

Assessment of the Hydrologic Interaction Between Imikpuk Lake and the Adjacent Airstrip Site Near Barrow, Alaska, 1993

By Kathleen A. McCarthy, Gary L. Solin, and Dennis C. Trabant

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

Multiply	By	To obtain
millimeter (mm)	0.03937	inch
centimeter (cm)	0.3937	inch
meter (m)	3.281	foot
kilometer (km)	0.6214	mile
hectare (ha)	2.471	acre
square meter (m ²)	0.0002471	acre
cubic meter (m ³)	264.2	gallon
meter per second (m/s)	3.281	foot per second
cubic meter per second (m ³ /s)	35.31	cubic foot per second
degree Celsius (°C)	$^{\circ}\text{F} = 1.8 \times ^{\circ}\text{C} + 32$	degree Fahrenheit (°F)

Mean sea level:

In this report, mean sea level refers to a tidal datum midway between the arithmetic means of the high-water heights and low-water heights for the Point Barrow tidal station. This is also called mean tide level. Mean sea level is 0.076 m above mean lower low water.

Other abbreviations used in this report:

g/cm², grams per square centimeter

m³/y, cubic meters per year

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Abstract

Imikpuk Lake serves as the drinking water source for the Ukpeagvik Inupiat Corporation-National Arctic Research Laboratory (UIC-NARL), formerly known as the Naval Arctic Research Laboratory, near Barrow, Alaska. During the 1970's and 1980's, accidental releases of more than 1,300 cubic meters of various types of fuel occurred at the airstrip site adjacent to the lake. To aid an assessment of the potential risk to the quality of water in the lake posed by fuel remaining in the subsurface, the hydrologic interaction between the lake and ground water at the airstrip site was examined.

The study area lies within the region of continuous permafrost where hydrologic processes are largely controlled by the short annual thaw season and the presence of near-surface permafrost. Runoff occurs for only a short period each year, typically from early or mid-June to late September, and a shallow ground-water system develops during approximately the same period as a result of shallow thawing of the subsurface.

During the spring and summer of 1993, snowpack and surface-water data were collected throughout the Imikpuk Lake basin, and subsurface-flow-system data were collected at the airstrip site. The total annual inflow to the lake was estimated to be approximately 300,000 cubic meters per year, based on four methods of estimation. The ground-water flow system at the airstrip site is complex, primarily because of variations in local land-surface topography. Subsurface frost-elevation data indicate that a permafrost ridge exists beneath one of the elevated building pads at the site. Similar ridges beneath elevated roadways at the site may act as impediments to ground-water flow, reducing the flux of subsurface water to Imikpuk Lake. However, on the basis of the assumption that such impediments do not reduce flux substantially, the ground-water flux from the airstrip site was estimated to be approximately 173 cubic meters per year—less than 0.1 percent of the estimated annual inflow to Imikpuk Lake.

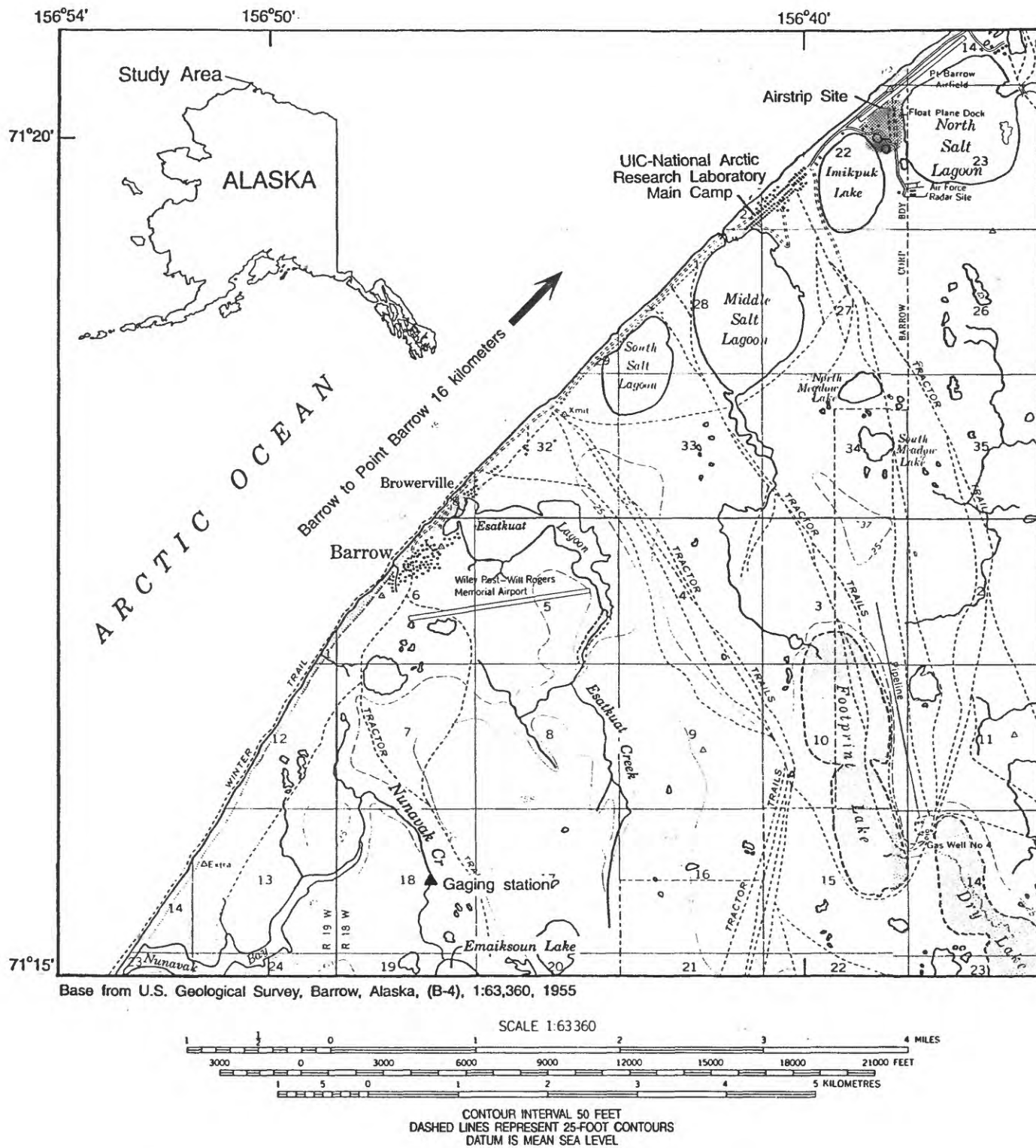


Figure 1. Location of study area near Barrow, Alaska.

INTRODUCTION

Imikpuk Lake, located 6 km northeast of Barrow, Alaska (fig. 1), is the source of potable water for the Ukeagvik Inupiat Corporation-National Arctic Research Laboratory (UIC-NARL), formerly known as the Naval Arctic Research Laboratory. The UIC-NARL airstrip site (fig. 1) is directly northeast of Imikpuk Lake and a large part of the site lies within the lake drainage basin.

Background

During the 1970's, approximately 1,300 m³ of various types of fuel were accidentally released at the airstrip site (Naval Energy and Environmental Support Activity, 1983). Another release, estimated to be as much as 60 m³, occurred in 1986 (Science Applications International Corporation, 1990). Although an estimated 600 m³ of the fuel from these spills have been recovered (Naval Energy and Environmental Support Activity, 1983; DOWL Engineers and Crowley Environmental Services, Inc., 1986) and an additional, unknown quantity was burned off (Naval Energy and Environmental Support Activity, 1983), a considerable volume migrated into the subsurface.

