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# An analysis of streamflow hydrology in the Kuparuk River Basin, Arctic Alaska: a nested watershed approach

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**Abstract**

A hydrologic monitoring program was implemented in a nest of watersheds within the Kuparuk River basin in northern Alaska as part of an interdisciplinary effort to quantify the flux of mass and energy from a large arctic area. Described here are characteristics of annual hydrographs and individual storm hydrographs of four basins draining areas of 0.026 km$^2$, 2.2 km$^2$, 142 km$^2$, and 8140 km$^2$; an assessment of the influence that permafrost has on those characteristics; and comparisons to rivers in regions without permafrost. Snowmelt runoff dominated the annual runoff in each basin. A typical storm hydrograph in the Kuparuk River basin had a fast initial response time, long time lags between the hyetograph and hydrograph centroids, an extended recession, and a high runoff/precipitation ratio due to the diminished storage caused by permafrost. The seemingly contradictory results of fast response times and extended recessions can be explained by the presence of a large saturated area occupied by hillslope water tracks. This saturated area provides a partial-source area for fast runoff generation that bypasses the storage capacity of organic soils and tundra vegetation. 

*Keywords:* Alaska; Arctic; Permafrost; Runoff; Streamflow

## 1. Introduction

The shape of a hydrograph reflects how a drainage basin transforms precipitation into runoff and embodies the integrated influence of several basin characteristics including the geology, soils, drainage-basin morphology, and vegetation. Hence, the quantitative description of hydrographs is a valuable tool for understanding the mechanisms by which the drainage basin controls hydrology, and offers a tool for comparing hydrologic characteristics between different physiographic regions.

The ubiquitous presence of permafrost is a dominant physical characteristic of all arctic basins. Several studies have shown that permafrost has significant influences on streamflow characteristics (Church, 1974; Dingman, 1970, 1973; Kane et al., 1989; Newbury, 1974; Slaughter and Kane, 1979; Slaughter et al., 1983; Woo and Steer, 1982, 1983). However, the database for watersheds in regions with permafrost is still sparse. An interdisciplinary effort called the Land–Air–Ice Interaction (LAII) Flux Study was initiated in 1993 to estimate the flux of mass and energy between the land, atmosphere, and the Arctic Ocean in the Kuparuk River basin in Northern Alaska (Weller et al., 1995). River discharge is a major export mechanism of mass and energy out of any drainage basin. Thus, we implemented a nested watershed

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study to understand the nature and variability of river discharge. The analysis of simple hydrographs is a first step to meet this need.

A nested watershed study involves investigating a cascade of basins, thereby providing a framework for studying how the physics of hydrologic processes is related across scales. This study included four basins, each approximately a factor of 60 greater than the previous: a hillslope flow path called a water track (0.026 $km^2$) (see study area), Imnavait Creek (2.2 $km^2$), the Upper Kuparuk River (142 $km^2$), and entire Kuparuk River (8140 $km^2$). The objective of this paper is to describe the physical characteristics of streamflow hydrology at those four scales for the years 1993, 1994, and 1995 through the analysis of annual hydrographs, rainfall–runoff relationships, and nested basin interactions. An underlying theme is a comparison of streamflow characteristics in the permafrost-dominated Kuparuk River basin with those of rivers in temperate regions. We show that streamflow is dominated by two overwhelming features of arctic ecosystems: snow and permafrost.

This paper is organized as follows. Section 2 contains a physical description of the region including each basin in this study, and highlights some important characteristics that influence basin hydrology. Section 3 summarizes our field methods. Section 4 summarizes our findings on streamflow characteristics at the annual and individual storm scales, and on downstream trends. Section 4.4 presents a hypothesis of how a network of hillslope water tracks allows for seemingly contradictory storm hydrograph characteristics: fast initial response times and extended recessions. Section 5 presents some summary conclusions of this study.

## 2. Study area

The Kuparuk River originates in the northern foothills of the Brooks Range and flows northward across the Arctic Coastal Plain to the Arctic Ocean near Prudhoe Bay, AK (Fig. 1). The flow season typically begins in mid-May in the headwaters, and in late May to early June near the coast. Freeze-up begins in mid-September, but the rivers and streams may not be completely frozen until October. Although neighboring watersheds have active glaciers, there are no glaciers in the Kuparuk River basin. There is, however, a permanent aufeis field 30 km downstream from the Dalton Highway crossing covering approximately 6–12 $km^2$ that may have a local moderating effect on streamflow. A small spring exists in the headwaters of the basin, but its source is believed to be from precipitation percolating through local gravel deposits (Kreit et al., 1992).

