dingman and others, 1980; Guymon, 1976; Mather and Thornthwaite, 1958). Consequently, summer precipitation does not usually contribute substantially to annual runoff. This is illustrated for the Nunavak basin in figure 2A, which shows very limited runoff following the snowmelt peak during June. Occasionally, however, this pattern is altered (fig. 2B). A period of unusually high precipitation and warm temperatures during September 1993 resulted in a second runoff peak in Nunavak Creek. This was the first time during the period for which streamflow records are available for Nunavak Creek (1972 to present) that the peak annual flow occurred outside the snowmelt period (U.S. Geological Survey, 1994).

Thawing of the active layer begins during the snowmelt period and continues throughout the summer. While investigating the development of the active layer in a small basin northeast of Barrow, Brown and others (1968) found that thaw penetration usually reached 75 percent of its maximum by early July and maximum penetration was typically reached by mid-August. Flow in the shallow ground-water system of the active layer can occur throughout the thaw season, but studies in areas of undisturbed tundra suggest that the flow is minimal (Dingman and others, 1980). In addition to the low hydraulic conductivity of the soils and the small hydraulic gradients typical in flat terrain, ground-water flux in such areas is limited both by the shallow depth of thaw and the large capacity of the fine-grained tundra soils to hold capillary water.

Freeze-Up

The final phase of the annual hydrologic cycle begins as temperatures drop below freezing, usually during late August or September, and the transition from summer to winter begins. As surface water freezes and precipitation falls as snow, streamflow decreases and generally ceases altogether during late September. The ground surface cools and freezes, and the freezing front progresses downward through the active layer. Although some freezing occurs upward from the top of the permafrost that marks the bottom of the active layer, freezing from land surface downward is generally much faster. During this period, accumulation of snow and desiccation of the active layer begin. Soil desiccation during this period results from downward migration of the upper freezing front. As soil moisture in the surface layer freezes, pore pressure within the soil matrix is reduced and moisture from underlying soil migrates upward in response to this pressure gradient. Kane and Chacho (1990) provide a discussion of the complex processes of moisture migration in freezing soils.

Flooding and Storm Surges

Flooding of streams resulting from high runoff volumes is generally not a serious problem in the Barrow area, although some flooding of low-lying areas does occur as a result of rapid snowmelt in the late spring and early summer. Conversely, inundation of coastal areas by storm surges, also referred to as storm tides, has had catastrophic effects. The astronomical tide at Barrow, with a total amplitude of less than 30 cm, is relatively insignificant. However, rises in sea level resulting from atmospheric low-pressure systems coupled with onshore winds can be substantial. In the Barrow area, the presence of ocean ice has a damping effect on both waves and storm surges. Even when the ice moves offshore in the summer, it is usually near enough to have some mitigating effects. Occasionally, however, ice moves far enough offshore to allow substantial storm tides to develop. The largest storm surge on record for the Barrow area occurred in October 1963 and had an estimated maximum tide of approximately 3.7 m (Hume and Schalk, 1967). Because the natives of Barrow had no recollections of storms equal to or greater in magnitude than the 1963 storm, Hume and Schalk (1967) considered the event to approximately represent a storm with a 200-year recurrence interval.

One of the potentially devastating effects of storm surges such as the one that occurred in 1963 is the inundation of coastal freshwater lakes by saltwater. For example, Imikpuk Lake, located approximately 7 km northeast of Barrow (fig. 1), was inundated with saltwater during the 1963 storm surge. The lake serves as the potable water supply for the Ukpeagvik Inupiat Corporation National Arctic Research Laboratory (formerly, the Naval Arctic Research Laboratory), and had to be annually pumped dry and allowed to refill with freshwater for three consecutive years following the storm surge (M.C. Brewer, U.S. Geological Survey, oral commun., 1994).