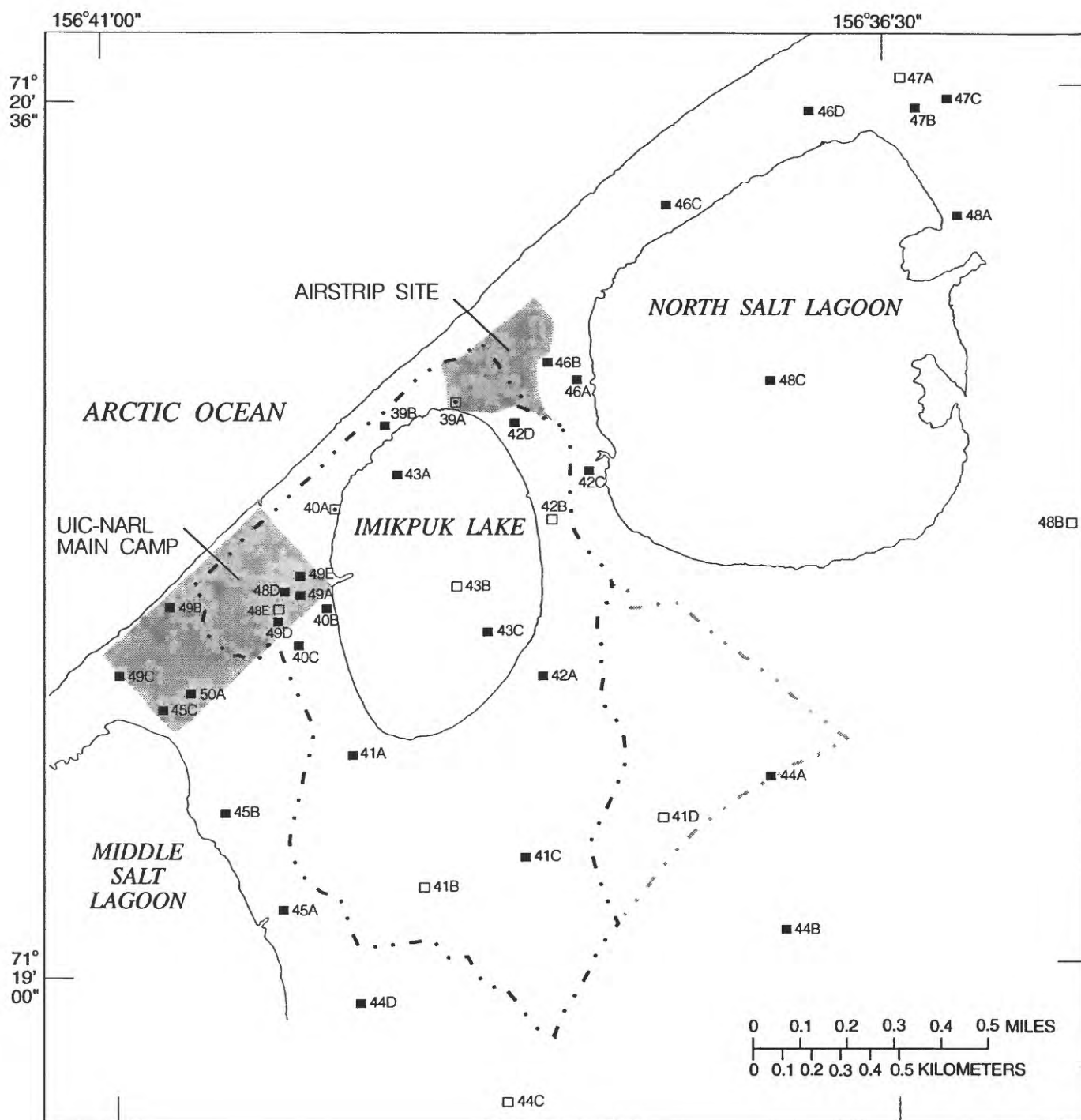
Fuel remaining in the subsurface as a result of previous spills poses a potential threat to the water quality of Imikpuk Lake because of the proximity of the airstrip site to the lake. Preservation of the quality of water in Imikpuk Lake is of particular concern because it is the only practical source of drinking water available to the UIC-NARL facility. Alternative sources of water in the Barrow area are either (1) frozen throughout most of the year, (2) insufficient in volume, (3) of poor quality, or (4) too costly to develop and distribute due to the Arctic climate and tundra terrain (McCarthy, 1994).

Purpose and Scope

To define the potential for degradation of the water quality of Imikpuk Lake resulting from spills at the airstrip site, the hydrologic interaction between Imikpuk Lake and the airstrip site was assessed. This report describes the assessment, which was based on estimates of the total annual flux of water to Imikpuk Lake and the annual flux of ground water from the airstrip site to the lake. This work was conducted in cooperation with the U.S. Navy, Engineering Field Activity Northwest.

Previous Investigations

A number of investigations have been conducted since the early 1980's in an effort to determine the nature and extent of anthropogenic contamination in the vicinity of Imikpuk Lake. The U.S. Navy conducted an investigation at the UIC-NARL facility to identify areas of potential environmental concern and identified the UIC-NARL airstrip area as the location of three fuel spills that occurred during the mid-1970's (Naval Energy and Environmental Support Activity, 1983). As part of an investigation of the 1986 fuel spill, DOWL Engineers and Crowley Environmental Services, Inc. (1986) installed 13 monitoring wells at the airstrip site, measured ground-water elevations and the depth to frost, and collected ground-water, surface-water, and soil samples for total-hydrocarbon analyses. Additional studies include Science Applications International Corporation (1987, 1989, 1990) and Tryck, Nyman, & Hayes and Shannon & Wilson, Inc. (1987). URS Consultants, Inc. and Shannon & Wilson, Inc. (1991, 1994) have conducted the most recent investigations; water-quality data from their investigations and the hydrologic information presented in this report will be used to develop and evaluate potential methods of remediation for the airstrip site.



EXPLANATION	
· · · · ·	IMIKPUKE LAKE SURFACE-WATER DRAINAGE-BASIN BOUNDARY
- - - - -	EXTENDED BASIN BOUNDARY FOR 1993 SNOWMELT PERIOD
■ 49B	Snow probe
□ 39A	Snow pits
□ 41B	Continuous sampling

Figure 2. Snowpack data-collection sites and basin boundaries, Imikpuke Lake area.

Acknowledgment

We wish to thank personnel from Shannon and Wilson, Inc., for their assistance and cooperation during their well-installation program in August 1993.

SITE DESCRIPTION

Imikpuk Lake and the surrounding study area are located along the northern coast of Alaska (fig. 1), approximately 6 km northeast of Barrow and 10 km southwest of Point Barrow, the northernmost extremity of the Arctic Coastal Plain. The area lies within the region of continuous permafrost where hydrologic processes are strongly influenced by freeze-thaw cycles and the presence of permafrost that extends from near the surface to depths of as great as 300 m in the immediate vicinity of Imikpuk Lake (Collins, 1961).

The northern part of the lake basin, from the UIC-NARL main camp in the west to the airstrip site in the northeast (figs. 1 and 2), has been developed. Shallow soils in this area are dominated by poorly sorted gravels and coarse sands, but include areas of finer grained material, particularly near the lake shore. During development, the area landward of the gravel beach ridges along the coast was drained and graded, and facilities closest to the coastline were built directly on beach gravels (Reed, 1958). However, as the airstrip area was further developed, facilities were built on beach-gravel fill placed directly over the tundra surface. There is little vegetation in this area and the total topographic relief is approximately 2 m. The land surface is dominated by buildings, gravel roadways, and areas of bare gravel. In areas of exposed sands and gravels, the maximum depth of thaw measured during this study typically ranged from 1.0 to 1.5 m.

The southern part of the lake basin (fig. 2) consists of relatively undisturbed tundra. This area is characterized by fine-grained, organic-rich soils overlying permafrost. Most of the land surface is covered by low-growing vegetation including sedges, grasses, mosses, and lichens. Both the high moisture content of these soils and the vegetative ground cover act as insulators during the summer. As a result, thaw depths in this part of the basin are typically much less than in the more developed areas. Maximum thaw depths measured during this study at undisturbed tundra sites were less than 0.5 m. Relief throughout most of the southern part of the basin is approximately 4 m, but increases to approximately 7 m in the extreme southern part, near the basin boundary. Most surface features in this part of the basin are the result of processes of the freeze-thaw cycle. Although these features are usually subtle, they can have an important effect on flow paths because of the low overall basin relief. Ice-wedge polygons, which are formed by extensive networks of interconnected frost cracks, are one example of such features. Polygons are common throughout the area, and surface water may flow in the troughs between polygons.

DATA COLLECTION METHODS

Snowpack, surface-water, ground-water, and thaw-depth data were collected in the Imikpuk Lake basin and surrounding areas during the spring and summer of 1993.

Snowpack

During May 1993, a survey was conducted to estimate the distribution and water content of the snowpack in the Imikpuk Lake drainage and surrounding area. The water equivalent of the snowpack was determined from continuous vertical samples at eight sites, and from discrete stratigraphic samples from snow-study pits at two sites (fig. 2). The mean snow depth was determined at each of these sites and at 31 additional sites to facilitate extrapolation from the snowpack water-equivalent measurements (fig. 2). The snow depth was measured by probing with steel tubing, and the depth at each site was defined as the mean of 10 or more probings. The number of probings was increased where the depth variability was large relative to the absolute depth.

Surface Water

In order to identify the boundaries of the Imikpuk Lake drainage, the flow paths followed by surface water were observed during June breakup and again during July and August. Discharge measurements were made throughout the thaw season at an existing stream-gaging station on nearby Nunavak Creek (fig. 1), approximately 9 km southwest of Imikpuk Lake. The hydrologic and basin characteristics of the Nunavak Creek drainage are similar to those of the Imikpuk Lake drainage and similar runoff patterns are therefore likely. (Discharge measurements from Nunavak Creek were used to estimate runoff in the Imikpuk basin and are presented in a later section of this report.)

Subsurface Flow System

Because of the considerable depth to which permafrost extends in the study area, only the shallow, suprapermafrost ground-water system is relevant to this study. Data collection therefore focused on the shallow part of the subsurface, commonly referred to as the "active layer," which thaws each summer and refreezes each winter.

Data were collected from 36 wells at the airstrip site (fig. 3). Wells labelled "TB" and "MW" were installed in 1986 by DOWL Engineers and Crowley Environmental Services, Inc. (1986) and Tryck, Nyman, & Hayes and Shannon & Wilson, Inc. (1987), respectively. Wells labelled "AFW" were installed in 1989 by Science Applications International Corporation (1989), and those labelled "ASW" were installed in 1990 by URS Consultants, Inc., and Shannon & Wilson, Inc. (1991). Well US17 was installed in July 1993 as part of the current study, and wells labelled "B" were installed in August 1993 as part of a concurrent investigation by URS Consultants Inc., and Shannon & Wilson, Inc. (1994).

The depth to static ground-water level was measured in 31 wells during July. After each measurement, the well was pumped using a manual peristaltic pump, and the response of the water level was monitored to assure that the well was hydraulically connected to the surrounding ground-water system. The static water level in each well was then remeasured at least one additional time. An open-hole well, which extended to the top of the subsurface frost, was constructed

at site US17 (fig. 3) using an 8-cm manual auger. The water level in the hole was monitored for one week, and the hole was then refilled. The vertical extent of the ground-water zone at each well was determined by measuring the depth of thaw either by augering to the top of the frost with an 8-cm manual auger, or by driving a metal probe into the ground to the depth of refusal. The depth of refusal was assumed to be the surface of the frost. At several sites, thaw depth was measured using both methods and agreement between the methods was good (± 5 cm).

To assess changes in the subsurface flow system as thawing progressed, depths to ground water and frost were remeasured during late August and early September. In addition to the 31 sites measured during July, data were collected from the five newly installed “B” wells (fig. 3).