The entire region lacks trees, is underlain by continuous permafrost, and is covered with snow for 7 to 9 months. Permafrost thickness ranges from around 250 m near the foothills to over 600 m near the coast (Osterkamp and Payne, 1981). Hence, the region is effectively isolated from deep groundwater. Subsurface flow occurs in a shallow active layer which increases in depth throughout the short summer. Soils typically thaw to maximum depths of 25–40 cm, but can thaw to 100 cm depending on several environmental factors including soil material and texture, soil moisture, slope, and aspect (Hinzman et al., 1991).

The smallest scale studied is a hillslope water track that drains 0.026 $km^2$ on a west facing slope in a headwater basin (Imnavait Creek) (Fig. 1). A water track is essentially a linear channel that flows directly down a slope draining an enhanced soil moisture zone, and is best detected by a change in vegetation from the surrounding hillslope (Hastings et al., 1989; Walker et al., 1989). The Imnavait Creek basin contains several water tracks that are generally spaced tens of meters apart, although their density varies (Walker et al., 1989). Only intermittently do incised channels exist in water tracks, but they are significant components of the hillslope hydrologic cycle. The water track ends in a peat-covered valley bottom through which water travels to Imnavait Creek as diffuse subsurface flow through the active layer, or as overland flow during extreme events.

Imnavait Creek, the second scale of study, is a small headwater stream occupying 2.2 $km^2$ in a north–northwest trending glacial valley which was formed during the Sagavanirktok glaciation (Middle Pleistocene) (Hamilton, 1986). The elevation of the basin ranges between 844 m and 960 m with an average of 904 m. The dominant vegetation in the Imnavait basin is tussock sedge tundra covering the hillslopes (Walker et al., 1989). An organic layer typically near 10 cm thick, but up to 50 cm thick in

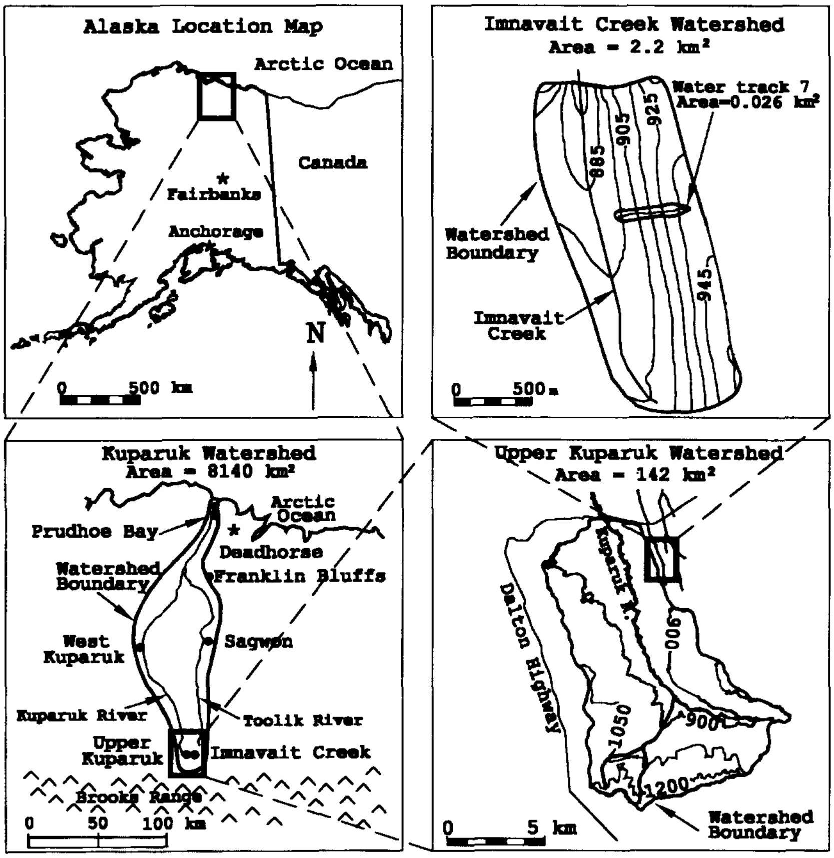


Fig. 1. Map showing the locations of the drainage basins in this study. The locations of meteorological stations are shown as dots on the map of the entire basin.

the valley bottom, overlies glacial till (Hinzman et al., 1991). The creek is essentially a chain of small ponds, called beads, that formed where the stream has eroded and melted massive ground-ice deposits. The stream bottom rarely cuts through to mineral soil but maintains itself in the organic layer. Imnavait Creek flows another 12 km beyond our gauging station and joins the Kuparuk River.

