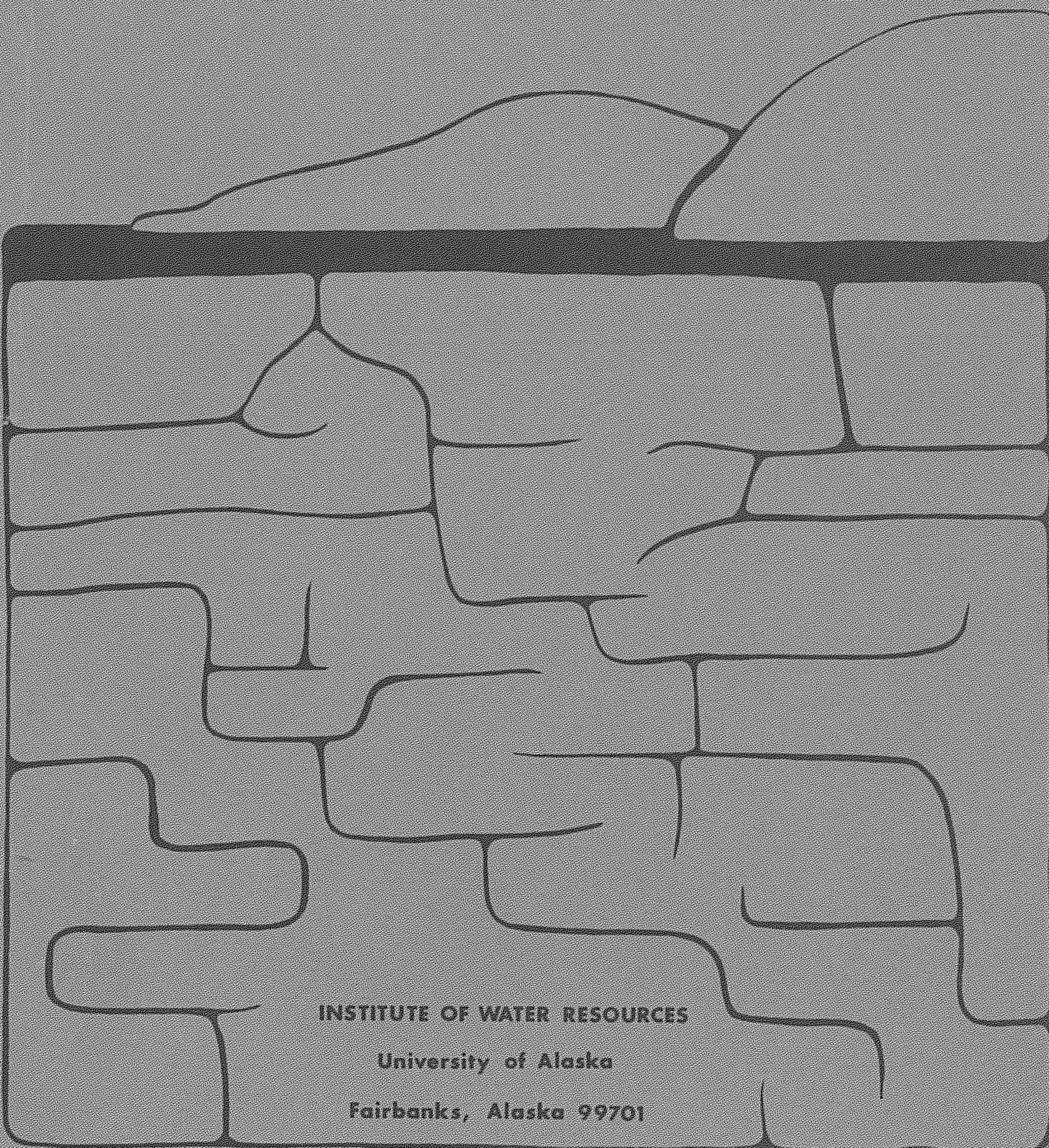
HYDROLOGY OF THE CENTRAL ARCTIC RIVER BASINS OF ALASKA



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HYDROLOGY OF THE CENTRAL ARCTIC RIVER BASINS OF ALASKA

Hydrology of the central Arctic river basins of Alaska
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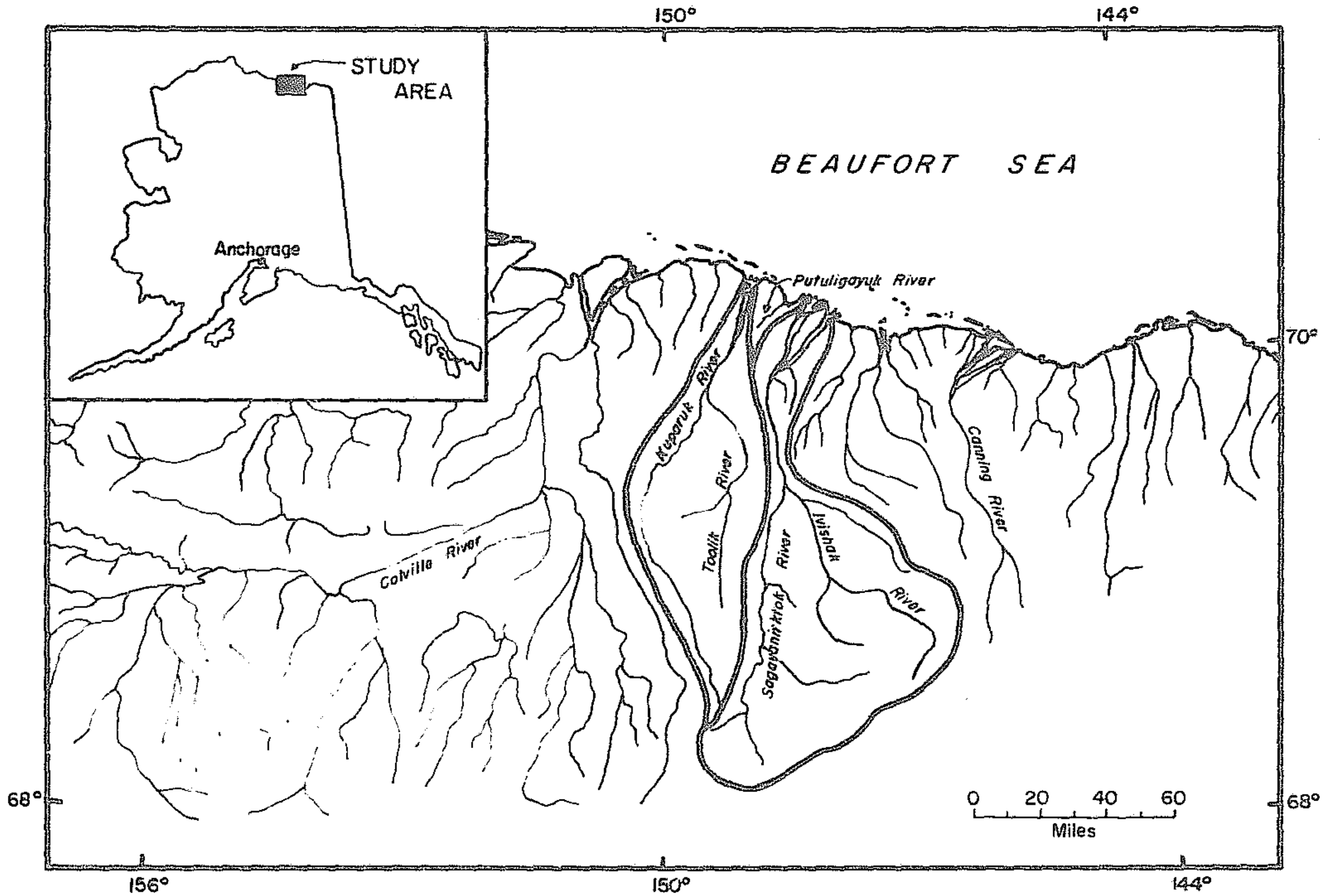

Figure 1 Location map showing the major drainages in Prudhoe Bay area.

INTRODUCTION

BACKGROUND

The need for more information about the Arctic's natural resources, particularly its water resources, became apparent with the advent of increased resource extraction and development activities, beginning in 1969. At that time, the Institute of Water Resources initiated a small, three-year project which attempts to synthesize hydrologic and water resource information available for the area. This work has led to an extensive data and literature survey and summary, gathering of field data and mathematical modeling of the spring breakup process. In addition, this report presents a general summary of the overall hydrology of the area. The results of the first three activities are listed in the Appendix.

Most hydrologic data is acquired for scientific studies or direct engineering application and analysis. The first type of study is generally short-term and the second usually continuous from the inception of the problem. Almost all studies north of the Brooks Range have been devoted to the gathering of scientific information with only a few directed toward continuous data collection. Short term collection is of limited engineering use for understanding the hydrologic system. This study was limited, however, largely to short-term data of necessity rather than choice; few hydrologic data activities existed in the Arctic before 1969.

Numerous design decisions dealing with waste disposal, water supply, stream crossings, both from snowmelt and rainfall events have already been made based on existing meager data and more decisions will certainly be made in the future. This report summarizes existing water resource data, the need for collecting future additional data, hydrologic processes of engineering importance and some simple engineering analyses. The primary area of the study includes the region of the Putuligayuk, Sagavanirktok and Kuparuk rivers on the North Slope of Alaska. In addition, data from Barter Island, Barrow, Colville River and a few other small streams are discussed.

SUMMARY OF THE HYDROLOGIC SYSTEM IN THE ARCTIC

Hydrologic processes of the Arctic are, in many ways, like those of other climatic regions. The dominant feature of Arctic hydrology is the spring breakup and snowmelt runoff processes. Because of this dominance, the other components of the hydrologic processes play only a minor role in the total hydrologic system. Thus, the modeling or interpretation of these processes can be greatly simplified.

Another important aspect of Arctic hydrology is the low precipitation and the concurrent reduction of the total volume of water comprising the other phases of the hydrologic system. The annual precipitation for the Arctic Slope area is generally in the range of 5-10 inches. As a result, runoff, subsurface recharge, and evapotranspiration cannot exceed this volume in addition to storage which may have accumulated during previous years. The lack of precipitation is primarily the result of a desert condition imposed for much of the year by the ice-covered Arctic Ocean.

Precipitation increases in an easterly direction. An examination of the precipitation records collected from 1949 to 1971 by the U. S. Weather Bureau shows that the annual precipitation at Barrow and Barter Island is 5 inches and 7.35 inches, respectively. The monthly precipitation increases in June, July and August and tapers off during the remaining months.

Snowfall accumulations begins in early September and continues until June when the snowmelt runoff processes start. Although the precipitation during the winter months is light, the total accumulation during this nine-month period can be substantial, resulting in significant flood peaks.

Because of the minimal amount of data, it is difficult to make valid inferences about snowmelt and summer rainfall runoffs. Three rivers in the Prudhoe Bay region and several small drainages near Barrow have gage records up to four years. Many of these records cover only a few months of the year, limiting their application. The maximum runoff of streams draining only the Arctic Coastal Plain occurs during snowmelt periods. Streams that have their headwaters in the Brooks Range show a response to summer precipitation and delayed snowmelt, resulting in flood peaks which are equal to or greater than spring snowmelt peaks.

Evaporation rates during the few summer months appear to be quite high in the Arctic due to constant winds and high incoming solar radiation. Transpiration from plant life appears to be moderate, although little is known about this process. A fair amount of sublimation might occur, especially early in the spring, when the incoming daily solar radiation is quite high and extensive snow cover exists.

Surface storage plays a dominant role in Arctic hydrology in several ways; the presence of a large number of lakes and poorly drained terrain greatly increases the active surface storage during the spring breakup and summer season. Also, since precipitation occurs in the form of snow during eight or nine months of the year, surface storage as snow cover is predominant. Another short term process peculiar to the Arctic is the occurence of aufeis or icing deposits which occur along the drainage channels. But, snow cover and aufeis surface storages seldom survive the warm summers while storage in the form of ponding on the surface may carry over into the following year.