Subsurface data were also collected in the vicinity of the UIC-NARL main camp northwest of Imikpuk Lake (fig. 1), and in two areas of undisturbed tundra in the vicinity of the lake. These data were used qualitatively to enhance understanding of the subsurface flow system at the airstrip site.

Surveying

In July, all data-collection sites were surveyed, including the water surfaces of Imikpuk Lake, North Salt Lagoon, and several small ponds. The elevation of land-surface datum at each well was determined using trigonometric and differential field leveling. The benchmark for the leveling was a monument (Lounsbury and Associates, written commun., 1981) referenced to mean sea level for the Point Barrow tidal station. The locations of most wells were determined by trigonometric surveying and referenced to horizontal control stations established by the National Ocean Survey. All sites were surveyed again during early September to determine whether well casings had shifted vertically as a result of the thawing process. No significant changes in the elevations of well casings were noted between July and September. The locations and land-surface elevations of each well are shown in figure 3.

ANNUAL HYDROLOGIC CYCLE OF THE IMIKPUK LAKE AREA

The hydrology of the Arctic Coastal Plain 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 that will be briefly described in the following sections.

Table 1. Mean monthly temperature data for Barrow, Alaska, for the period 1949-87

[Data from Leslie, 1989; values in degrees Celsius]

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
-25.4	-28.4	-26.3	-19.0	-7.3	0.9	3.9	3.3	-0.8	-9.7	-18.2	-24.3

Winter

The winter season in the study area typically begins in late September and continues through early to mid-June. Subfreezing temperatures prevail throughout this period (table 1) and therefore streamflow does not occur, freshwater lakes less than approximately 2 m deep freeze to the bottom, and the subsurface is frozen from land surface to depths of as great as 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 typically thin (less than 0.5 m except in wind drifts), winter snowfall often accounts for more than half of the total annual precipitation recorded for the Barrow area (table 2). Sublimation and evaporation during the winter can be considerable, however, largely because of the strong temperature gradients that develop within the snowpack and shallow soil. These gradients produce a substantial upward flux of water vapor and, as a result of air convection within the snowpack, this flux may be as much as an order of magnitude greater than that due solely to diffusion. This upward movement of moisture desiccates the surface vegetative mat and a shallow layer of the underlying soil, resulting in the formation of large, low-density, depth-hoar crystals at the base of the snow cover.

Table 2. Mean monthly precipitation data for Barrow, Alaska, adjusted for gage efficiency

Month	Mean total precipitation (millimeters) ^a	Mean precipitation adjusted for gage efficiency		
		Rain (millimeters) ^b	Snow (water equivalent, millimeters) ^c	Total (millimeters)
January	5.1	0.0	15.2	15.2
February	4.6	0.0	13.7	13.7
March	3.8	0.0	11.4	11.4
April	5.1	0.0	15.2	15.2
May	4.1	0.0	12.2	12.2
June	9.1	5.0	13.7	18.7
July	22.1	24.3	0.0	24.3
August	24.6	27.1	0.0	27.1
September	16.3	8.9	24.4	33.3
October	13.0	0.0	38.9	38.9
November	6.9	0.0	20.6	20.6
December	4.3	0.0	13.0	13.0
Annual total	119	65	178	244

^aMean total precipitation for the period 1949-87 (Leslie, 1989).

^bMean rainfall, adjusted by a factor of 1.1 for gage efficiency. Precipitation occurring from mid-June through mid-September was assumed to be rain.

^cMean water equivalent of snow, adjusted by a factor of 3 for gage efficiency. Precipitation occurring from mid-September through mid-June was assumed to be snow.

Snowmelt Period

The snowmelt period marks the transition from winter to summer in the Arctic. In the Imikpuk basin, the brief thaw season 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 total annual runoff (Church, 1988). The discharge hydrograph for Nunavak Creek for a typical water year, 1992, illustrates this phenomenon (fig. 4A) (U.S. Geological Survey, 1993).

Although discharges are high during this period, a substantial part of the snowpack is also lost to the atmosphere through evaporation and sublimation. These processes are complex during the snowmelt period. As radiant energy penetrates the shallow snow cover and is absorbed by underlying materials, the continuous snow cover is rapidly breached. Once the snow cover becomes discontinuous, large variations in surface albedo, and hence temperature, result in complex spatial patterns of evaporation and condensation. For example, Ohmura (1982) found condensation on remaining snow patches occurring simultaneously with intense evaporation from nearby exposed ground. Evaporation and sublimation processes are further complicated and enhanced by air convection within the snowpack. Daytime loss rates from the snow surface averaging 0.17 g/cm^2 were measured near Barrow (Benson, 1969). These rates are comparable to those cited by Sabo (1956) and are only slightly lower than the average daily pan evaporation rate of 0.2 g/cm^2 measured near Barrow by Brown and others (1968).

Infiltration during the snowmelt period is slight. 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, and as a result, infiltration is initially restricted. 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.

In contrast to the snowpack, only part of the lake ice melts during this period. During the early part of the snowmelt period, the entire lake surface remains covered by ice, and snowmelt runoff into the lake occurs on top of the lake ice. Ice is generally thinnest at the shallow edges of lakes, and as thawing progresses, the edges disintegrate more quickly than the interior of the ice cover. When the entire circumference of the lake ice has thawed, the remaining interior ice—no longer landfast—floats free and rises to the surface. This initially massive ice block typically requires several more weeks to melt completely. During this period, continual winds shift the ice, resulting in substantial lake turbulence and shore erosion.

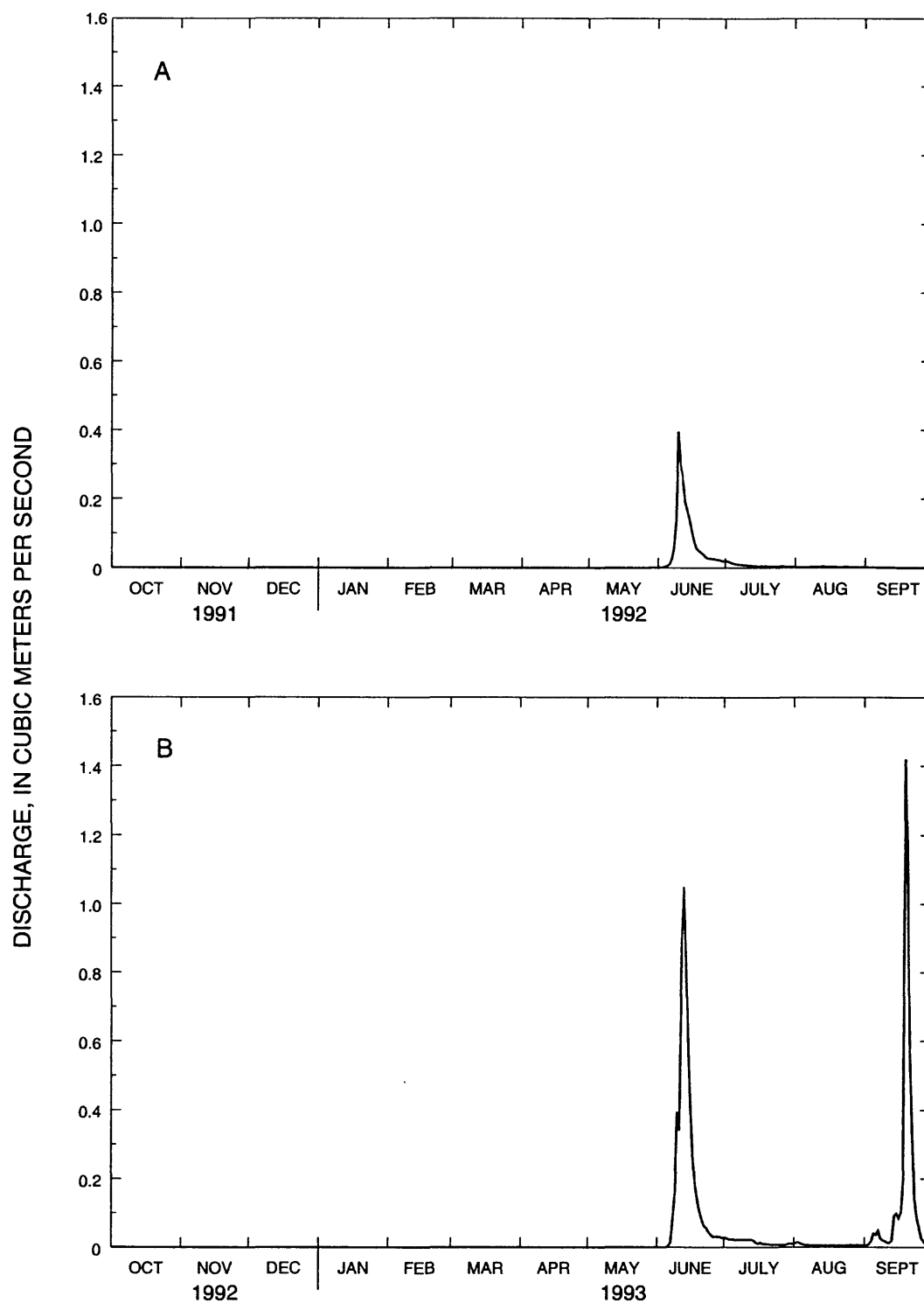


Figure 4. Discharge of Nunavak Creek, water years 1992 (A) and 1993 (B).