The third scale of study, called the Upper Kuparuk River basin, occupies 142 $km^2$ in the Kuparuk River headwaters. At the intersection with the Dalton highway, the Kuparuk River is a fourth order stream on a USGS 1:63360 map. However, the hillslopes and tributary valleys contain a complex network of water tracks, basins similar to Imnavait Creek, and rocky headwater streams that render the actual stream order difficult to estimate. Two streams join together at the base of steep hills near the headwaters forming the main channel, which occupies a north–northwest trending valley parallel to the Imnavait Creek basin. The main basin length is 16 km, with a channel length of 25 km. The elevation ranges between 698 m and 1464 m with an average of 967 m. Vegetation consists of alpine communities at higher elevations and moist tundra communities, predominantly tussock sedge tundra, at lower elevations. Dwarf willows and birches up to 1 m in height occupy portions of the banks and water tracks (Walker et al., 1989).

Beyond the Dalton Highway, the Kuparuk River flows through rolling foothills and eventually enters the flat coastal plain before it flows into the Arctic Ocean. The drainage area at the US Geological Survey gauging site is 8140 $km^2$, with a basin length of nearly 250 km. The average elevation of the entire

Kuparuk River basin is 245 m. The coastal plain was never glaciated, and is characterized by abundant, wind-oriented thaw lakes (Walker et al., 1989). The dominant export of water during the summer from small basins close to the coast is by evaporation, with little overland and channel flow due to the low gradients (Rovansek et al., 1996). However, several large drainage channels originate in the foothill regions that cross the coastal plain.

## 3. Methods

An annual field program began with snow surveys in late April each year to determine the total precipitation on the ground that fell as snow ($P_{sn}$) in each basin. $P_{sn}$ can be difficult to estimate, particularly over large areas, due to the high spatial variability of factors that control snow distribution such as slope, aspect, elevation, vegetation, and wind patterns (Woo and Marsh, 1978; Woo et al., 1983). $P_{sn}$ in the Imnavait Creek basin was estimated from approximately 90 snow-water equivalent (SWEQ) measurements with an Adirondack snow sampler in a 900 m transect across the basin. $P_{sn}$ in the water track basin was not measured. $P_{sn}$ in the two larger basins was estimated by traveling throughout the basins on snow machines and helicopters, and performing snow surveys in spots that were representative of landscape units, based on slope, aspect, elevation, and latitude. At least ten measurements of SWEQ and 20 snow-depth measurements were performed at each station, then weighted averages based on landscape units were calculated for each basin.

Streamflow was monitored at the water track, Imnavait Creek, and the Upper Kuparuk River from the onset of snowmelt in the spring to near freeze-up in the fall using stilling wells with Stevens F-1 water-level recorders mounted with variable resistance potentiometers to obtain digital data. Campbell Scientific CR10 data loggers recorded the stream stage every minute, and averaged over hourly increments. The US Geological Survey provided hourly stage readings and daily flow averages at the mouth of the Kuparuk River. Instantaneous discharge values were obtained at the water track by reading values calibrated to water level on the face of a small weir through which all flow was channeled. We performed velocity–area measurements in Imnavait Creek and the Upper Kuparuk River to obtain instantaneous discharge values. An H-type flume was used during snowmelt at Imnavait Creek to aid discharge measurements. Discharge measurements at all stations were made at several different stages to produce rating curves each year, from which continuous records of discharge were calculated. Several discharge measurements were taken daily during the spring snowmelt period until ice cleared from the channels and the stage–discharge relations became reliable. Six meteorological stations recorded precipitation, wind speed and direction, air temperature, relative humidity, and various radiation terms between the foothills and the coast. Fig. 1 shows the locations of the meteorological stations. Two stations close to each other in the foothills capture elevation gradients. The following analyses include the period between snowmelt and September 7th each year because that is the latest date for which consistent data are available for all three years.

## 4. Results and discussion

### 4.1. Annual hydrographs

Fig. 2(a)–2(l) show the 1993, 1994, and 1995 hydrographs respectively, for each basin. Hyetographs from a rain gauge located on the eastern ridgetop of the Imnavait Creek basin are included on the plots for this drainage. Table 1 summarizes the hydrologic inputs and outputs for each basin and year. The most significant conclusions reported in this section are that snow is a major component of the annual runoff at all scales and that the ratios of runoff to precipitation are high.

Snow is a significant hydrologic input. The ratio of the amount of precipitation which comes as snow before ablation ($P_{sn}$) to the total precipitation is $P_{sn}/P_t$ in Table 1, and it was approximately 33% in the upper basins and averaged 44% for the entire basin. Typically, snow depth and $P_{sn}$ decrease from the mountains to the ocean so that the upper basins have higher $P_{sn}$ than the entire basin. However, in 1993 the Upper Kuparuk River basin and the entire basin had approximately the same $P_{sn}$.