Little is known about subsurface soil retention and storage in Arctic soils. The active soil system is quite shallow because of the underlying permafrost. In early June, this active layer is completely frozen and by late summer this layer may reach a maximum unfrozen depth of 3 to 4 feet. Near bodies of water, the distance down to the top of the permafrost will vary and may extend to several hundred feet. Reported maximum permafrost thicknesses have ranged from 1200 to 2000 feet. Whether any unfrozen zones extend completely through the permafrost such that subsurface groundwater flow can occur is unknown. Shallow groundwater aquifers are known to exist below the major drainages. Distribution and thickness of permafrost are not well defined; it is generally assumed to be continuous. Because of this permafrost barrier, groundwater recharge and discharge is greatly reduced. Groundwater flow systems probably do not play a dominant role in the hydrologic system.

In summary, the major processes which take place in the Arctic basins are: precipitation, evaporation from water bodies, surface storage, and surface runoff. Short-term changes in the amount of water stored in the shallow soil system may be significant.

PHYSIOGRAPHICAL ELEMENTS

REGIONAL PHYSIOGRAPHY

Alaska, the large northwestern peninsula of North America, is characterized by mountainous and hilly terrain interspersed with broad plains along the major drainages and coastline. The North Slope area has similar physiographic features. Wahrhaftig (1965) divides the state into several physiographic divisions. The Sagavanirktok and Kuparuk Rivers transcend three physiographic regions, while the Putuligayuk River is confined to one physiographic region, the Arctic Coastal Plain. The Sagavanirktok and Kuparuk drainages originate in the Brooks Range, flow through the Arctic foothills, and empty into the Beaufort Sea after flowing across the Arctic Coastal Plain.

The Brooks Range is an extension of the Rocky Mountain system in Canada and the continental United States. This range can be described as rugged with east-trending ridges. The elevation of most mountain peaks range from 6000 to 8200 feet. Presently, no glaciers are found in the headwaters of the Kuparuk and Sagavanirktok River basins. This area is generally considered to be one of continuous permafrost.

The arctic foothills are made up of low mountains and rolling plateaus with intervening tundra plains. Wahrhaftig (1965) divided the foothills into two divisions, the northern and southern sections. The northern part of the foothills consists of broad east-trending ridges with local mesa-like ridges that vary in elevation from 600 to 1200 feet. The southern section rises in altitude from 1200 to 3500 feet with irregular buttes, mesas, and east-trending ridges. Few lakes are found in the major river valley bottoms. The flow direction is northward. The entire area is underlain with permafrost with the thickness increasing northward.

The Arctic Coastal plain extends from the ocean to the arctic foothills. The width of the plain in the Sagavanirktok and Kuparuk River basins is about 100 miles. The plain at the shoreline begins just a few feet above sea level and reaches 600 feet. The area has very poor drainage, numerous lakes, and permafrost. The maximum measured thickness of permafrost exceeds 2000 feet. The depth of summer thaw ranges from ½ to 4 feet.

PHYSICAL STRUCTURE OF BASINS

Due to the strong interaction of climate and geology, an understanding of hydrologic behavior can be derived from certain morphological indices. For example, Melton (1959) correlated drainage density with the ratio of average annual precipitation divided by the average annual evaporation and Carlston (1963) showed a decrease in the groundwater contribution to streamflow with greater drainage densities.

As mentioned previously, the three basins vary substantially in their physical make-up. The drainage areas vary from 5,360 $miles^2$ for the Sagavanirktok River basin to 222 $miles^2$ for the Putuligayuk River basin, with the Kuparuk River draining an area of 3,560 $miles^2$. Dimensionless hypsometric curves for the Kuparuk and Sagavanirktok watersheds are shown in Figure 2. Curves below the dashed line indicate that a basin is in the monadnock phase of development; such is the case when a single or group of hills and mountains of resistant rock surmount a peneplain, an eroded surface of considerable area and slight relief. The dashed line represents basins that have reached a mature stage (equilibrium), while any plot above this line indicates a young basin still undergoing physical change to reach equilibrium.

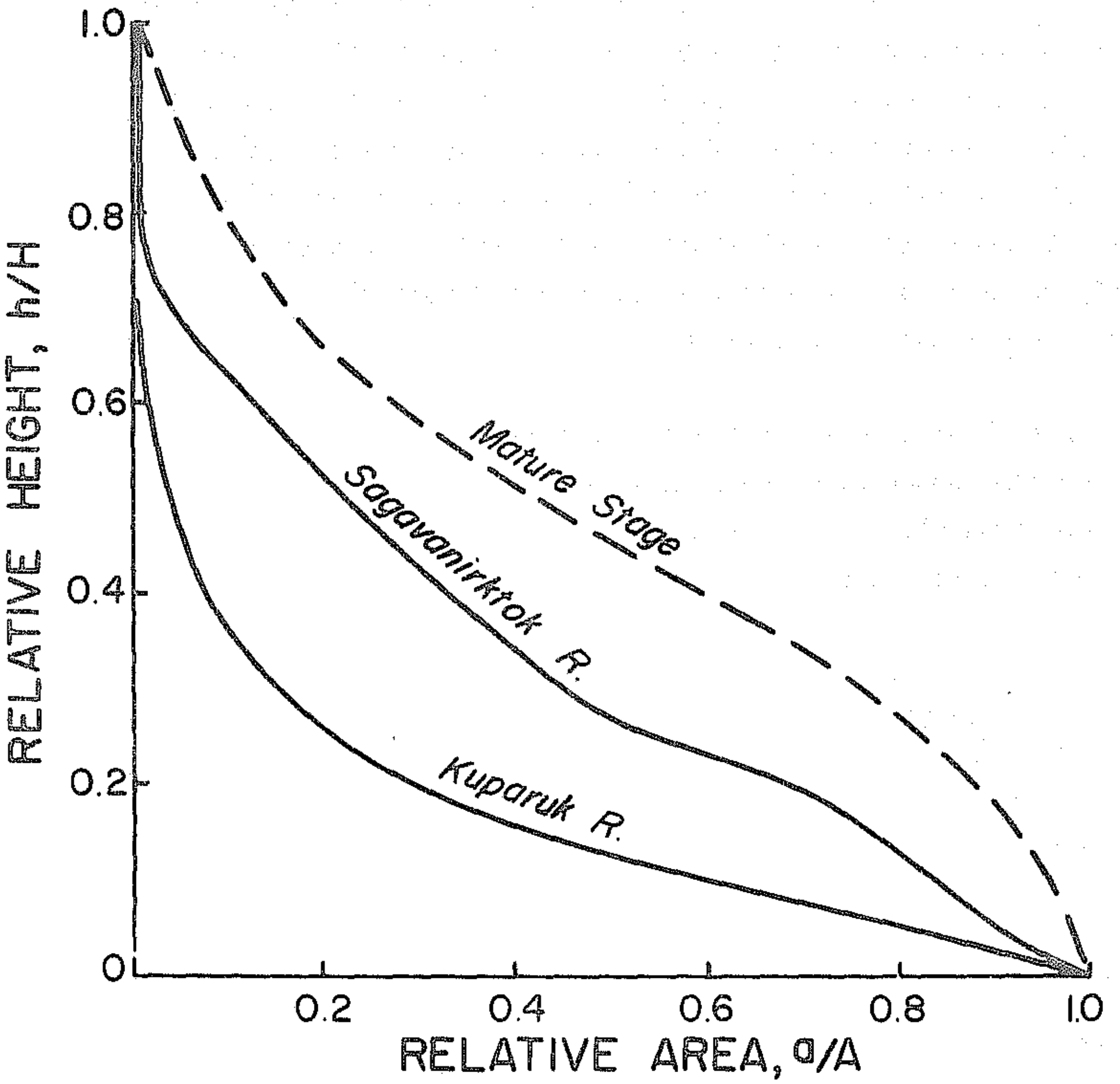

Figure 2 Hypsometric Curve, H = maximum elevation, A = total drainage area, and a = drainage area above a given elevation h.

The area-elevation curves shown in Figure 3 indicate both the range of elevation and the per cent of area above a given elevation. The same curve could not be plotted for the Putuligayuk River from available maps. The elevation of the Putuligayuk River watershed varies from sea level to 260 feet, with the length of the basin approximately 34 miles. Two area-elevation curves are shown for the Sagavanirktok River, one for the entire basin and one for the area above the U.S. Geological Survey gaging site. An examination of the runoff curves for the three basins shows a substantial difference in the average unit runoff during the summer. Snowmelt water contribution to streamflow at higher elevations accounts for most of the differences. Another possible reason may be increased orographic precipitation.

The following table indicates the highest stream order for each basin and the number of streams in each order. The stream order was determined from blue-line streams on U.S. Geological Survey maps (1:250,000 and 1:63,300).

TABLE 1. THE NUMBER OF STREAMS IN EACH ORDER

River Basin	Stream Order					
	1	2	3	4	5	6
Sagavanirktok	503	103	28	5	2	1
Kuparuk	185	62	12	3	1	
Putuligayuk	4	1				

A comparison of stream order ratios for these streams shows results similar to those obtained by Strahler (1952). The stream order ratio equals the number of streams in one order divided by the number of streams in the next higher ratio. For both Strahler's (1952) work and ours, this ratio is very near 4. There appears to be no correlation with relief.

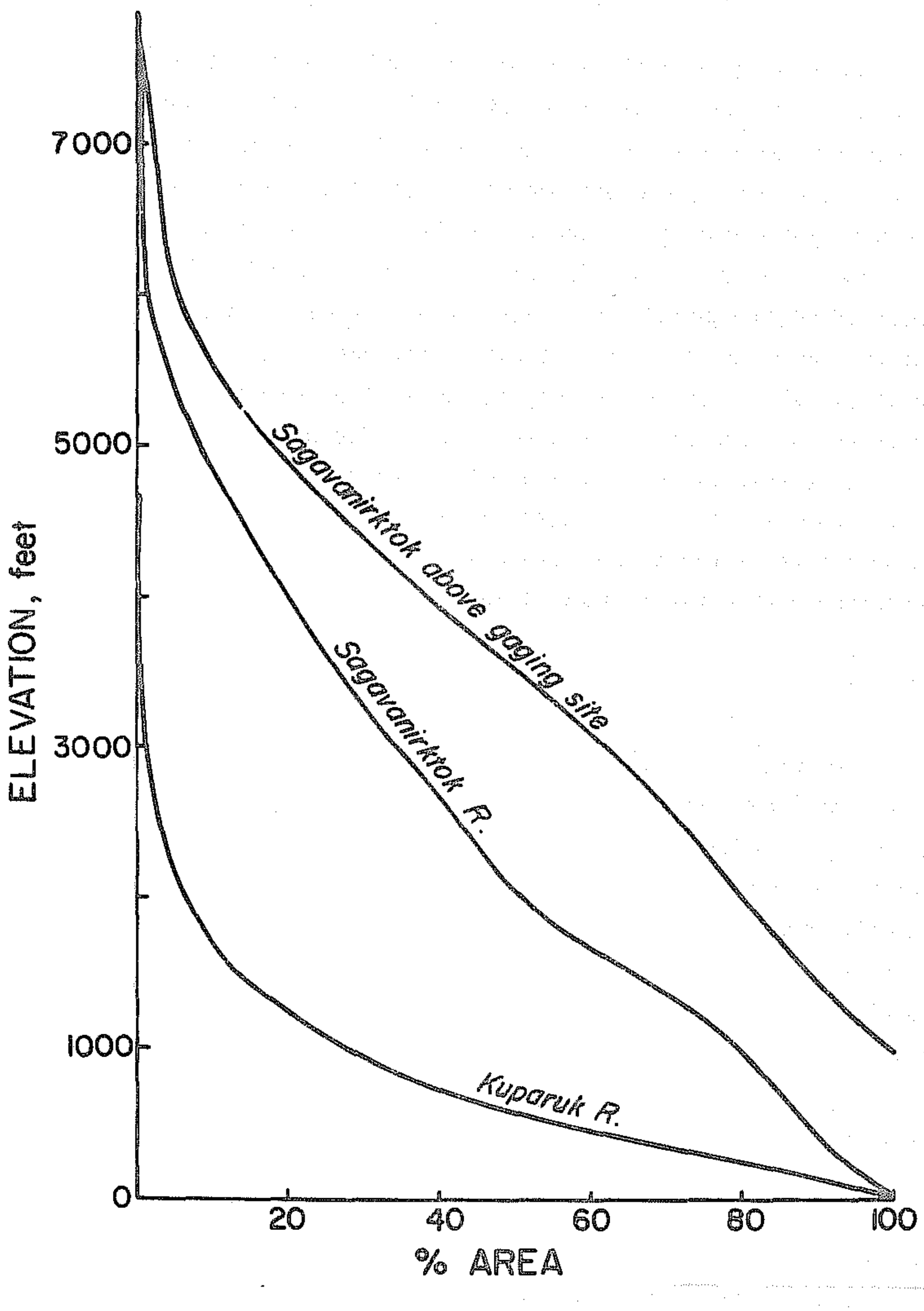

Figure 3 Area-elevation curve illustrating the percentage of the total drainage area above a given elevation.