Transport of Contaminants by Surface and Ground Water

Because both streams and the active layer ground-water system in the Barrow area remain frozen for most of the year, transport of contaminants by flowing water would be restricted to the brief thaw season. Directions of surface transport could be highly variable as a result of changes in drainage patterns resulting from soil cracks, snow drifts, or the plugging of streams, polygon troughs, or culverts by ice. Directions of ground-water transport could also vary considerably as a result of ice-wedge polygon formation, differential thawing as the active layer develops throughout the summer, and the small scales at which distinct flow regimes exist in the shallow active layer flow system. These changes in directions of surface- and ground-water flow are likely to occur over the course of individual thaw seasons, as well as from year to year.

The large volume of runoff that occurs during the snowmelt period—up to 90 percent of the annual total—has important implications for environmental contamination. Because flowing water is a primary mechanism of contaminant transport, most of the annual migration of surface contaminants may occur during this brief period.

Storm surges may also transport contaminants. It is possible that a storm surge, within a period of hours, could transport contaminants over distances that would take several years, or even decades, under more typical conditions. Furthermore, storm-surge transport may occur in directions contrary to prevailing flow paths.

DRINKING WATER

Water supply poses a unique challenge in the Arctic. One of the primary difficulties in developing reliable, year-round water supplies is the short open-water season. Most freshwater lakes in the Barrow area are less than 2 m in depth and thus freeze completely during the winter. Esatkuat Creek and Nunavak Creek are the only substantial streams in the area. Esatkuat Creek drains an area of approximately 3.7 km^2 to the southeast of the FAA facility and discharges into Esatkuat Lagoon, which is located approximately 2 km to the north and east of the station (fig. 1). Nunavak Creek drains an area of approximately 7.2 km^2, including Emaiksoun Lake, approximately 4 km south of Barrow, and discharges to Nunavak Bay, approximately 5 km southwest of the city (fig. 1). Flow in both of these streams, however, is limited to the short thaw season (fig. 2).

Another important consideration in developing water supplies in the Arctic is the construction and maintenance of storage, treatment, and distribution systems. The extreme climate and the presence of permafrost make construction of these systems challenging and expensive, particularly if water must be distributed a considerable distance from its source.

Present Drinking Water Supply

Esatkuat Lagoon, which lies approximately 2 km to the north and east of the FAA facility (fig. 1), remains partially unfrozen year round. The lagoon is separated into sections by artificial berms and the upper lagoon serves as the primary source of drinking water for the City of Barrow. Water drawn from the lagoon is treated by filtration and distributed through a utilidor system to multiple watering points throughout the city. Approximately 97 percent of the housing units in Barrow are served by this distribution system (Alaska Department of Community and Regional Affairs, 1991). Water use averages less than 200,000 L/d. However, demand peaks in winter, and monthly usage during this period can exceed 850 million liters (Alaska Consultants, Inc., 1983).

Alternative Drinking-Water Sources

Few alternative sources of drinking water are available in the Barrow area because, as discussed previously, streamflow ceases entirely during the winter, and only a small number of lakes, including Emaiksoun and Imikpuk Lakes (fig. 1), remain partially unfrozen year round. Even these lakes, however, are not well suited as alternative drinking water sources for the city because of their limited volumes and relatively distant locations.

Development of ground water as an alternative source of drinking water has proven to be impractical in the Barrow area and currently no water wells are in use (Alaska Department of Community and Regional Affairs, 1991). Shallow ground water within the active layer is not suitable as a source of drinking water for two reasons. First, this water remains frozen for most of the year and second, even during the period of maximum thaw, the volume of water available in this shallow system is not adequate to meet the needs of even a small part of the City of Barrow. Some attempts have been made to explore the availability of deeper, subpermafrost ground water, but in many places the permafrost is too extensive to allow economical development of this water. Furthermore, subpermafrost ground water is generally too saline to serve as a source of drinking water. In a few places, such as beneath Esatkuat Lagoon, unfrozen ground water has been found at shallower depths (J.B. O'Sullivan and R.W. Faas, consulting geologists, written commun., 1962). However, this water is unfrozen as a result of its high salinity, which is approximately twice that of sea water, and is thus unsuitable as a source drinking water.