Summer

The short summer season in the Imikpuk Lake basin 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 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 (Mather and Thornthwaite, 1958; Brown and others, 1968; Guymon, 1976; Dingman and others, 1980) indicate that total thaw-season evapotranspiration is approximately equal to total precipitation for the same period (table 2). Consequently, summer precipitation does not usually contribute substantially to annual runoff. This is illustrated for the Nunavak basin in figure 4A, which shows very limited runoff following the snowmelt peak during June. Occasionally, however, this pattern is altered (fig. 4B). 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 most of the summer. While investigating the development of the active layer in a small basin near Imikpuk Lake, Brown and others (1968) found that thaw penetration usually reached 75 percent of its maximum by early July and near-maximum penetration was typically reached by mid-August. Thaw depths measured at the airstrip site during the current study are generally consistent with these findings. 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). Water flux in such areas is limited both by the shallow depth of thaw and the considerable capacity of the fine-grained tundra soils to hold capillary water.

Freeze-Up Period

The final phase of the annual hydrologic cycle begins as temperatures drop below freezing, typically during late August or September, and the transition from summer to winter begins. As surface water freezes and precipitation shifts from rain to 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, the 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 moisture in the near-surface layer of soil 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.

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HYDROLOGIC INTERACTION BETWEEN IMIKPUK LAKE AND THE AIRSTRIP SITE

In the following sections, the total annual inflow to Imikpuk Lake and the flux of ground water from the airstrip site to the lake are estimated.

Total Inflow to Imikpuk Lake

The first step in estimating total inflow to Imikpuk Lake was to determine the area that contributes water to the lake by defining the drainage basin boundaries (fig. 2). The extent of the lake basin, which covers approximately 210 ha, was determined from observations of local topography and surface-water flow paths. Hydrologic basin boundaries on the Arctic Coastal Plain, however, are seldom straightforward. Because of the low relief, even minor drainage features, such as polygon troughs, can intersect basin divides and result in complex drainage patterns. The blocking of streams, polygon troughs, or culverts by ice or snow can also result in temporary changes in surface drainage patterns. For example, during the 1993 snowmelt period, an area to the southeast of Imikpuk Lake, which normally drains into North Salt Lagoon, was observed to be draining to the lake. The resulting extended drainage basin, which covers a total area of approximately 250 ha, is shown in figure 2. This altered drainage pattern was attributed to a temporary blockage of a culvert by ice and persisted until the blockage melted near the end of June. Recalling that up to 90 percent of annual runoff can occur during the snowmelt period, it is clear that such changes in drainage patterns during the month of June can affect basin water budgets considerably.

Several assumptions were used in the process of estimating annual inflow to the lake:

- (1) The only source of inflow to the lake basin is precipitation;
- (2) Except for losses due to sublimation, evaporation, and transpiration, all inflow to the basin flows into the lake;
- (3) Precipitation from June 16 through September 15 occurs as rain; precipitation from September 16 through June 15 occurs as snow;
- (4) The extended drainage basin (fig. 2), with an area of 250 ha, contributes runoff from the beginning of the snowmelt period through the month of June; the more limited basin, with an area of 210 ha, contributes runoff during the remainder of the thaw season;
- (6) Mean values of recorded precipitation reflect gage efficiencies of 90 percent for rain and 33 percent for snow.

The first assumption implies that inflow to the basin resulting from interbasin surface- and ground-water flow is negligible. Although some interbasin surface-water flow undoubtedly occurs through polygon troughs and frost cracks, observations in the field indicate that it is reasonable to assume that such flow is small relative to total basin inflow. Because of the presence of extensive, areally continuous permafrost, the subpermafrost, regional ground-water flow system can be neglected and interbasin ground-water flow is limited to the active-layer ground-water system. Ground-water flux in the active layer is restricted by the shallow depth of thaw and the tendency of the fine-grained tundra soils to hold capillary water, and it is therefore reasonable to assume that this flux is small across basin boundaries. Active-layer ground water within the basin results from infiltration of local precipitation and is accounted for as part of the basin inflow. The first assumption is therefore justified.

The second assumption implies that the channel from Imikpuk Lake to North Salt Lagoon is the only basin outflow and that other interbasin surface- and ground-water outflow is negligible. Observations in the field, coupled with the preceding discussion of interbasin flow, support this assumption.

Assumption (3) is a simplifying generalization of the annual hydrologic cycle. Although snow in the study area can fall during any month of the year and the onset and duration of the thaw season varies from year to year, it is believed that the error introduced by this assumption is small relative to the overall hydrologic budget of the lake.

Assumption (4) is an estimate based on field observations and implies that culvert blockages such as the one observed during June 1993 are a common annual occurrence. Because snow accumulates throughout the winter and most of the runoff from snowmelt takes place during June, this assumption also implies that snowfall that accumulates throughout the extended basin from September 15 to June 30 contributes to Imikpuk Lake inflow.

The final assumption addresses the efficiency of standard precipitation gages. Gage undercatch of snow in windy environments, such as Barrow, was first demonstrated by Black (1954), who estimated the gage catch to be no more than 25 to 50 percent of the total precipitation. Dingman and others (1980) suggest that actual snowfall is approximately three times that recorded by standard gages. Benson (1982) conducted a four-year comparison of snow catch by standard and wind-shielded (Wyoming) gages at Barrow and Barter Island, also on the northern coast of Alaska, and estimated that standard gages catch approximately one-third as much snowfall as wind-shielded gages. Accurate measurement of summer precipitation in the Arctic is also difficult, primarily because of the large proportion that occurs as fog and trace amounts of rainfall. Brown and others (1968) suggest that thaw-season precipitation recorded by gages in the Barrow area averages approximately 90 percent of actual precipitation.

Total inflow to the lake was estimated by four different methods. Because long-term conditions are of interest, precipitation data used are monthly means (corrected for gage efficiency) available from the National Weather Service station at Barrow for the period 1949 through 1987. Each method and any additional associated assumptions are described in the following sections and the results of the methods are summarized in table 3.

Table 3. Estimated annual inflow to Imikpuk Lake

	Method 1	Method 2	Method 3	Method 4	Average of methods 1 through 4
Total annual inflow (cubic meters per year)	340,000	280,000	290,000	260,000	300,000

Estimation of lake inflow, method 1.—The first method used to estimate inflow to Imikpuk Lake is a simple mass balance:

$$INFLOW = [(SNOWPACK) - (LOSSES)] + [(RAINFALL) - (LOSSES)] \quad (1)$$

In this expression, the snowpack term includes the water equivalent of the snowpack estimated from measurements during mid-May 1993, plus estimated additions from snowfall that occurred from mid-May through mid-June. On the basis of the snowpack data (table 4), the extended-basin snowpack water equivalent in mid-May was approximately 500,000 m³. Using National Weather Service data, corrected for gage efficiency (table 2), additions to the snowpack from mid-May through mid-June were estimated to be 49,000 m³. Loss from the snowpack due to sublimation and evaporation for the 50 days from mid-May (when snowpack measurements were made) through the end of June (approximately the end of snowmelt) was assumed to occur at an average daily rate of 0.17 g/cm² (Benson, 1969). This rate results in a loss of 211,000 m³ of water for the extended basin. Thaw-season precipitation (rainfall) was taken from National Weather Service data, corrected for gage efficiency (table 2). Using these data, 0.0050 m of rainfall during June, occurring over the extended basin, contributed 12,400 m³ of water; 0.0603 m of rainfall during July, August, and September, occurring over the more limited basin, contributed 126,500 m³ of water. Finally, using estimates from the Barrow area by Brown and others (1968), rainfall losses from evapotranspiration during the thaw season were assumed to be 95 percent of total thaw-season precipitation, which is 132,000 m³ of water. On the basis of these data, the total annual inflow to Imikpuk Lake is estimated to be approximately 340,000 m³:

$$[(500,000+49,000) - (211,000)]m^3 + [(12,400+126,500) - 0.95 \times (12,400+126,500)]m^3 \quad (2)$$

Estimation of lake inflow, method 2.—The second method used to estimate inflow to Imikpuk Lake is based on long-term streamflow data from nearby Nunavak Creek. This method is predicated on the assumption that the average unit runoff (runoff per unit area) in the Nunavak Creek basin is equal to the average unit runoff in the Imikpuk Lake basin. This is a reasonable assumption because of the proximity and similarity of the two basins. To estimate annual inflow to Imikpuk Lake by this method, monthly average total discharge data for Nunavak Creek were multiplied by the appropriate basin-area ratio (Imikpuk basin area divided by Nunavak basin area) and summed (table 5). The average annual inflow to Imikpuk Lake estimated by this method is approximately 280,000 m³.

Estimation of lake inflow, method 3.—The third method used to estimate annual inflow to Imikpuk Lake is based on the broad generalization that approximately 50 percent of annual precipitation in the Barrow area is lost to sublimation, evaporation, and transpiration, and the remaining 50 percent becomes runoff (Brown and others, 1968). Applying this generalization to the adjusted precipitation data (table 2), average annual lake inflow was estimated to be approximately 290,000 m³:

$$[(0.178 \text{ m} \times 250 \text{ ha}) + (0.065 \text{ m} \times 210 \text{ ha})] \times 0.5 \quad (3)$$

Table 4. Snow data for Imikpuk Basin and vicinity, May 1993

Site number (fig. 2)	Land-surface elevation (meters above mean sea level)	Snow depth (millimeters)	Snow density (kilograms per liter)	Water equivalent of snow (millimeters)
39A	1.8	210	0.31	70
39B	2.3	160	0.35	60
40A	1.1	430	0.36	150
40B	1.5	420	0.35	150
40C	2.3	280	0.35	100
41A	1.9	320	0.35	110
41B	2.8	360	0.41	150
41C	3.0	450	0.35	160
41D	3.5	450	0.31	140
42A	2.9	320	0.35	110
42B	2.0	530	0.33	170
42C	0.7	190	0.35	70
42D	0.6	210	0.35	70
43A	0.6	200	0.35	70
43B	0.6	270	0.38	100
43C	0.6	200	0.35	70
44A	5.1	170	0.35	60
44B	1.6	390	0.35	140
44C	7.2	480	0.33	160
44D	3.0	250	0.35	90
45A	1.7	330	0.35	120
45B	2.6	290	0.35	100
45C	1.5	290	0.35	100
46A	0.9	1390	0.35	490
46B	1.6	200	0.35	70
46C	1.6	390	0.35	140
46D	1.6	330	0.35	120
47A	1.2	320	0.31	100
47B	1.0	160	0.35	60
47C	0.1	280	0.35	100
48A	0.6	430	0.35	150
48B	2.3	370	0.36	130
48C	0.0	330	0.35	120
48D	2.4	0	0.35	0
48E	3.4	1300	0.37	480
49A	1.9	240	0.35	80
49B	3.4	290	0.35	100
49C	2.5	250	0.35	90
49D	1.6	2900	0.35	1020
49E	2.2	3480	0.35	1220
50A	1.5	3100	0.35	1090
Total basin average	—	—	—	200^a

^aAssumes that drift traps influence 7 percent of the basin.