Lakes deserve mention because of their importance as a storage facility. The Arctic Slope has literally thousands of them. Measurement of surface water area in the Putuligayuk River basin indicates that 20% of the basin is covered with water. These measurements were made on the new orthophoto maps (U.S. Geological Survey, 1:24,000). The same measurement on the 1:250,000 scale U.S. Geological Survey maps for the Kuparuk and the Sagavanirktok River basins indicate that 2% of the Kuparuk basin and 1% of the Sagavanirktok basin are covered with water. Realistically, these values may be double that shown because smaller lakes are eliminated at the given scale. The main reason for the difference results from the type of relief that is drained. The Arctic Coastal Plain constitutes a small percentage of the Kuparuk and Sagavanirktok River basins, whereas the Putuligayuk River basin is entirely contained within the coastal plain.

GEOLOGY

Keller, *et al.*(1961) summarized the general geology of this area as dating from Mississipian to Tertiary ages, with a Pennsylvanian system not present. Visible outcroppings include the Mississippian Lisburne group, the Permian and Triassic Sadlerochit formation, the Triassic Shublik formation, the Jurassic Kingak and Tiglukpuk formations, numerous Cretaceous formation, and the Tertiary Sagavanirktok formation. Structurally, the area is characterized by high-angle reverse faults, thrust faults, and anticlines.

Geology of Brooks Range:

Karlstrom (1964) defined the surficial geology of the Brooks Range in the upper reaches of the Sagavanirktok and Kuparuk Rivers as undifferentiated alluvium and slope deposits, dominantly coarse rubbley deposits with high percentages of bedrock exposures. The bedrock was mapped by

Lathram in 1965. The major bedrock formations are sandstone-siltstone (Sadlerochit formation), conglomerate (Noatak Sandstone), limestone (Lisburne Formation), and shale. Dutro and Payne (1957) described the upper Devonian sedimentary rock as marine and non-marine conglomerate, quartzite, sandstone, and shale. They report the upper Mississippian sedimentary rock as limestone with some chert, shale, and dolomite. The major valleys reflect the effect of glaciation during the Pleistocene epoch with modified moraines and associated drift present. Presently, no glaciers exist in the study area.

Geology of Arctic Foothills:

The foothills typically have undifferentiated glacial and glacio-fluvial deposits, not deposited during the latest glaciation. Karlstrom (1964) mapped the surficial geology as dominantly fine-grained quaternary deposits associated with sloping hills exhibiting rare bedrock exposures. Dutro and Payne (1957) mapped the bedrock geology of the foothills as Cretaceous rocks, predominantly sandstone, graywacke, and shale with minor amounts of conglomerate.

The White Hills adjacent to the Arctic Coastal Plain are mapped as coarse and fine-grained deposits associated with moderate to steep-sloped mountains and hills with bedrock exposures limited to higher elevations. Areas bordering to the east and south of the White Hills are mapped as Eolian deposits of silt more than 5 feet thick covering upland interfluve areas. Lathram (1965) indicated that the bedrock in these hills is mainly conglomerate and sandstone of the Sagavanirktok formation.

Geology of Arctic Coastal Plain:

The coastal deposits as indicated by Karlstrom *et al.* (1964) include interstratified alluvial and marine sediments with some local, glacial drift. Dutro and Payne (1957) mapped the Arctic Slope area as undifferentiated quaternary deposits consisting of alluvium, beach deposits, and terrace deposits. Likewise, Lathram (1965) described the geological units of alluvium and glacial material not deposited during the Pleistocene epoch.

Geology Along the Sagavanirktok River:

Due to resource interest and the possible construction of a pipeline from Prudhoe Bay south to Valdez, a set of geological maps were assembled along the proposed route. Ferrians (1971) published maps relating to the North Slope area, primarily along the Sagavanirktok River. Because of the control geology exerts on the stream morphology development, a brief description of the geology along this major river valley is presented here.

Ferrians (1971) describes the active flood plain as consisting of coarse sand gravel and sand with minor amounts of silt. These deposits are reported to be extensive along the Sagavanirktok and Ivishak Rivers, with smaller deposits along the Putuligayuk River, the thickness varying from less than 20 to more than 50 feet.

Numerous alluvial terraces of coarse, sandy gravel and sand with traces of silt characterize the lower reaches of the Sagavanirktok valley. The terraces are generally mantled with two or more feet of organic rich silty sand. Permafrost is generally present within a couple of feet of the ground surface. Progressing upstream, terraces of an older origin are found. Adjacent to all three river systems, numerous naturally drained lake basins exist.

The geology in the foothills and Brooks Range differ from that of the Arctic plain. They have colluvium, alluvial fans, and older morraines. The area around the Kakuktukruich Bluff consists of old morraines and old alluvial terraces. The colluvium is a mixture of unsorted and poorly sorted, gravelly sand silt with numerous angular rock fragments. The alluvial fans consist of poorly sorted silty gravel and sand. Typically, coarse material is found at the apex and finger-grained material at the toe, interspersed with boulders. Terraces are composed of coarse, sandy gravel and sand with some silt; gravels are subrounded to rounded.

Consolidated bedrock along the Sagavanirktok River is made up of tertiary sediments along the Franklin Bluffs, cretaceous sandstone and conglomerate between the Ivishak and Lupine Rivers, and a continuous assortment of bedrock formations above Ribdon River in the Brooks Range.

SOILS AND VEGETATION

Soils of arctic areas follow the same mode of development as the soils of temperate areas. Tedrow and Cantlon (1958) list five factors of importance in soil-development processes: climate, parent material, relief, biotic elements and time. Climate, the major factor responsible for the presence of various biotic communities, is the major distinguishing factor that separates arctic soils from their southern counterparts. The production and decomposition of organic material is severely affected by low temperatures. Suppression of pedologic processes occurs in a northward direction, as in areas of higher elevation. For the most part, soils in this area can be described as mineral in nature with some organic soils, poorly drained, and underlain with permafrost.

Tedrow and Brown (1967) classified Arctic soils into four groups: mineral gley (Tundra), bog, well drained (Arctic Brown), and miscellaneous This division of soils is based mainly on the drainage characteristics of the soil as described by Tedrow *et al.* (1958).

Mineral gley (Tundra) soils are imperfectly to poorly drained, underlain with permafrost with an active layer approximately one foot deep, and a layer of organic material at the surface with a thickness from near 0 to several inches. Distribution of mineral gley soils is widespread from the coast to the mountains. They would constitute 60% to 70% of all soils.

Bog soils are the second most common soil of this area. These organic soils have an active layer of about 1 foot which is composed of sphagnum and sedge peat. These soils are often saturated throughout the summer months with peat thicknesses varying from 2 to 5 feet and sometimes more. These soils are usually found on the coastal plain with lesser amounts in the major valleys of the foothills.

Arctic Brown soils are well-drained, having formed under free drainage. Their areal extent is generally confined to ridges, glacial morraines, and alluvial terraces of moderate slope.

Various shallow soils are found in areas of steep slopes with bedrock exposures. These are found extensively in the Brooks Range and, to a lesser extent, in the foothills. Because of the steep gradient, rates of mass-wasting are accelerated, ensuring minimal thickness of less than a few inches. The soil types differ mainly because of the type of parent material.

Spetzman (1959) summarized the plant life by classification into the following six divisions:

1. Tussock meadows
2. Wet sedge meadows
3. Dry upland meadows
4. Flood-plain and cutbank vegetation
5. Outcrop and talus vegetation
6. Aquatic vegetation.

This grouping is made primarily on the drainage characteristics of the area. In lakes and ponds, both submerged-rooted and emerged-rooted aquatic plants are abundant. More than one-half of the coastal plain and one-quarter of the foothills are covered by wet sedge meadows, primarily composed of sedge (*Carex*). Most of the remaining area is covered with tussock meadows of tussock-forming cottongrass (*Eriophorum*). Dry upland meadows consist of the plant, *Dryas octopetela*, and lichens. Maximum growth of all these plants is less than 4 feet. Only the feltleaf willow (*salix abxensis*) reaches greater size, 10 to 25 feet. Due to leaf shading, the soil temperature is reduced sufficiently to eventually eliminate the willow and replace it with other plant forms.

HYDROLOGICAL ELEMENTS

PRECIPITATION

The sparseness of hydrologic data is particularly critical in an attempt to describe precipitation inputs in the hydrologic system. This is particularly true in Alaska's Arctic due to both the proximity of an open body of water for part of the year and a great range of elevation due to the mountainous terrain. Almost all of the data collected north of the Brooks Range in Alaska has been near the coastal plain and the Bering Sea. Precipitation records of any duration are located in Barrow and Barter Island, 340 miles apart, west and east respectively from the Prudhoe Bay development area. Therefore, little is known about precipitation intensity, storm movement patterns and variation in depth and duration relationships throughout the area. Even the accuracy of the present available data is questionable because of the continuous high wind intensity and the frequent occurrence of trace precipitation.

Monthly mean and annual mean precipitation for Barter Island and Barrow during the period 1949 to 1971 are shown in Figure 4. As can be seen from this graph, the major precipitation occurs during the months of June, July, August, September and October. The remaining months have a fairly constant precipitation amount. Figure 5 shows the cumulative precipitation for the same two stations during the same period of time. The cumulative total at Barter Island is substantially greater than at Barrow. Therefore, the average annual precipitation at Prudhoe Bay would likely fall somewhere in between the precipitation amount of Barrow and

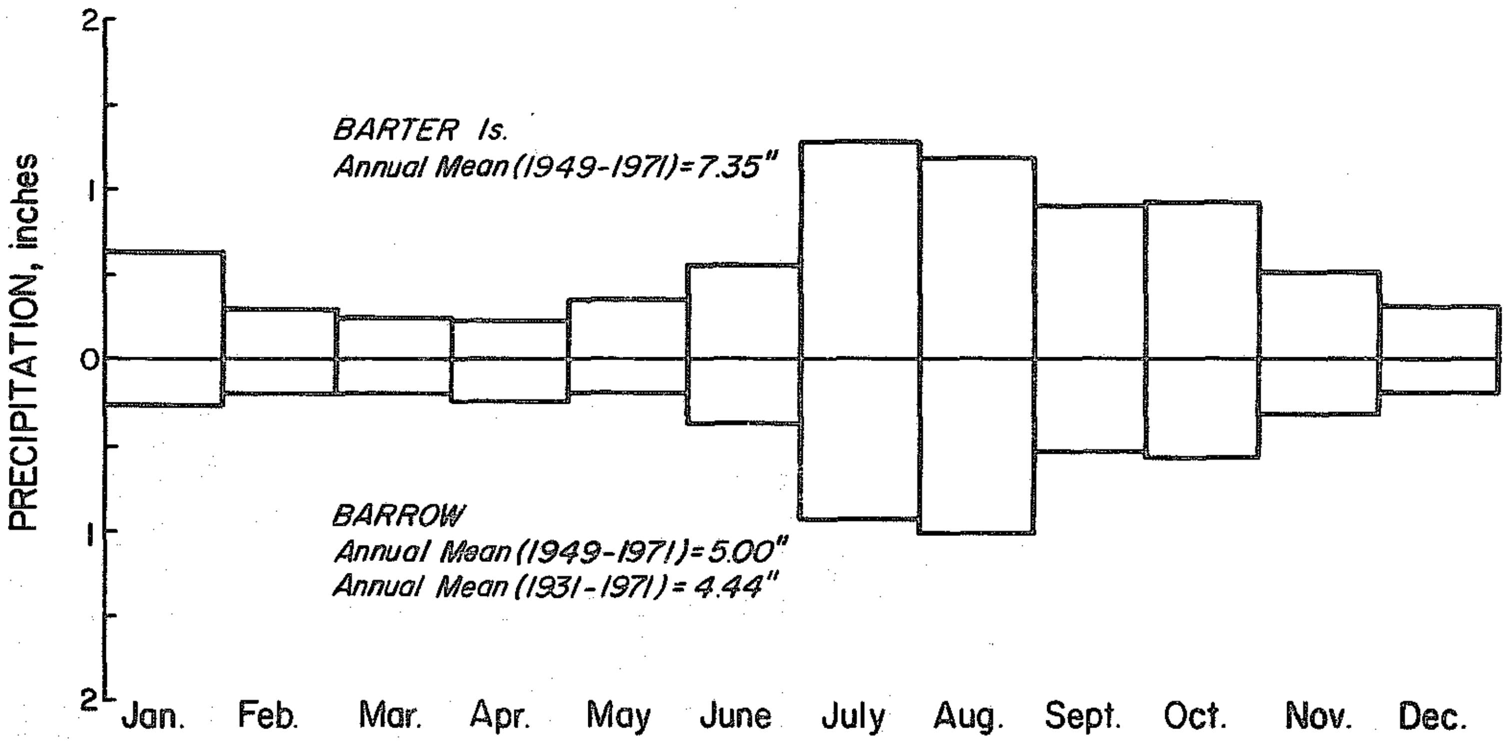

Figure 4 Mean monthly precipitation at Barrow and Barter Island, 1949-1971 (Data source: U. S. Weather Bureau).