Melted snow and ice have been used as sources of water in many areas (Grainge, 1969; Ryan, 1990; Williams, 1974). However, such sources are seldom satisfactory for large, long-term settlements. One of the primary drawbacks of utilizing melted snow and ice as long-term sources of water is the large amount of fuel required for the melting process. The expense of fuel tends to make this an economically prohibitive source of water for most communities.

Desalinization of deep ground water or seawater could theoretically provide an alternative source of drinking water for the community of Barrow. However, similar to other alternatives, construction, operation, and maintenance of a desalinization facility in the extreme Barrow climate would be expensive.

SUMMARY

The Barrow area is characterized by an arctic climate, which is reflected in the landscape features, vegetation, wildlife, and annual hydrologic cycle of the area. Because of its remote location and the extreme climate, air travel is the only year-round means of transportation that is available for either passengers or freight. This isolation is one reason that many residents continue to adhere to the traditional subsistence lifestyle followed by previous generations. The community is thus heavily dependent on the natural arctic environment, which is particularly susceptible to damage by human activity. Disturbance of the land surface, for example, may result in changes in the thermal regime of the underlying permafrost and lead to long-term changes in the landscape. Contamination of surface water, ground water, or soil can also be especially damaging in the arctic. The short open-water season, limited recharge, low rates of biodegradation, and restricted vertical movement of ground water all reduce the environment's capacity to attenuate contamination.

The most important factors governing hydrological processes in the Barrow area are the short open-water season, presence of near-surface permafrost, and limited variations in land-surface elevation over large distances. Because of the short open-water season, both surface and shallow ground-water flow are limited to the brief thaw season each year. The thaw season typically extends from early or mid-June through late September, but a substantial percentage of the annual runoff—up to 90 percent—occurs within the first 2 weeks. However, the subsurface is still largely frozen during this period, and ground-water flow in the active layer is negligible.

The subsurface flow system thaws gradually over the summer, typically reaching its maximum depth by mid-August. The presence of near-surface permafrost limits the vertical extent of this shallow flow system and restricts vertical ground-water flow, thereby impeding drainage. As a result, surface water and shallow ground water tend to be isolated from the deeper, regional ground-water flow system.

As a result of ~~the limited~~ relief of the tundra surface, few well-developed stream channels exist, and a substantial part of surface-water flow occurs in ice-wedge polygon troughs and other small channels. As a result of the limited relief and limited depth of thaw, distinct flow regimes in the shallow ground-water system often occur over distances ranging from centimeters to tens of meters. The local scale of both the surface-water and ground-water flow systems can result in considerable variations in the magnitude and direction of flow over relatively small distances.

In the Barrow area, transport of contaminants by either surface or ground water would be limited to the brief thaw season each year. Transport by both surface and ground water would likely be complex, however, due to changes in these flow systems that occur over the course of individual thaw seasons, as well as from year to year. The majority of the annual migration of surface contaminants would probably take place during the snowmelt period, when most of the annual runoff occurs. However, even during this brief period, directions of surface transport could vary considerably as a result of soil crack formation, snow drifts, or the plugging of flow channels by ice or snow. Transport by active-layer ground water would occur more gradually over the course of the thaw season, but directions of subsurface transport could also vary considerably as a result of ice-wedge polygon formation, differential thawing as the active layer develops throughout the summer, and the small scales at which distinct flow regimes exist in this shallow flow system. In addition to the usual annual migration of contaminants via surface or ground water, storm surges could result in the transport of contaminants over distances that would typically take several years.

Esatkuat Lagoon, located approximately 2 km to the north and east of the FAA facility, is the present drinking-water supply for the City of Barrow. Lakes, streams, ground water, snow, ice, and seawater are also available in the area, but are not suitable as alternative sources of drinking water because of limited volume, poor quality, high development costs, or because they are thawed for only a short period each year.

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