Table 5. Estimated monthly inflow to Imikpuk Lake using Nunavak Creek streamflow data

[NA, not applicable]

Month	Nunavak Creek discharge ^a (cubic meters)	Basin-area ratio ^b	Estimated inflow to Imikpuk Lake (cubic meters)
January	0	NA	0
February	0	NA	0
March	0	NA	0
April	0	NA	0
May	13,652	0.344	4,700
June	576,169	0.344	200,000
July	140,311	0.290	41,000
August	54,608	0.290	16,000
September	80,737	0.290	23,000
October	2,124	0.290	620
November	0	NA	0
December	0	NA	0
Annual total	—	—	280,000

^aMean monthly discharge for the period 1972-93 (U.S. Geological Survey, 1994).

^bNunavak Creek basin area is 723 ha (U.S. Geological Survey, 1994); the effective Imikpuk basin area contributing to streamflow is assumed to be 250 ha for the months of May and June, and 210 ha for the months of July, August, September, and October.

Estimation of lake inflow, method 4.—The fourth method of estimating inflow to Imikpuk Lake is based on another broad generalization. Dingman and others (1980) report the average annual runoff on the Arctic Coastal Plain to be 0.11 m. On the basis of precipitation records (table 2) and flow in Nunavak Creek (table 5), it was assumed that approximately 70 percent of annual runoff occurs during May and June, when the extended basin is effective. The average annual runoff using this method was estimated to be approximately 260,000 m³:

$$(0.7 \times 0.11 \text{ m} \times 250 \text{ ha}) + (0.3 \times 0.11 \text{ m} \times 210 \text{ ha}) \quad (4)$$

Ground-Water Flux from the Airstrip Site to Imikpuk Lake

The hydrologic flow system at the airstrip site is complicated by the presence of roadways and building pads that are elevated relative to the surrounding land surface. For example, wells TB1, TB3, MW2, and MW3 are located in a local topographic depression, referred to as the “north depression” (fig. 3). Wells MW9, MW10, TB2, and TB5 are situated in another local depression, referred to as the “south depression,” bordered by elevated roadways and the pad beneath Building 136 (fig. 3). Surface water is routed through culverts from the north depression into the south depression and then toward North Salt Lagoon. As a result, the position of the surface-water drainage divide within the airstrip site (figs. 2 and 3) is fairly straightforward to define. In contrast, the location of the ground-water drainage divide within the airstrip site is ambiguous. Permafrost ridges within elevated roadways and building pads can act as impediments—or even complete barriers—to subsurface flow. An example of this phenomenon is illustrated in figure 5, which shows the top of the frost near the north corner of Building 136, as measured during August 1993. These data support the assumption that a depression in the surface of the permafrost, commonly referred to as a thaw bulb, is present under the building and indicate that the thaw bulb is isolated from surrounding ground water by a subsurface frost ridge. Water-level elevations measured during July and August 1993 in well MW11, near the north corner of Building 136, support this hypothesis (figs. 6 and 7). In July, the 1.97-m water-level elevation was substantially higher than the elevations measured in nearby wells, which were 1.3 m or less. This suggests that well MW11 may not be in hydraulic communication with these other wells. The location of well MW11 relative to the frost ridge (fig. 5) further suggests that it may be located within the building’s thaw bulb and therefore isolated from nearby wells. In August, no water was present in well MW11, indicating that the

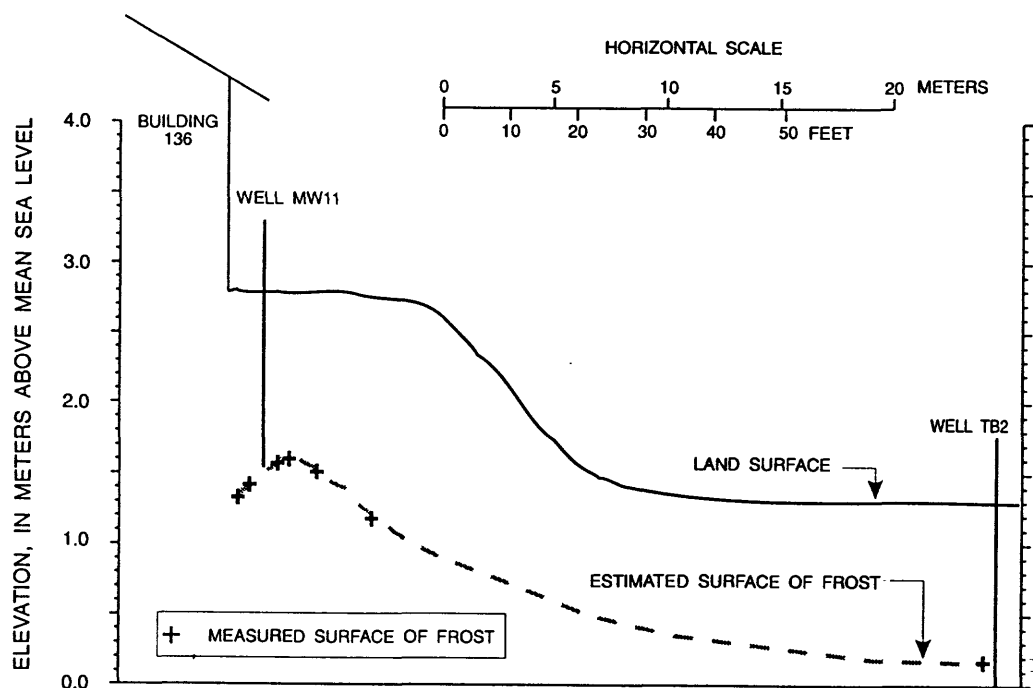


Figure 5. Sketch of the subsurface frost near Building 136 and wells MW11 and TB2, at the airstrip site, Imikpuk Lake. August 1993.

water table was below the bottom of the well and therefore, probably below the level of the frost ridge. If similar permafrost ridges are present beneath elevated roadways at the site, ground water underlying the two local depressions mentioned earlier may be at least partially isolated from Imikpuk Lake.

The presence of the runway and apron (fig. 3) may also influence the depth of thaw and thus affect the ground-water drainage divide. The runway is constructed of a single layer of pierced steel planking, and the apron is constructed of several layers of the same material. If heat conducted by this metal during the thaw season promotes thawing of the underlying frost, it is possible that a depression in the frost surface forms. In addition, plowing of the runway and apron extends the period of increased albedo for these surfaces, which may also promote deeper thawing of the subsurface. If an area of deeper thaw occurs, ground water may be retained in the depression, thereby reducing the ground-water flux from the area. However, part of the runway and apron are elevated relative to the surrounding land surface, and this higher elevation may, at least partially, offset the effects of enhanced subsurface thaw.

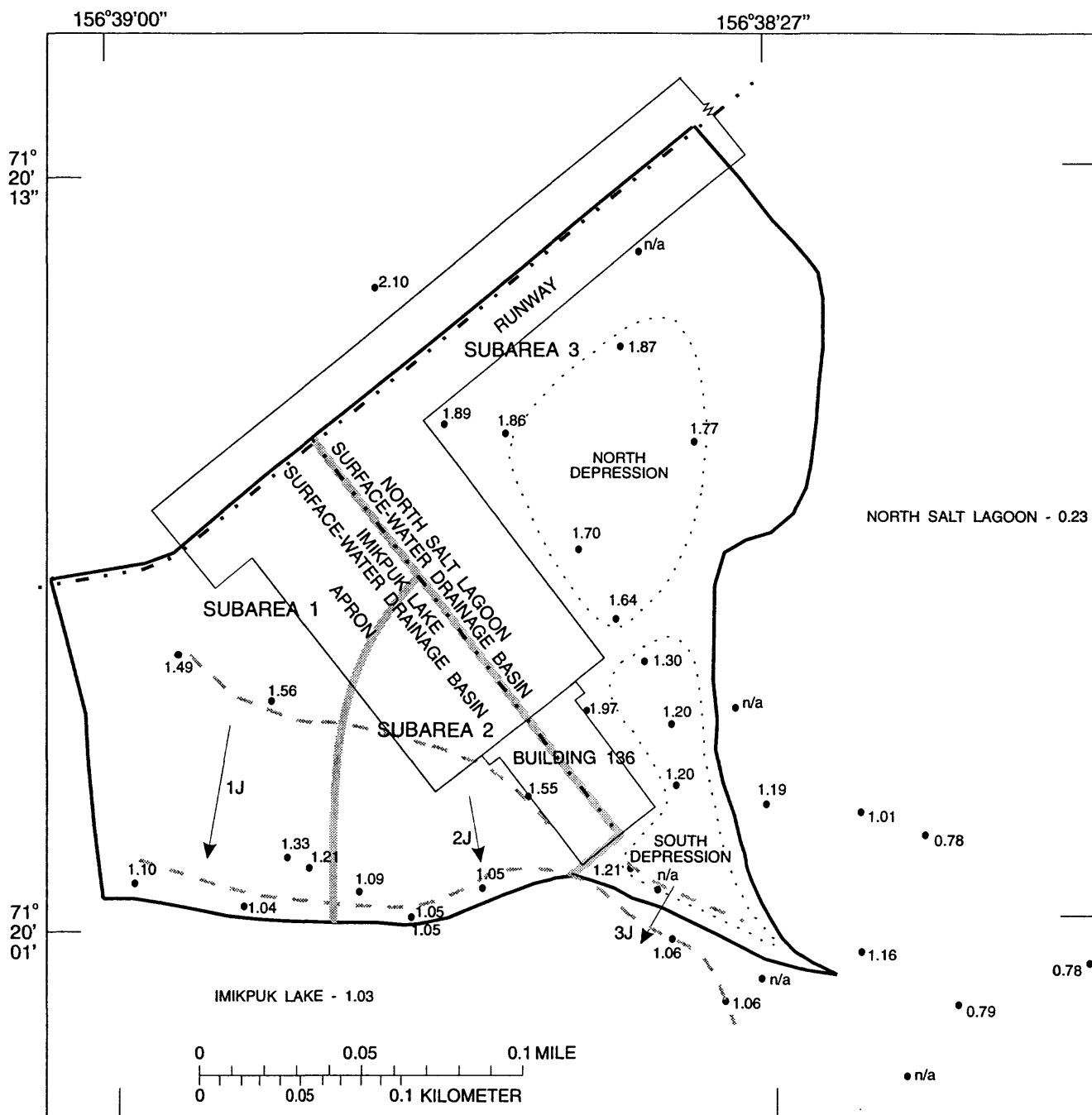
Ground-water flux calculations.—Ground-water flux from the airstrip site to Imikpuk Lake was estimated using the Darcy equation:

$$Q = -\left(\frac{\partial h}{\partial l}\right) \cdot z \cdot w \cdot K \quad (5)$$

where

- Q is the ground-water flux ($\text{length}^3 \cdot \text{time}^{-1}$);
- $\partial h / \partial l$ is the hydraulic gradient (dimensionless);
- z is the distance from the top of the subsurface frost to the water table (length);
- w is the width, perpendicular to the direction of flow, of the cross-sectional area through which the flux is occurring (length); and
- K is the hydraulic conductivity of the active layer ($\text{length} \cdot \text{time}^{-1}$).

To estimate hydraulic gradients, the site was divided into three subareas (figs. 6-9). Two approximate flow lines for each subarea, one constructed from July data (lines 1J, 2J, and 3J, fig. 6) and one constructed from August data (lines 1A, 2A, and 3A, fig. 7), were used to estimate representative hydraulic gradients. Because of the complexities in the subsurface flow system described previously, extrapolation of the data to produce a contoured water-table map of the site was considered inappropriate. Therefore, the equipotential lines (lines of equal ground-water head) shown in figures 6 and 7 are limited to short segments necessary to calculate hydraulic gradients for each subarea. An average value for the thickness of the ground-water zone in each subarea was estimated from data collected during July (fig. 8) and August (fig. 9). The width of the cross-sectional flow area from each subarea was taken from figure 6. Finally, soil in the active layer in the southern part of the site, nearest the lake, is composed of a mixture of silt, sand, and gravel. The hydraulic conductivity of this material was estimated from information provided by Bear (1979), Freeze and Cherry (1979), and U.S. Department of the Interior (1985). The values used for each variable in equation 5 are summarized in table 6.



EXPLANATION			
	AIRSTRIp SITE BOUNDARY		EQUIPOTENTIAL LINE
	SURFACE-WATER DRAINAGE-BASIN BOUNDARY		2.10
	SUBAREA BOUNDARY		WATER-TABLE ELEVATION, IN METERS ABOVE MEAN SEA LEVEL ("n/a" INDICATES NO DATA AVAILABLE)
	APPROXIMATE FLOWLINE AND NUMBER	IMIKPUK LAKE - 1.03	SURFACE-WATER ELEVATION, IN METERS

Figure 6. Water-table and surface-water elevations measured in July 1993, and subareas and flowlines used to estimate ground-water flux, near Imikpuk Lake.

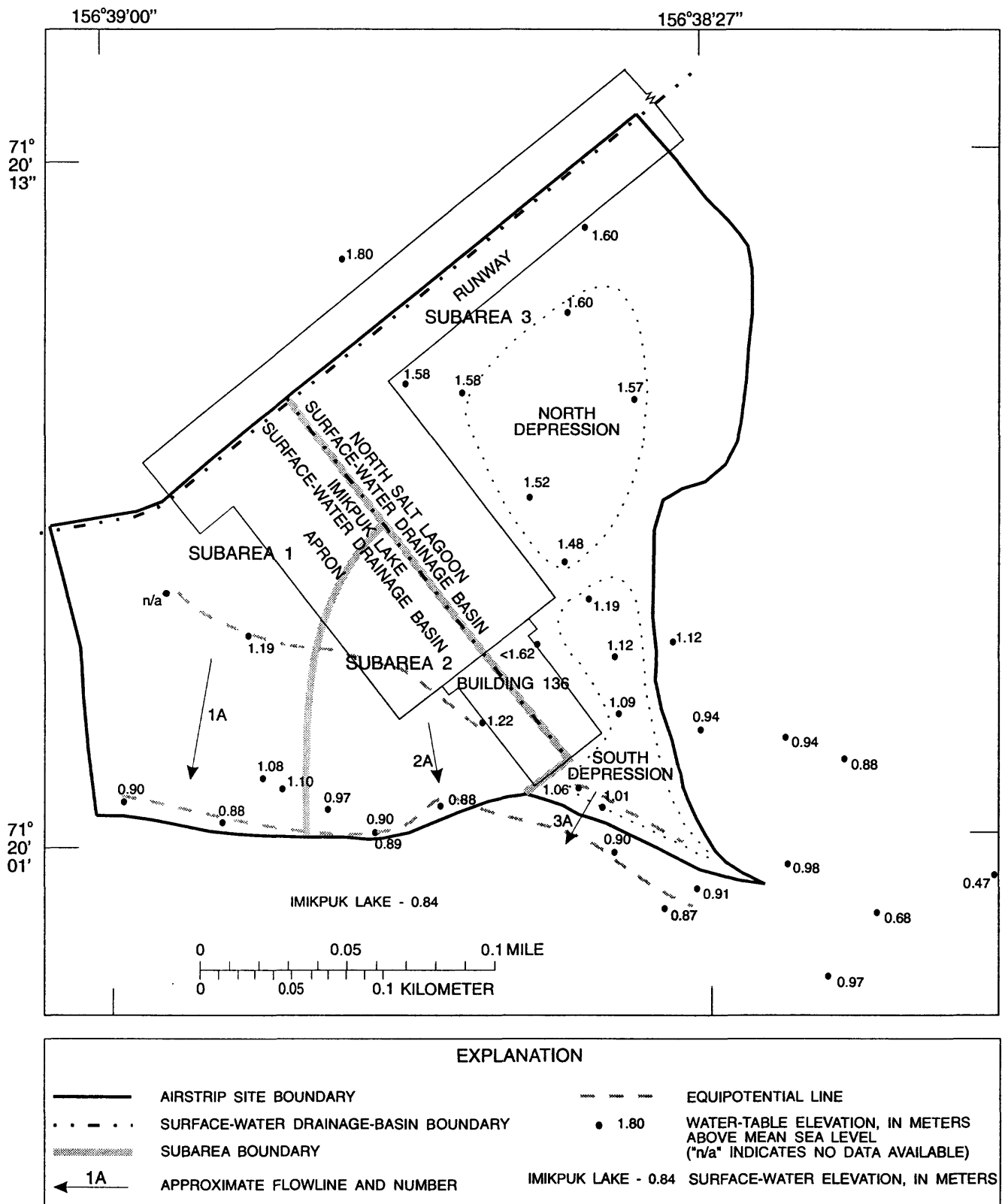


Figure 7. Water-table and surface-water elevations measured in August 1993, and subareas and flowlines used to estimate ground-water flux, near Imikpuke Lake.