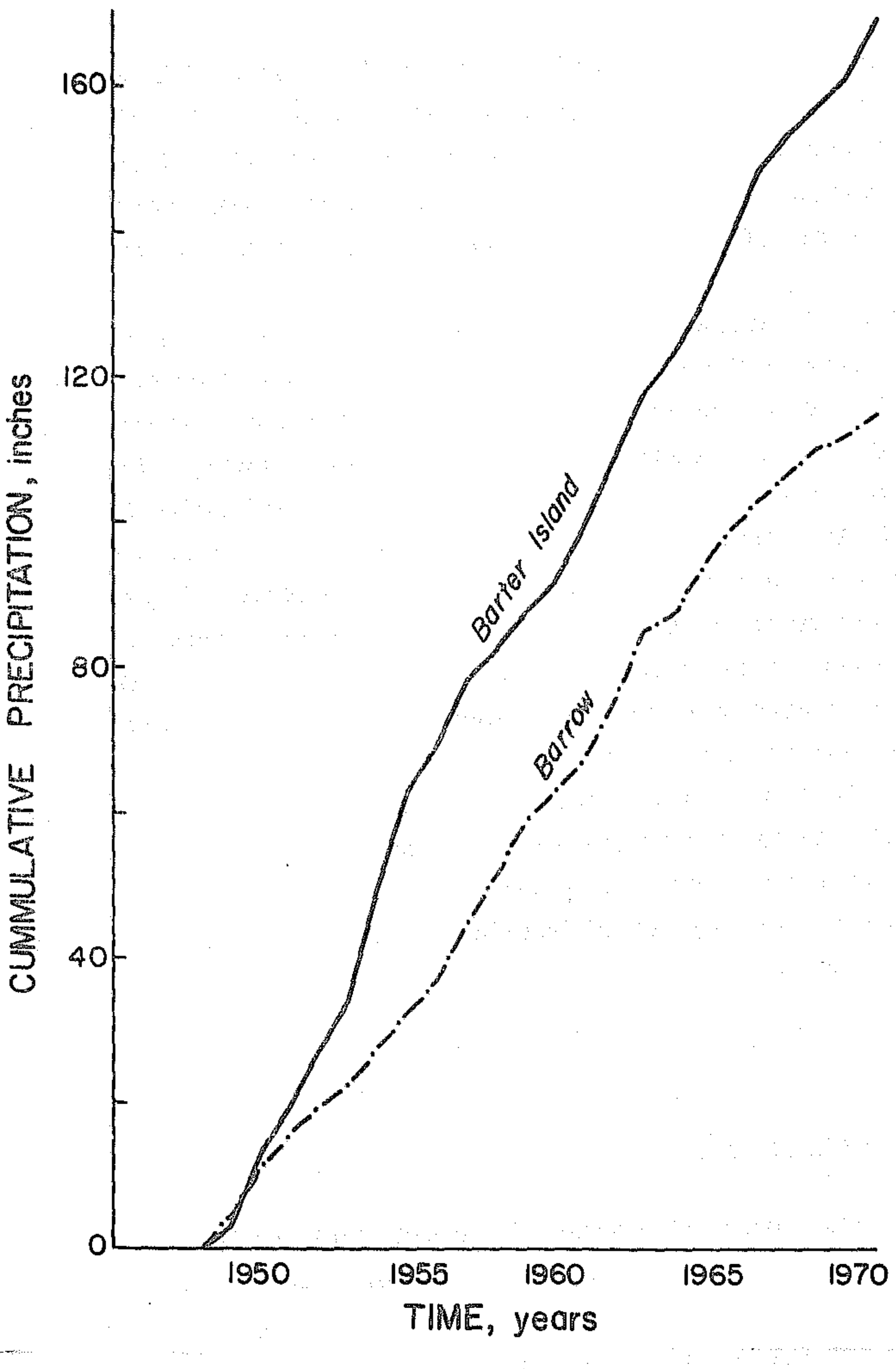

Figure 5 Cumulative precipitation at Barter Island and Barrow, 1949-1971 (Data source: U. S. Weather Bureau).

Barter Island. Both the Institute of Water Resources (IWR) and the International Biological Program (Weller and Brown, 1972) collected precipitation at Prudhoe Bay during the summer of 1971 (Figure 6). The descrepancy between these two sources for the summer months amounts to 0.75 inches of precipitation, about one-half of the IWR amount.

The U.S. Weather Bureau has reported the snowfall depth for a number of years both at Barrow and Barter Island. The mean snowfall depth at Barter Island for the period of record is 45.9 inches. Approximately 10% of this amount occurs during the three summer months. Therefore, 90% of the snow precipitation is available as runoff during the snowmelt period in the spring. The mean snow precipitation at Barrow during the period of record is 29 inches. The same percentage is available as snowmelt runoff in the spring. As with rainfall, there is little understanding of the snowfall distribution with elevation. Only infrequent measurements of the snowpack density have been made. To determine spring runoff from the winter snowpack, adequate snow surveys and detailed climatological collection are needed. Although the monthly mean precipitation during the winter months is low, the accumulation of the snow over nine months in conjunction with the rapid snowmelt in the spring during peak periods of incoming short wave radiation accounts for very high runoffs.

RUNOFF

General Characteristics:

The most important element of the hydrologic cycle from an engineering point of view is runoff. Both peak flow from snowmelt and rainfall, as well as the minimum flow are important. Peak flow influences the design of natural drainage crossings, while low flow establishes the minimum levels for water supply and maximum effluent loads from waste treatment facilities.

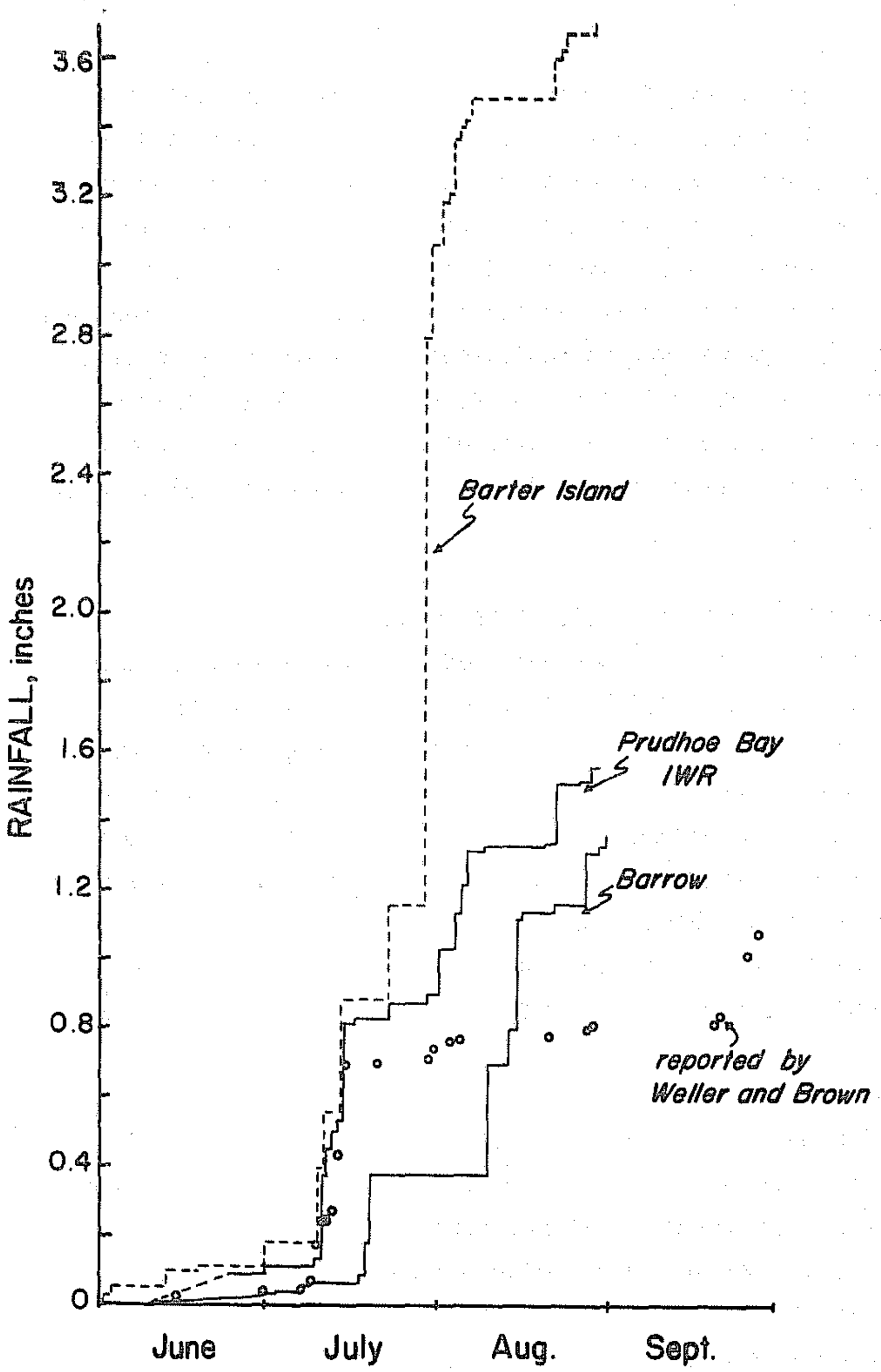

Figure 6 Cumulative plot of daily precipitation at selected sites, Summer, 1971.

The collection of surface runoff data has been very sparse in the Arctic until recently; only miscellaneous measurements had been made. The first creek to be measured in a continuous fashion for any period of time in the Arctic was Ogotoruk Creek, located near Point Hope with a drainage area of approximately 35 mi^2. The flow of this stream was measured during the summer periods from August, 1958, to September, 1961, (Figure 7). The maximum instantaneous discharge for this site was 1450 cfs on September 4, 1961, or 41 cfs/mi^2. This compares with the mean daily discharge per unit area of 25 cfs/mi^2. As can be seen in Fig. 7, the peak discharges occurred during the months of July, August and September.

In 1962, Arnborg *et al.* (1966) made the first intensive measurements on the Colville River. They measured a maximum snowmelt runoff of 214,000 cfs for the 19,305 mi^2 basin. The equivalent unit area runoff is 11.0 cfs/mi^2. The average unit runoff during the year was 0.9 cfs/mi^2 and for the period of ice-free flow, 2.3 cfs/mi^2. They reported flow from 25 May to 20 October. It now seems that flow exists continually through the winter, although in quantities which are substantially less than summer flow. Since the recent resource interest in this area, this same group has made additional measurements of discharge and sediment on the Colville River. This data has not been published to date.

Brown *et al.* (1968) measured the discharge on a small stream near Barrow for the period from 1963 to 1966. Measurements of discharge did not include periods of ice cover or spring breakup. They reported that the average amount of summer precipitation to leave the basin as runoff was 5%; however, this value varied from 1% to 70%, depending upon rainfall intensity. The maximum runoff reported was 1.3 cfs (August, 1963) for the 0.6 mi^2 drainage.

In 1969, the Geological Survey, Water Resources Division began making discharge measurements on three rivers located in the central arctic of Alaska; they are the Sagavanirktok, Kuparuk, and the Putuligayuk Rivers.

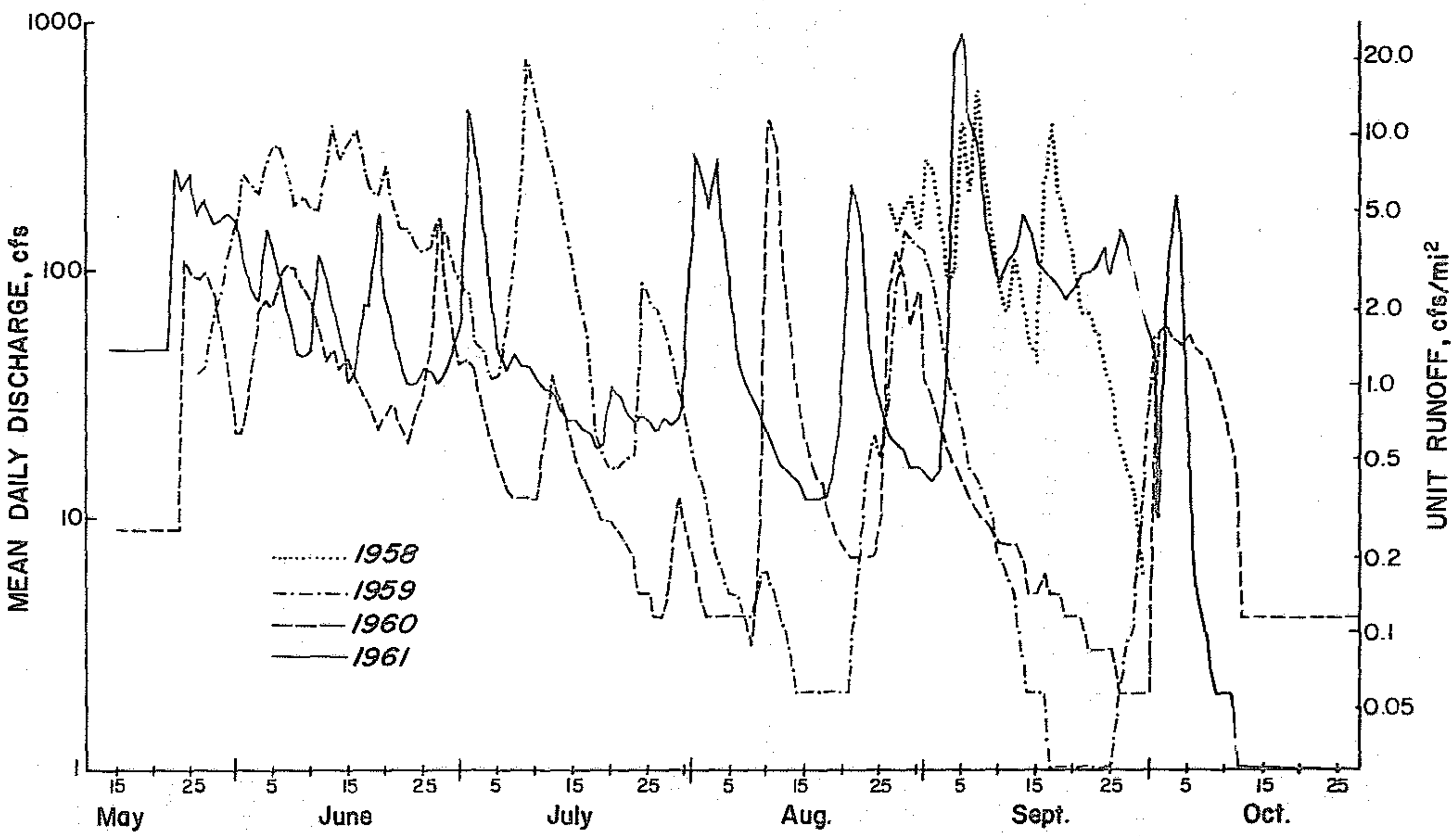

Figure 7 Hydrograph of mean daily discharge, Ogotoruk Creek near Pt. Hope (Data source: U. S. Geological Survey).

Figures 8, 9, and 10 show the mean daily discharge through 1971 and Table 2 gives the volume of runoff from the watersheds in inches for monthly increments.

As can be seen for the few years of record, most of the runoff for the Kuparuk and Putuligayuk Rivers occurs during the spring snowmelt while the Sagavanirktok River has large volumes of water discharged continually throughout the summer. There are two possible reasons for the continual high runoff in the Sagavanirktok River. First, there is the constant process of snowmelt that takes place at higher elevations throughout the summer. Second, there is a possibility of greater precipitation at these higher elevations on terrain which would yield a greater percentage of runoff water. Referring back to Figure 3, the area-elevation curve shows that maximum elevations are greater in the Sagavanirktok Basin and that the percentage of higher terrain drained by the Sagavanirktok River is greater.

TABLE 2. MONTHLY VOLUME OF RUNOFF IN INCHES

	May	June	July	August	September
1969					
Sagavanirktok		4.47 (15-30)*	2.30	5.0	---
1970					
Putuligayuk	.002	2.13	.026	.23	.002
Kuparuk	.26 (28-31)*	1.13 (1-11)*	---	---	---
Sagavanirktok		---	---	1.08 (11-31)*	0.55
1971					
Putuligayuk	.003 (26-31)*	2.90	.05	.012	.009
Kuparuk	.08 (31)*	6.37	.10	.15	.04 (1-15)*
Sagavanirktok		4.81	2.79	1.37	---

Notes:

* Partial Record (Days Recorded in Parenthesis)
-- No record

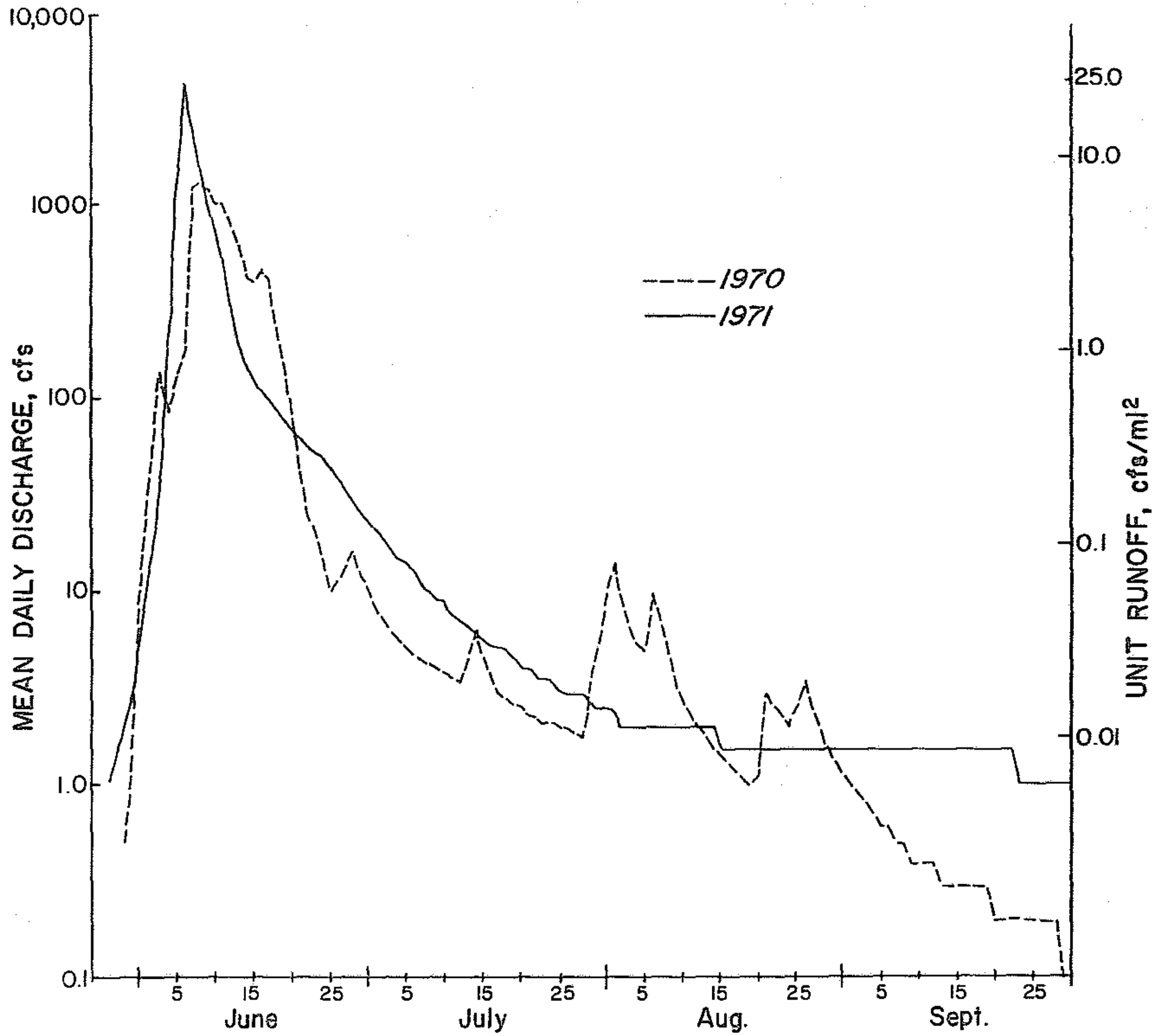

Figure 8 Hydrograph of mean daily discharge, Putuligayuk River (Data source: U. S. Geological Survey).

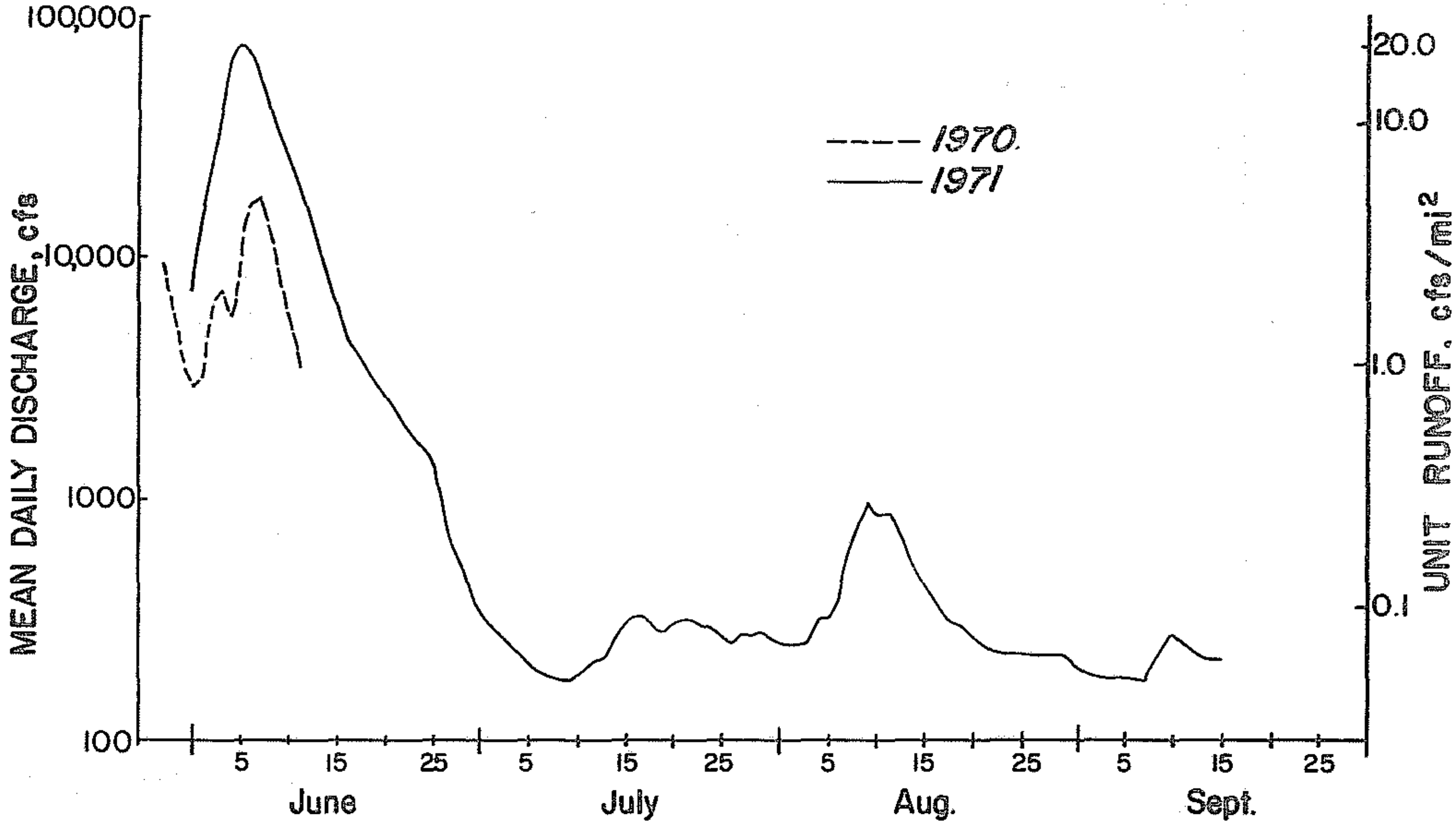

Figure 9 Hydrograph of mean daily discharge, Kuparuk River (Data source: U. S. Geological Survey).