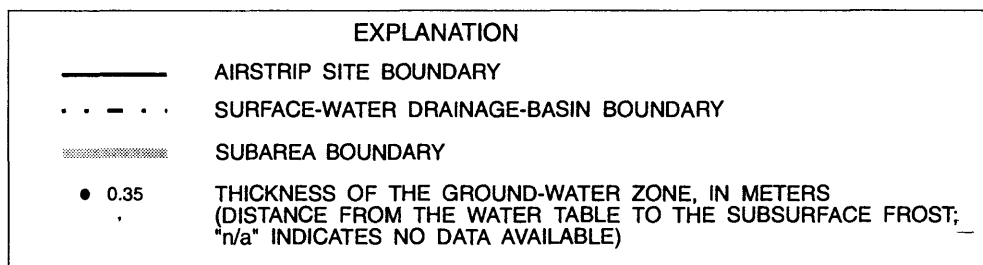
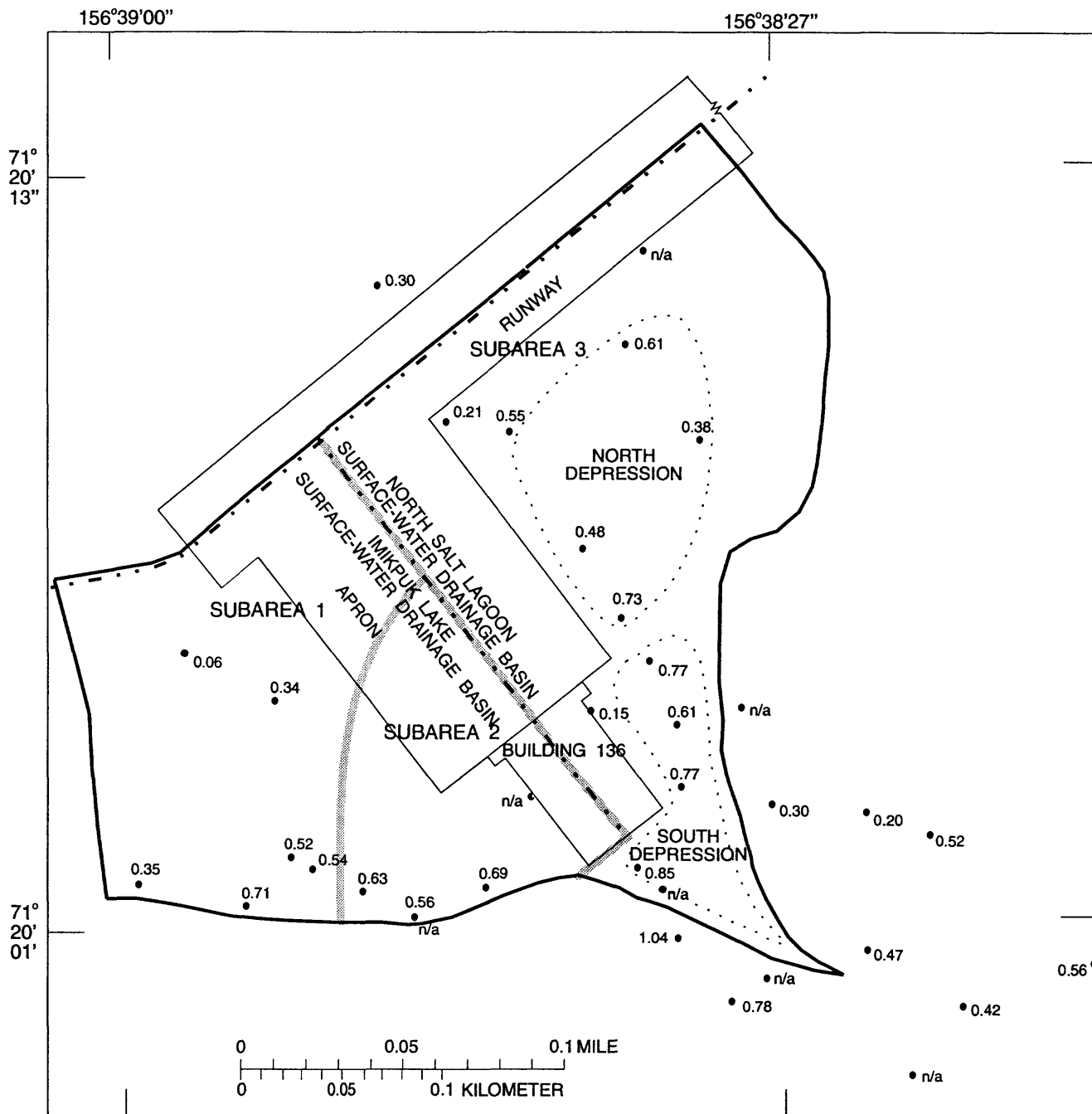
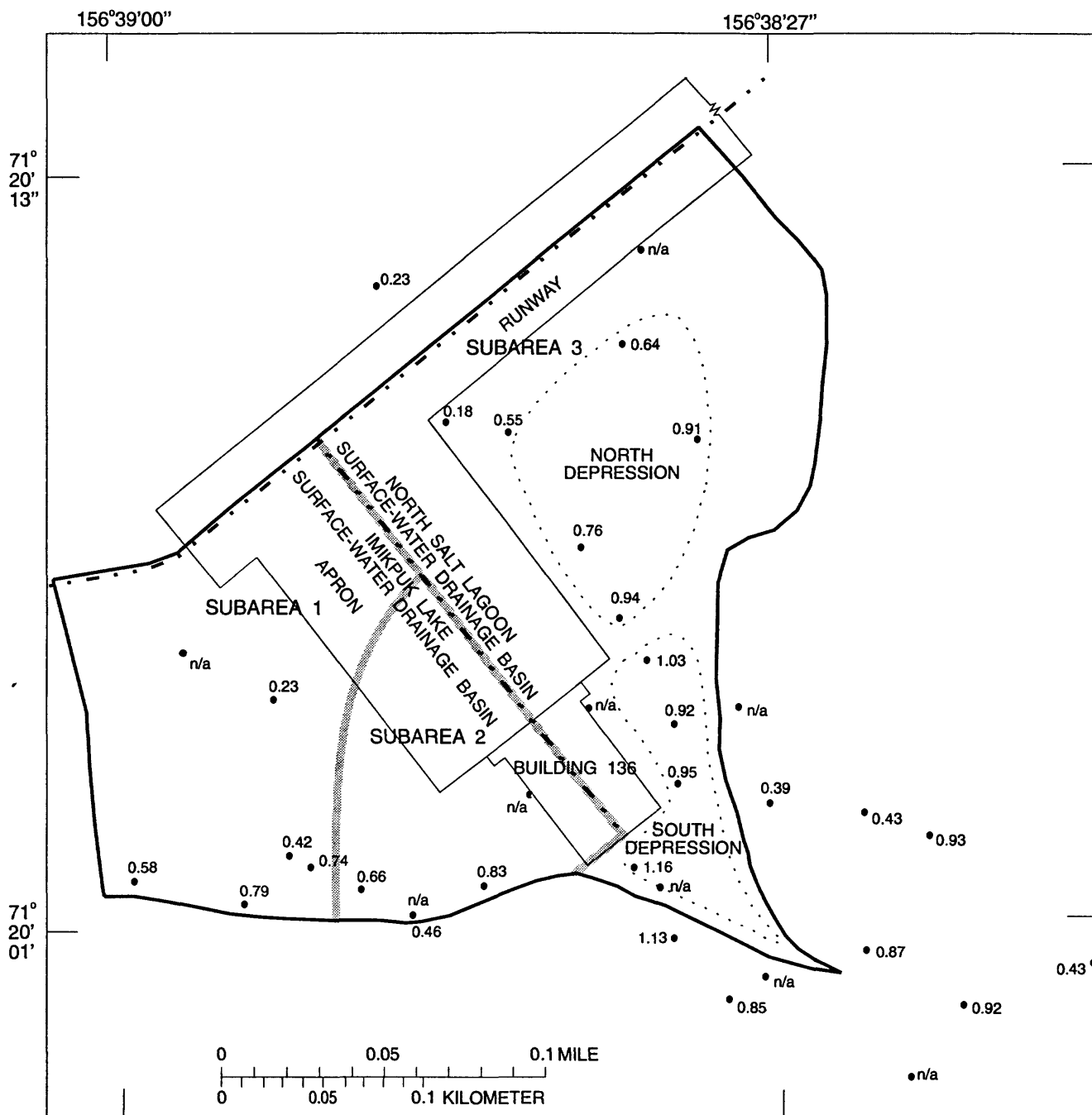


Figure 8. Thickness of the ground-water zone at the airstrip site, measured in July 1993, near Imikpuk Lake.



EXPLANATION	
	AIRSTRIP SITE BOUNDARY
	SURFACE-WATER DRAINAGE-BASIN BOUNDARY
	SUBAREA BOUNDARY
	THICKNESS OF THE GROUND-WATER ZONE, IN METERS (DISTANCE FROM THE WATER TABLE TO THE SUBSURFACE FROST; "n/a" INDICATES NO DATA AVAILABLE)

Figure 9. Thickness of the ground-water zone at the airstrip site, measured in August 1993, near Imikpu Lake.

In view of the complex nature of the subsurface flow system at the airstrip site, a number of assumptions were necessary to simplify the calculations summarized in table 6:

- (1) The entire airstrip site contributes ground-water flow to Imikpuk Lake;
- (2) Ground-water flux from the site occurs from July through mid-October (107 days) and the average estimated instantaneous flux (table 6) applies during this entire period;
- (3) The hydraulic gradient in each subarea can be adequately represented by one value;
- (4) The hydraulic conductivity in each subarea can be adequately represented by one value.

Table 6. Estimated ground-water flux from the airstrip site to Imikpuk Lake

Flow line	Hydraulic gradient ($\partial h/\partial l$) (dimensionless)	Active layer vertical thickness (z, meters)	Width of flow area (w, meters)	Hydraulic conductivity (K, meters per second)	Instantaneous ground-water flux (Q, cubic meters per second) ^a	Average annual ground-water flux ^b (Q, cubic meters per year)
Subarea 1						
1J	0.004	0.5	120	10^{-5}	$2.6 \cdot 10^{-6}$	23
1A	0.003	0.7	120	10^{-5}	$2.5 \cdot 10^{-6}$	
Subarea 2						
2J	0.008	0.6	120	10^{-5}	$5.6 \cdot 10^{-6}$	44
2A	0.005	0.7	120	10^{-5}	$3.8 \cdot 10^{-6}$	
Subarea 3						
3J	0.008	1.0	140	10^{-5}	$1.1 \cdot 10^{-5}$	105
3A	0.008	1.1	140	10^{-5}	$1.2 \cdot 10^{-5}$	
Total						173 ^c

^aThe product of row calculations may differ from the value given due to rounding.

^bBased on the instantaneous flux occurring over a 107-day period from July 1 through October 15.

^cColumn values do not sum to column total due to rounding.

The first assumption may overestimate ground-water flux to the lake. For example, if frost beneath elevated roadways acts as an impediment to ground-water flow, as suggested previously, ground water from a substantial part of the airstrip site may flow toward North Salt Lagoon. In this case, ground-water flux to Imikpuk Lake from subarea 3, approximately half of the total area, would be at least partly eliminated.