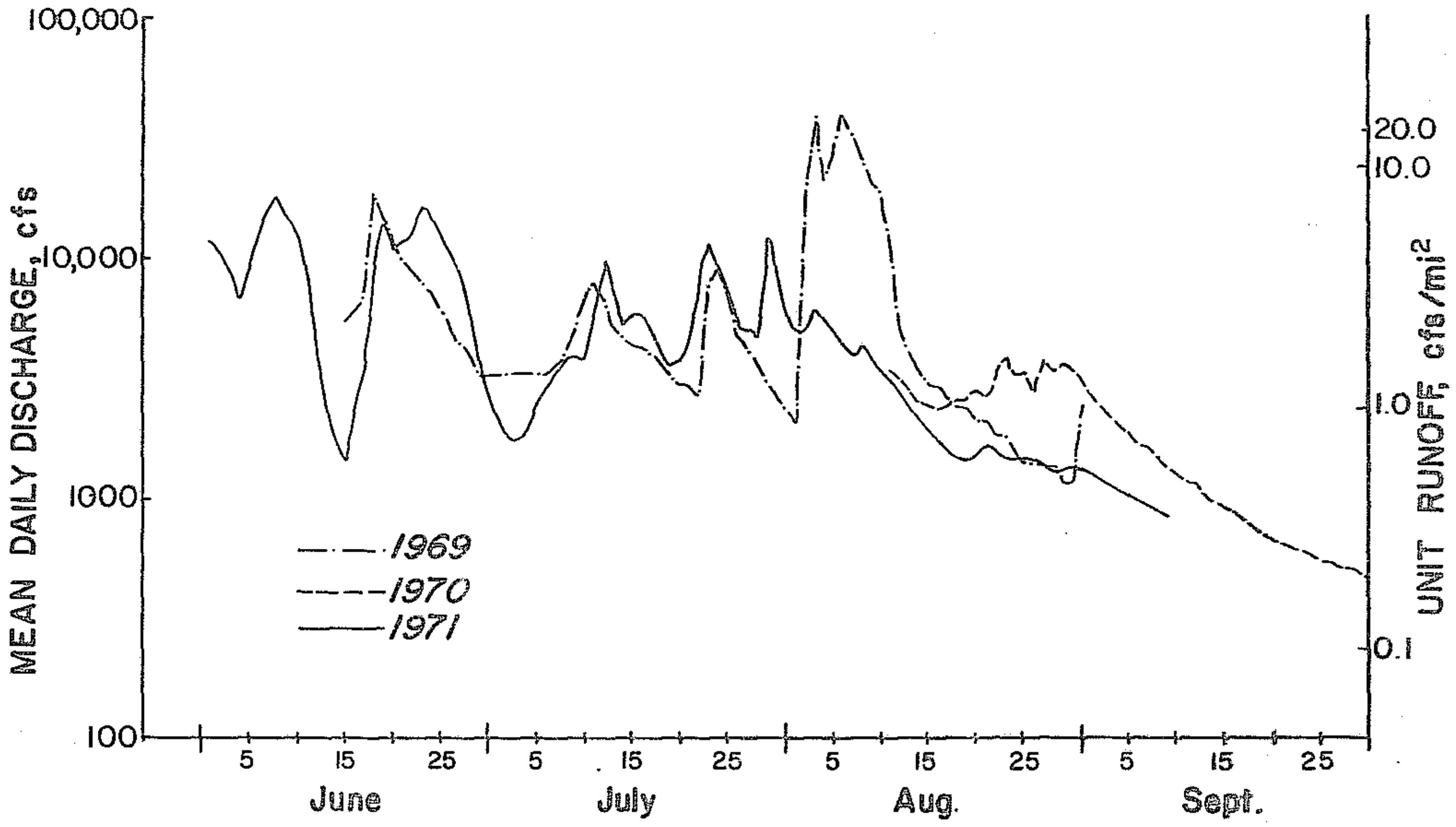

Figure 1.0 Hydrograph of mean daily discharge, Sagavanirktok River (Data source: U. S. Geological Survey).

Streamflow Analysis:

The primary tools used for predicting flood flows are the unit hydrograph, flood-routing, and flood frequency analysis. The success of these methods depends upon the length of record of runoff and precipitation. In the Arctic Slope area, these techniques are, of course, inhibited by short-term records. For example, to develop a unit hydrograph of runoff from an area, simultaneous measurements of runoff and rainfall for several years are needed. Since this data is not available, synthetic unit hydrographs can be developed using the procedure as outlined by Snyder (1938).

This technique is applied to the peak discharge in the Kuparuk and Sagavanirktok Rivers for an equivalent runoff of 1 inch over the entire basin. Snyder's method of synthetic unit hydrographs was based on relationships derived for basins of 10 to 10,000 mi^2 in the Appalachian Highlands. Various physiographic watershed characteristics are correlated with the lag time and peak discharge. The lag time t_l is defined as:

$$t_l = C_T \, (L \, L_{ea})^{0.3}$$

where

t_l = lag time from centroid of unit rainfall excess to peak of unit hydrograph, hour

C_T = coefficient for variation in slope and storage, 1.8 to 2.2

L = length of main stream channel, miles

L_{ea} = length of main stream channel to a point opposite watershed centroid, miles.

The duration of the unit hydrograph is a function of lag time

$$t_r = \frac{t_l}{5.5}$$

where

t_r = duration of unit rainfall excess, hour.

The equation for peak discharge can be written as:

$$Q_p = 640 \frac{C_p' A}{t_l}$$

where

Q_p = peak discharge, cfs

C_p = coefficient accounting for flood wave and storage conditions, 0.4 - 0.8

A = watershed size, mi^2.

The time base of the synthetic unit hydrographs was determined using the equation:

$$T = 3 + \frac{t_l}{8}$$

where

T = time base of synthetic unit graph, days.

Viessman *et al.* (1972) state that when a snow-pack accumulation produces the runoff, values of C_T will be reduced between one-third to one-sixth of the given values. Also, methods are available for determining the 50% and 75% values of peak flow. The results for the Sagavanirktok and Kuparuk are shown in Table 3.

Other Arctic Rivers:

Several other rivers in the Arctic, both in Alaska and Canada have been gaged for short periods of time. The U.S. Geological Survey collected runoff data on Neroukupkkonga Creek, located southwest of Barter Island at the outlet of Lake Schrader. This 123 mi^2 drainage was gaged from 23 June 1958 to 1 September 1958. The maximum daily runoff was 706 cfs and the minimum daily runoff was 193 cfs. The total runoff in inches for the months of July and August was 8.62 inches reflecting a much higher yield for basins located at higher elevations. Recently, Jones (1972) has reported on the discharge of three small streams near Barrow for the summer of 1972. The measured runoff, including snowmelt, for these basins was 1.63 (2.79 mi^2), 2.66 (1.46 mi^2) and 2.83 (3.52 mi^2) inches. Most of this runoff occurred during snowmelt.

The discharge of Canadian arctic streams is discussed in a number of papers, MacKay (1966, 1967), McCann and Cogley (1972), McCann *et al.* (1972), Clark and Peterson (1972), and Canadian National Committee, International Hydrological Decade (1969, 1972). Most of the runoff data is for the MacKenzie River. Comparisons of this river to the Putuligayuk, Kuparuk, and Sagavanirktok Rivers is difficult because the headwaters of the MacKenzie originate quite far south in British Columbia and Alberta. The work reported by McCann *et al.* (1972) was done on Cornwallis and Devon Islands. The Inland Waters Branch, Department of Environment, has collected some surface flow data on Baffin Island.

TABLE 3. DATA FROM SYNTHETIC HYDROGRAPH COMPUTATIONS

	Summer Precipitation		Snowmelt Runoff	
	Sagavanirktok	Kuparuk	Sagavanirktok	Kuparuk
A-mile^2	2,208	3,130	2,208	3,130
C_T	1.8	1.8	0.6	0.6
L-mile	82	178	82	178
L_{ca}-mile	49	92	49	92
t_l-hour	22	33	7.2	11.0
t_r-hour	3.8	6	---	---
C_p	0.8	0.8	0.4	0.4
Q_p-cfs	52,300	48,400	78,500	72,000
q_p cfs/inch/mile^2	23.7	15.5	35.6	23.3
T-days	5.8	7.1	3.9	4.4

A regional summary of surface water quality, sediment contents, and surface runoff is presented by Feulner *et al.* (1971) and the U.S. Geological Survey (1969). Arnborg *et al.* (1966, 1967) have published papers on the sediment and discharge of the Colville River.

One of the rapid and dramatic processes of the Arctic is the spring break-up. MacKay (1965, 1966, 1969) has studied the break-up of the MacKenzie River in Canada. In Alaska, Johnson and Kistner (1967) reported on the break-up of the Meade River east of Barrow. Several other papers have included data on the break-up: Arnborg *et al.* (1966), Brown *et al.* (1968), and Jones (1972).

EVAPORATION

The accurate determination of moisture transfer from land and plants back to the atmosphere has long eluded researchers. This is apparent when one examines the numerous methods that have been used to estimate evaporation: water budget, energy budget, mass transfer techniques, and pan evaporation data.

Mather and Thornthwaite (1958) measured and computed the evapotranspiration for several sites near Point Barrow. The calculated evapotranspiration was based on heat balance; while the measured values were obtained from evapotranspirometers. Table 4 gives calculated and measured values of evapotranspiration.

TABLE 4. EVAPOTRANSPIRATION AT POINT BARROW

	Computed from Heat Balance	Measured by Large Evapotranspirometers
July and August, 1957	10.2 cm	8.1 cm
July and August, 1958	5.2 cm	8.1 cm

These values were determined by taking 13 daily values for July and August as reported by Mather and Thornthwaite, dividing these values by the number of observations, and multiplying by the number of days in the months of July and August.

The Institute of Water Resources measured values of pan evaporation and decline in lake level at Prudhoe Bay for the summer of 1971 (Figure 11). The lake in which the measurements were made is located in Section 3, T11N, R14E (about 6 miles west of Prudhoe Bay) and the surface elevation of the lake is 29 feet msl. The maximum relief in the vicinity of the lake is approximately 60 feet. This lake had no observable surface channel inlets or outlets. Daily values of pan evaporation were initiated on June 24 and variations in lake level were measured after June 30. The evaporation pan was installed on June 8; two weeks passed before the next reading.

Values of accumulative pan evaporation and calculated lake evaporation for the months of July and August are 13.6 cm and 10.2 cm respectively. These values are greater than the values of evapotranspiration that were calculated and measured by Mather and Thornthwaite (1958). The ratio of the calculated lake surface evaporation to the pan evaporation is slightly greater than 0.85 for the two months of July and August. For Class "A" weather pans built of galvanized iron, it is generally reported that the actual evaporation from large bodies of water can be determined by multiplying the pan evaporation by a coefficient of 0.70 to 0.75. There appear to be two main reasons for the difference in pan coefficients. First, there seldom exist periods of calmness (Figure 12) and second, the mean daily water temperature of the evaporation pan was generally greater than the mean daily air temperature (Figure 13). The minimum average daily windspeed was 2.3 mph. The calculated lake evaporation was based on Kohler's equation as described by Gray (1970):

$$E_L = 0.70 \ [E_P = 0.00051 \ P \ \alpha P \ (0.37 + 0.0041 \ M) \ (T_o - T_a)^{0.88}]$$

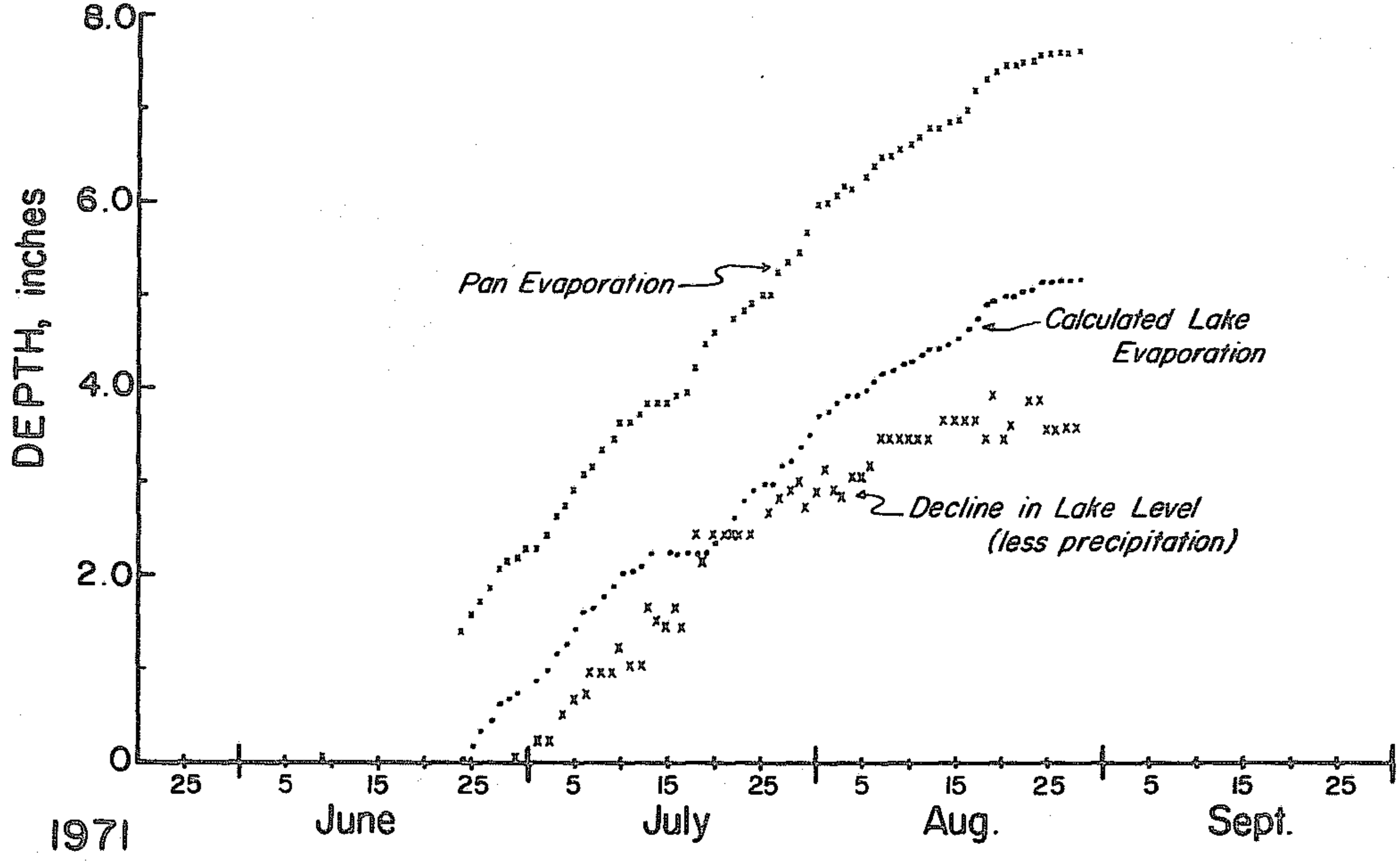

Figure 11 Calculated and measured rates of evaporation from a small lake near Prudhoe Bay.

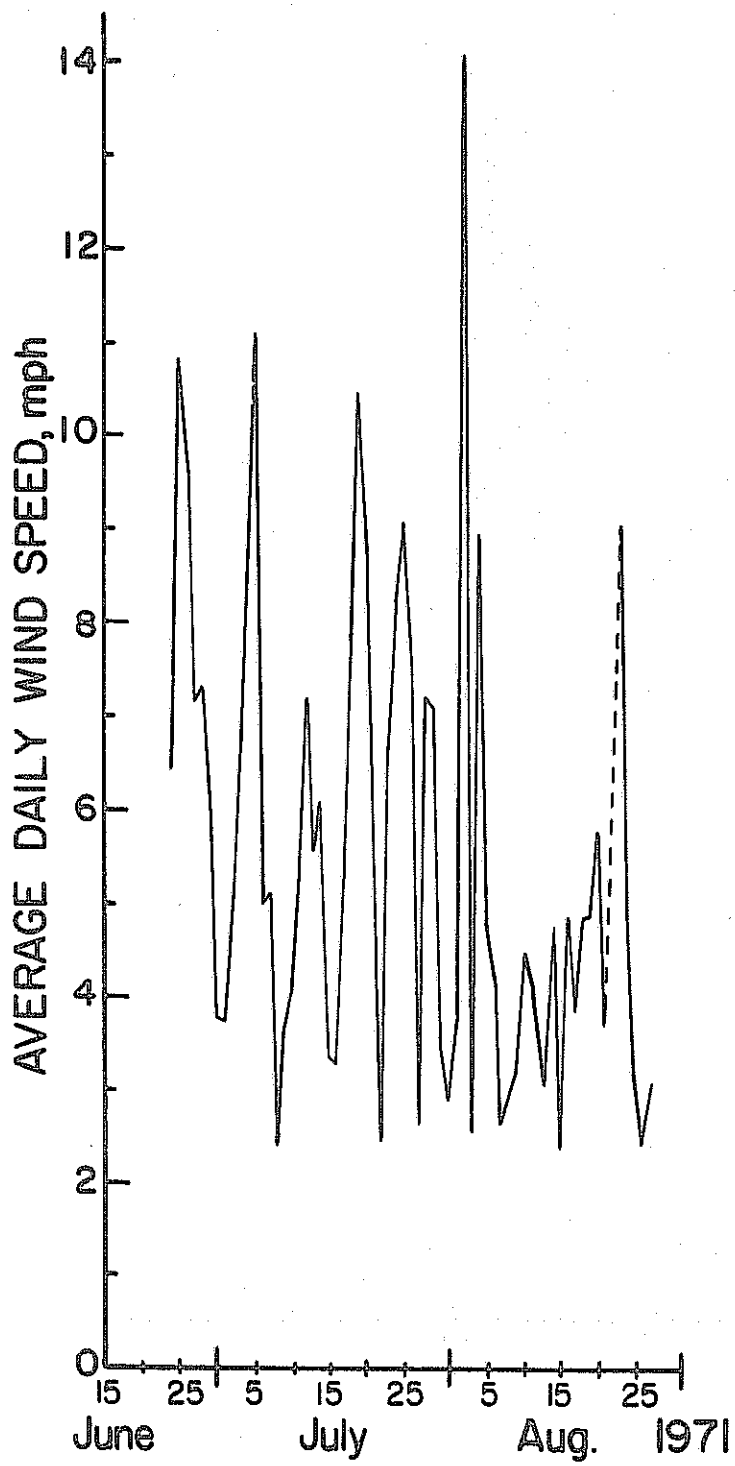

Figure 12 Average daily wind speed (miles/hour) near Prudhoe Bay.

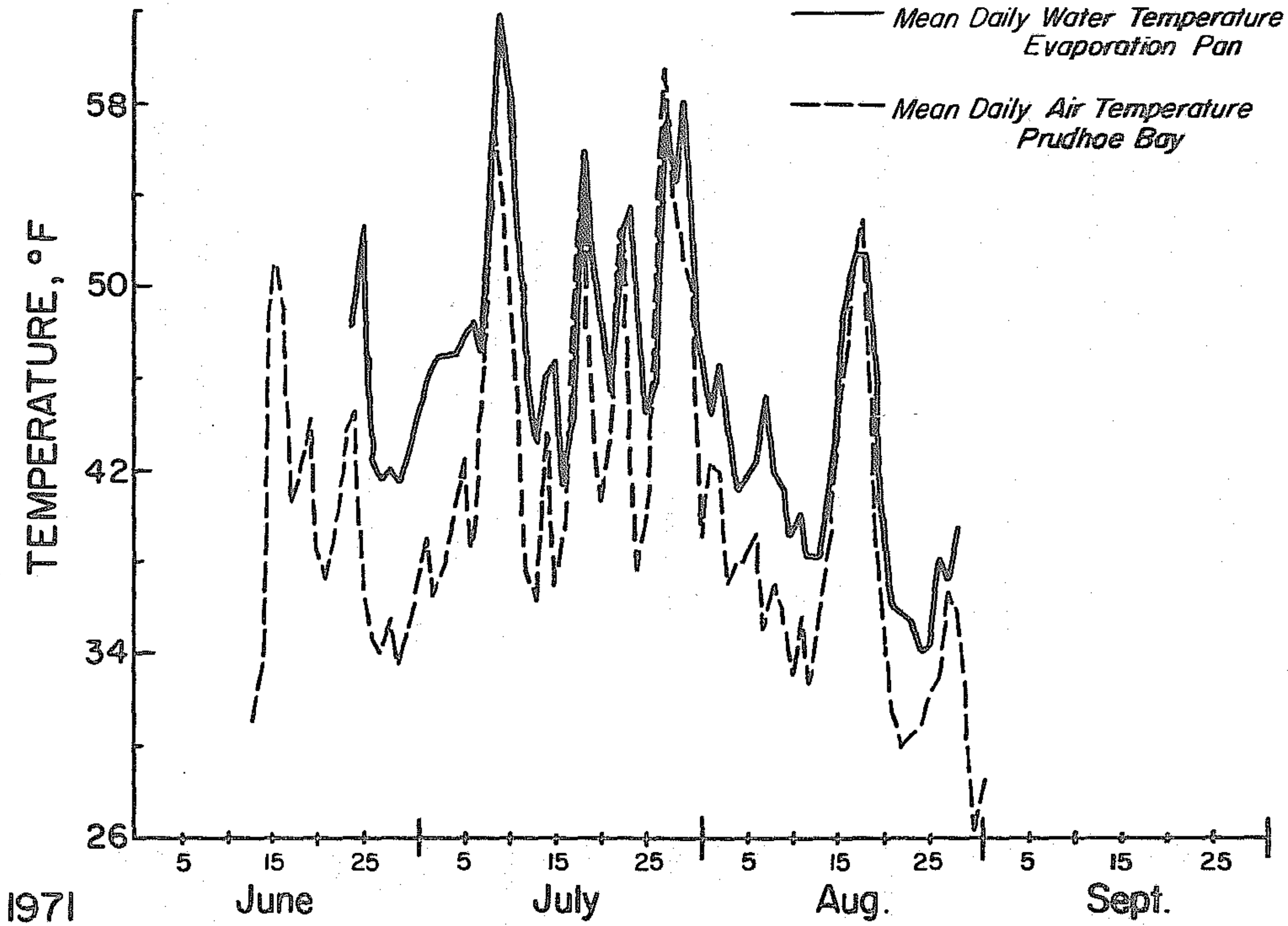

Figure 13 Comparison of mean daily water temperature in evaporation pan to mean daily air temperature near Prudhoe Bay.

E_L = Lake evaporation (inches/day)
E_P = Pan evaporation (inches/day)
P = Atmospheric pressure (inches of Hg.)
α_P = Proporation of Advected Energy utilized for pan evaporation
M = Wind speed (mpd)
T_o = Surface Water Temperature (°F)
T_a = Air Temperature (°F)

Water temperature and air temperature extremes were measured daily with max-min thermometers. Wind speed was measured by a mechanical contact anemometer which was read daily. A Class "A" evaporation pan, 4 feet in diameter, 10 inches deep was used to measure daily evaporation rates. The amount of advected energy was determined from the elevation, pan water temperature, and wind movement as outlined by Gray (1970).