The second assumption is clearly an oversimplification. In reality, the active layer typically begins thawing sometime in June, and does not refreeze completely until sometime in October or later. However, the thaw penetration is limited during the early part of the thaw season, and once freeze-up begins, the vertical extent of the active layer begins to diminish. As a result, ground-water flux is probably greatest during July and August, when the data used in calculations were collected, and substantially reduced during the remainder of the flow period. It is therefore probable that the second assumption leads to an overestimate of ground-water flux to the lake.

The similarity among the six values of hydraulic gradient calculated from the data (table 6) indicates that this property does not vary substantially, either spatially across the site or temporally over the period from mid-July through late August. This limited variation indicates that the third assumption is reasonable.

The final assumption is likely the greatest source of error in the ground-water flux estimates. Hydraulic conductivity is typically the most difficult flow-system property to estimate with reasonable accuracy. This results primarily from the inherent variability of porous media, which can be considerable, even over small distances. Such variability can result in hydraulic conductivity values that range over one or more orders of magnitude, even for apparently similar materials. It should therefore be noted that the hydraulic conductivity value used introduces uncertainty into the flux estimates.

On the basis of the preceding assumptions, the annual flux of ground water from the airstrip site to Imikpuk Lake was estimated to be approximately $173 \text{ m}^3/\text{y}$ (table 6). This low flux, which constitutes approximately 0.06 percent of the total inflow to Imikpuk Lake, is primarily the result of the limited vertical thickness of the active layer and the brief thaw season.

SUMMARY AND CONCLUSIONS

Imikpuk Lake serves as the drinking-water source for the UIC-NARL facility near Barrow, Alaska. During the 1970's and 1980's, more than $1,300 \text{ m}^3$ of fuel were accidentally released at the airstrip site adjacent to the lake, which poses a potential threat to water quality in the lake. To determine the magnitude of this threat, the hydrologic interaction between the lake and the airstrip site was assessed by estimating total annual inflow to the lake and annual ground-water flux from the site to the lake. Total annual inflow to Imikpuk Lake was estimated by four methods. The results from all four methods are similar, with an average value of $300,000 \text{ m}^3/\text{y}$.

The flux of ground water from the airstrip site to Imikpuk Lake was also estimated. Data collected during July and August 1993 were used to calculate hydraulic gradients and the cross-sectional area available for flow. The value used for hydraulic conductivity was estimated from the literature and is likely the greatest source of error in the flux estimates. The total annual flux from the site was estimated to be approximately 173 m^3 . Because of the unrestrictive nature of the assumptions used, this is likely an overestimate of actual flux from the site and probably represents a "worst-case" scenario in terms of the hydrologic impact of the airstrip site on Imikpuk Lake.

The water-flux estimates presented here indicate that the ground-water flux to the lake from the airstrip site constitutes approximately 0.06 percent of the estimated annual inflow to Imikpuk Lake. Even allowing for an error of more than an order of magnitude in the ground-water flux estimates, ground-water flow from the airstrip site contributes less than 1 percent of the total lake inflow.

REFERENCES CITED

- Bear, Jacob, 1979, *Hydraulics of groundwater*: New York, McGraw-Hill Book Company, 569 p.
- Benson, C.S., 1969, The seasonal snow cover of Arctic Alaska: Arctic Institute of North America Research Paper 51, 88 p.
- , 1982, Reassessment of winter precipitation on Alaska's Arctic Slope and measurements of the flux of wind blown snow: University of Alaska Fairbanks, Geophysical Institute Research Report UAG R-288, 26 p.
- Black, R.F., 1954, Precipitation at Barrow, Alaska, greater than recorded: American Geophysical Union Transactions, v. 35, p. 203-206.
- Brown, Jerry, Dingman, S.L., and Lewellen, R.I., 1968, Hydrology of a drainage basin on the Alaskan coastal plain: U.S. Army Cold Regions Research & Engineering Laboratory, Materiel Command, Research Report 240, 18 p.
- Church, M., 1988, Floods in cold climates, *in* Baker, V.R., Kochel, R.C. and Patton, P.C., eds., *Flood geomorphology*: New York, John Wiley, p. 205-229.
- Collins, F.R., 1961, Core tests and test wells, Barrow area, Alaska, *with a section on* Temperature measurement studies, by M.C. Brewer: U.S. Geological Survey Professional Paper 305-K, p. 569-644.
- Dingman, S.L., Barry, R.G., Weller, G., Benson, C., LeDrew, E.F., and Goodwin, C.W., 1980, Climate, snowcover, microclimate, and hydrology, *in* Brown, Jerry, Miller, P.C., Tieszen, L.L., and Bunnell, F.L., eds., *An arctic ecosystem—The coastal tundra at Barrow, Alaska*: Stroudsburg, Pennsylvania, Dowden, Hutchinson & Ross, Inc., 571 p.
- DOWL Engineers and Crowley Environmental Services, Inc., 1986, Fuel spill assessment study UIC/NARL Facility, Barrow, Alaska: Anchorage, Alaska, 92 p. [prepared for Ukeagvik Inupiat Corporation, Barrow].
- Freeze, R.A., and Cherry, J.A., 1979, *Groundwater*: Englewood Cliffs, N.J., Prentice-Hall, 604 p.
- Guymon, G.L., 1976, Summer moisture-temperature for arctic tundra: *Journal of the Irrigation and Drainage*, Proceedings of the American Society of Civil Engineers, v. 102, no. IR4, p. 403-411.
- Kane, D.L., and Chacho, E.F., 1990, Frozen ground effects on infiltration and runoff, *in* Ryan, W.L., and Crissman, R.D., eds., *Cold regions hydrology and hydraulics*: Technical Council on Cold Regions Engineering Monograph, American Society of Civil Engineers, p. 259-300.
- Leslie, L.D., 1989, *Alaska climate summaries* (2d ed.): University of Alaska, Anchorage, Arctic Environmental Information and Data Center, Alaska Climate Center Technical Note No. 5.
- Mather, J.R., and Thornthwaite, C.W., 1958, Microclimatic investigations at Point Barrow, Alaska, 1957-1958: Centerton, N.J., Drexel Institute of Technology, Laboratory of Climatology, Publications in Climatology, v. XI, no. 2, 177 p.
- McCarthy, K.A., 1994, Overview of environmental and hydrogeologic conditions at Barrow, Alaska: U.S. Geological Survey Open-File Report 94-322, 17 p.
- Naval Energy and Environmental Support Activity, 1983, Navy assessment and control of installation pollutants—Initial assessment study of Naval Arctic Research Laboratory (NARL), Point Barrow, Alaska: Naval Energy and Environmental Support Activity Report 13-026, unpagged.
- Ohmura, Atsumu, 1982, Evaporation from the surface of the arctic tundra on Axel Heiberg Island: *Water Resources Research*, v. 18, no. 2, p. 291-300.
- Reed, J.C., 1958, Exploration of National Petroleum Reserve No. 4 and adjacent areas, northern Alaska, 1944-53—Part I, History of the exploration: U.S. Geological Survey Professional Paper 301, 192 p.
- Sabo, E.D., 1956, Evaporation from the snow cover in the Ergeni District, *Sbornik "Shegitalye vody"*: Izdatel'stvo Akademii Nauk SSSR, Translated from Russian, Israel Program for Scientific Translation Catalog No. 653, p. 44-51.

- Science Applications International Corporation, 1987, Evaluation of hazardous materials and potential environmental contamination at the Naval Arctic Research Laboratory, Point Barrow, Alaska: Oak Ridge, Tenn., 75 p. + appendixes [prepared for the U.S. Department of Energy; submitted to Naval Facilities Engineering Command, Silverdale, Wash.].
- ____ 1989, Investigation of environmental concerns at the Naval Arctic Research Laboratory, Point Barrow, Alaska, March 1989: Oak Ridge, Tenn., 110 p. + appendixes [prepared for the U.S. Department of Energy; submitted to Naval Facilities Engineering Command, Silverdale, Wash.].
- ____ 1990, Investigation of environmental concerns at the Naval Arctic Research Laboratory, Point Barrow, Alaska, April 1990, Volume I, Technical Report: Oak Ridge, Tenn., 66 p. + appendixes [prepared for the U.S. Department of Energy; submitted to Naval Facilities Engineering Command, Silverdale, Wash.]. p.
- Tryck, Nyman, & Hayes and Shannon & Wilson, Inc., 1987, Naval Arctic Research Laboratory fuel spill investigation: Anchorage, 47 p. + appendixes [prepared for Department of the Navy, Naval Facilities Engineering Command, Silverdale, Wash.].
- URS Consultants, Inc., and Shannon & Wilson, Inc., 1991, Supplemental remedial investigation, Naval Arctic Research Laboratory, Point Barrow, Alaska: Seattle, Wash., [prepared for the Naval Facilities Engineering Command, Silverdale, Wash.] 176 p.
- ____ 1994, Supplemental site characterization of the airstrip fuel spill area, Imikpuk Lake, North Salt Lagoon, and selected meltwater ponds, Naval Arctic Research Laboratory, Point Barrow, Alaska: Seattle, Wash., [prepared for the Naval Facilities Engineering Command, Silverdale, Wash.] variously paged.
- U.S. Department of the Interior, 1985, Ground water manual: U.S. Government Printing Office, Water Resources Technical Publication, 480 p.
- U.S. Geological Survey, 1993, Water resources data for Alaska—Water year 1992: U.S. Geological Survey Water-Data Report AK-92-1, 417 p.
- ____ 1994, Water resources data for Alaska—Water year 1993: U.S. Geological Survey Water-Data Report AK-93-1, 369 p.