Sublimation losses at Palmer, Alaska occurred during diurnal periods with both increasing temperatures and winds, while sublimation gains occurred during diurnal periods of decreasing temperatures with little or no wind. They estimated that the water equivalent sublimation loss was 3.12 cm for the 1968-1969 season. By extending the pan evaporation data of July and August, 1971, annual estimate for evaporation from water bodies is near 6.3 inches (16 cm).

Patric and Black (1968) have determined yearly potential evapotranspiration losses by Thornthwaite's classification. For most of the arctic coastal area, they report a value of 8 inches (20 cm). This value is very near the total loss by evaporation and sublimation estimated above.

A comparison of the lake level and the calculated lake evaporation is shown in Figure 11. Some of the scatter as shown in the lake level decline is caused by the inability to read the staff gage accurately due to wave conditions caused by the wind. In late August, the calculated lake evaporation and the measured water level decline begin to depart.

It is possible that some subsurface flow to the lake occurs at this time; the depth of the active layer is near its maximum. The average depth of the active layer around the lake was 18 inches on 28 August 1971. It appears that there was very little subsurface recharge to the lake in early summer; the main contributions to the lake are direct precipitation and overland flow during the snowmelt period.

Values of solar radiation during the summer of 1971 were collected for possible use in energy computations of evaporation. Although this data was not used in this paper, it is presented in Figure 14 for possible future use.

SUBSURFACE FLOW

The collection of basic data on subsurface flow north of the Brooks Range is limited. Hopkins *et al.* (1955) summarized knowledge of subsurface flow with the statement that:

> "Potable ground water in large quantities is known only in deep lakes and major perennial streams scattered throughout the Arctic Slope and in hot-spring areas in the Brooks Range."

Williams (1970) reported that wells drilled in the Umiat area on the Colville River penetrated brackish and saline groundwater aquifers at a depth of 1055 feet in the arctic foothills and 750 to 800 feet on the valley terraces. Generally, the permafrost distribution in this area is reported as continuous. Kane and Slaughter (1973) reported on the discontinuity of permafrost in the near vicinity of water bodies near Fairbanks. Johnston and Brown (1964) showed that a permafrost-free zone existed below a lake near the MacKenzie River delta at a depth of 230 feet. Brewer (1958) found that the depth to the permafrost table was 190 feet below the surface of a freshwater lake near Barrow.

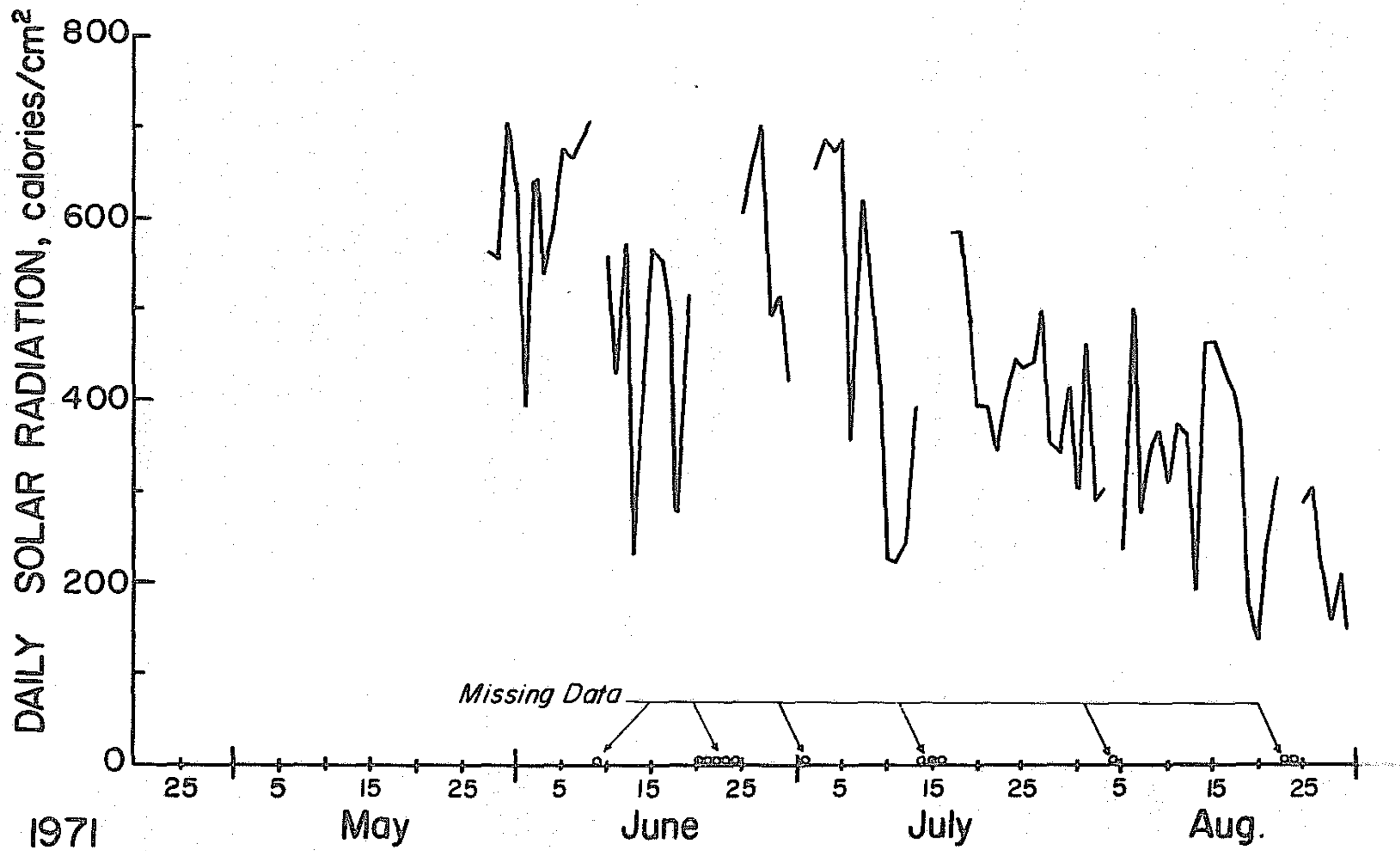

Figure 14 Daily solar radiation near Prudhoe Bay.

The above-cited work summarized the effort to understand subpermafrost groundwater flow in permafrost areas. Less work has been done to understand suprapermafrost groundwater systems. From visual observations, certain conclusions have been made about the presence of flow systems. Several surface drainage features indicate that subsurface flow exists. The best indication of groundwater discharge is the presence of springs. The U.S. Department of the Interior (1969) summarized many of the large springs located north of the Brooks Range. It is reported that most of these springs issue from faults in limestone. It is likely that smaller, less defined springs can be found in the same area. If areas of groundwater discharge occur, then there must also be areas of groundwater recharge. This would infer that permafrost-free areas exist in the mountanous and hilly regions in and adjacent to the Brooks Range.

Streamflow measurements on the larger rivers indicate that flow does exist throughout the winter. Open reaches on the rivers also indicate the movement of water. If such were not the case, an ice cover would form. The accumulation of aufeis deposits throughout the winter in the channel are another visual indication of subsurface flow. Kane *et al.* (1973) concluded that a small stream near Fairbanks derived the winter base flow from subpermafrost groundwater instead of bank storage. The volume of water in bank storage increased throughout the winter as the depth of aufeis increased.

It appears that subpermafrost groundwater discharging into the major rivers along the northern foothills of the Brooks Range sustains the winter flow in these rivers. Rivers that drain just the Arctic Coastal plain receive little, if any, groundwater discharge during the winter months. Therefore, they have little or no channel flow. Observation of the unit runoff curves indicates that the Putuligayuk River approaches zero flow in the fall months more rapidly than the Sagavanirktok and Kuparuk Rivers. It appears that the greater the drainage area in the

Brooks Range, the greater the base unit runoff. From the mean daily discharge curves, it can be seen that the Sagavanirktok River appears to have a slightly higher unit runoff than the Kuparuk River. An inspection of the area elevation curves will show that the Sagavanirktok River drainage is composed of a greater percentage of the Brooks Range and arctic foothills. It is in this same zone that most of the visible springs have been located.

Movement of soil moisture through the active layer and contributions of water to the surface drainages from the active layer would appear to be minimal. In early June, this zone is completely frozen. By late August, the maximum depth of thaw would be 3 feet or less. The depth of thaw is a function (in addition to climatic variables) mainly of vegetation type, soil moisture content, soil types, surface slope and slope aspect. From the study of lake evaporation which was reported earlier in the report, it would appear that there was no suprapermafrost groundwater contribution to the lake until possibly in August.

WATER BALANCE - PUTULIGAYUK RIVER BASIN

From the data collected for one summer, an attempt was made to quantify various components of the hydrologic cycle. The following equation was used to express the water balance for this arctic basin:

$$(P_r + P_s) - (E_L + ET = RO) = dSM + dL + dGW$$

where

P_r = Rainfall precipitation - inch

P_s = Snowfall precipitation, water equivalent - inch

E_L = Lake evaporation - inch

ET = Evapotranspiration - inch

RO = Surface runoff - inch

dSM = Change soil moisture storage - inch

dL = Change in lake storage, excluding evaporation - inch

dGW = Change in groundwater storage - inch

For an arctic basin, the two most important terms on the right side are soil moisture and lake storage. Where groundwater aquifers are present, they are quite shallow and found only along major drainages. Three terms on the left-hand side of the equation are measured directly: P_r, P_s, and *RO*. Estimates of lake evaporation (E_L) can be made from pan evaporation calculations. If changes in groundwater, soil moisture, and lake storage are minimal, an estimate of terrestrial evapotranspiration can be made.

The total snowfall accumulation for the winter of 1969 was measured using standard snow survey equipment. The water content of the snowpack in the Prudhoe area was determined to be 2.12 inches. The total rainfall measured during the summer with a standard 8-inch rain gage was 1.56 inches. The total precipitation for the 1969-1970 year was 3.68 inches. Runoff measurements by the U.S. Geological Survey for the Putuligayuk River indicated that the total volume of runoff leaving the basin amounted to 2.97 inches. Assuming that 21% of the area is covered with water, calculations indicate that evaporation from lakes would account for a loss of 1.08 inches. If it were assumed that there were no change in the storage components, the balance of the equation would indicate that there were a negative evapotranspiration of 0.37 inches. This approach indicates that there are possibly significant storage component changes that account for the negative evapotranspiration value. If it is assumed that subpermafrost groundwater plays a minor role, then a decrease in lake storage and soil moisture storage in the active layer could occur.

Several other possibilities exist. The accuracy of field measurements is always questionable. Field measurements of precipitation may be low. The water content of the snowpack was based on 50 measurements made on the northern part of the basin. There has been considerable debate on whether the summer precipitation is measured accurately due to the high winds. Those who believe that the wind has a minimal effect on measured precipitation indicate that greater deviation may be due to the number of trace precipitation occurrences.

TABLE 5. WATER BALANCE - PUTULIGAYUK BASIN (222 MI^2)

Freezeup 1969 - Freezeup 1970				
		Monthly values inches	Total inches	Balance inches
Water Equivalent - Snowfall (28 May 1970)			+ 2.12	+ 2.12
Rainfall:	June	.11		
	July	.93		
	August	.52		
			+ 1.56	+ 3.68
Runoff:	May	0		
	June	2.90		
	July	.05		
	August	.01		
			- 2.96	+ 0.72
Lake Evaporation:	June*	0.32 (2.19)		
	July*	0.53 (3.76)		
	August*	0.23 (1.63)		
			1.08	- 0.36

*Distributed over entire basin, assuming 21% of the basin covered with water (actual values shown in parenthesis).

CONCLUSIONS

The previous discussion has presented a summary of the available data and of the various components of the hydrologic system of Alaska's Arctic. In attempting to form a hypothesis of the characteristics of the arctic hydrologic system, a most severely limiting factor is availability of basic data, particularly climatic data and streamflow. Most work has tended to be short-term data collected for research purposes such as the IWR data reported here. Generally, the value of each short-term data is extremely limited. There is a great need for long-term data stations particularly with attention to distribution with elevation. As is true in much of Alaska, most data recorded in the Arctic is at sea level while most of the area is much higher.

Although basic hydrologic data is essential to most resource development activities, data efforts have been quite minimal. The present data plan is particularly incongruous in view of the rapidly accelerating resource extraction development in the Arctic which is of great importance to the nation and the world as a whole.

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APPENDIX

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