In each year, the summer precipitation ($P_s$) over the entire basin was approximately one half the summer

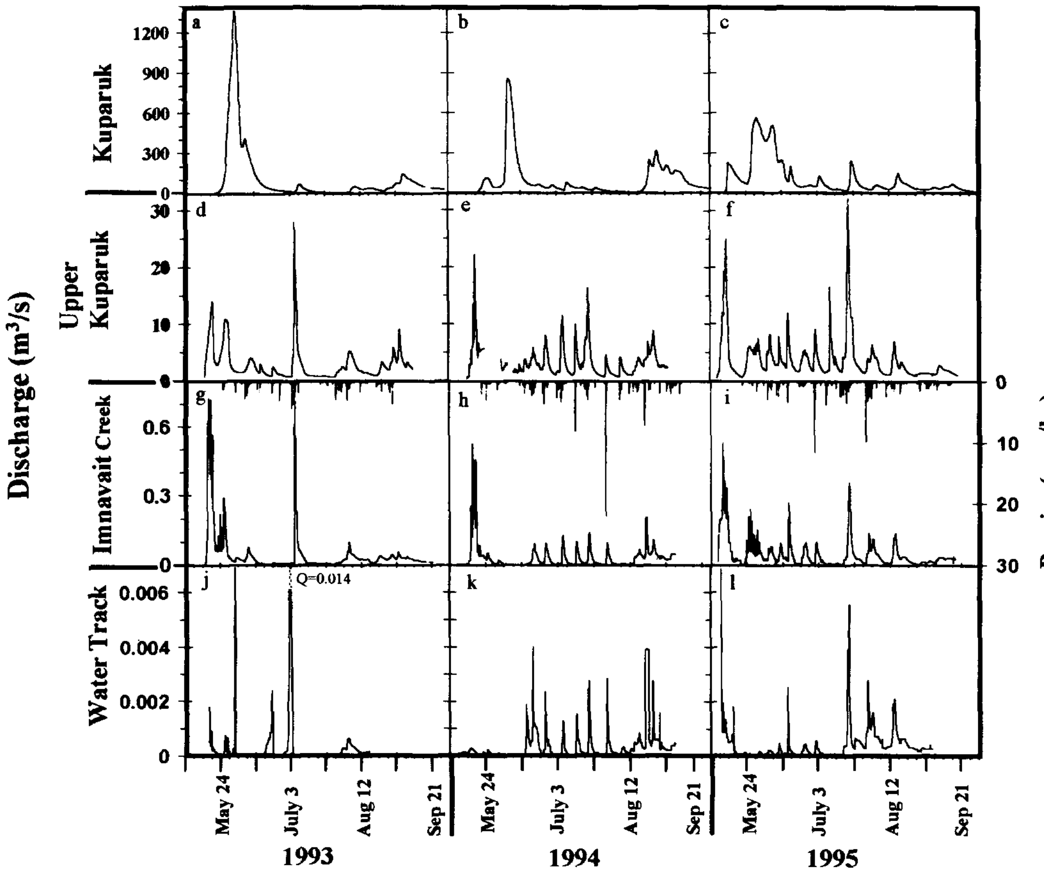


Fig. 2. Hydrographs for the entire Kuparuk River, the Upper Kuparuk River, Imnavait Creek, and the water track for the flow seasons of 1993, 1994, and 1995.

precipitation in the Upper Kuparuk River basin, where 'summer' is defined as the period of time between the onset of snowmelt and September 7th. Some snow may fall during this period, but most summer precipitation is rain. Table 2 summarizes the summer precipitation for each weather station. Nine-year averages at each station were obtained from previous studies in the Kuparuk Basin (National Snow and Ice Data Center, 1994). Basin average rainfalls were estimated by kriging the station data to a 1 km resolution then averaging the resultant points. The 1993 basin average precipitation was close to the nine-year average, and both 1994 and 1995 were considerably higher than average.

Snowmelt is typically a major runoff event in all arctic watersheds as precipitation that falls over approximately an eight month period is released as potential runoff usually within a period of two weeks or less. In Table 1, $R_{sn}/R_t$ is the fraction of annual runoff due to the snowmelt period. The snowmelt period contributed between 34% and 46% of the annual runoff in Imnavait Creek, 17–30%, and 52–80% in the Upper Kuparuk River and Kuparuk River, respectively. Occasionally, a large summer rainstorm reached peak flow rates that rivaled and sometimes exceeded the snowmelt peaks in the upper basins. However, the volume of snowmelt runoff was always considerably greater than that of any individual summer storm in each basin.

Runoff ratios were obtained by dividing runoff by precipitation for different periods: $R_t/P_t$, $R_{sn}/P_{sn}$, and $R_s/P_s$ for total runoff ratio, snowmelt runoff ratio, and summer runoff ratio, respectively. The snowmelt runoff ratios were considerably higher than the total

Table 1
Annual hydrograph characteristics in the Kuparuk River basin

| | | Water Track | | | | Imnavait Creek | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 1993 | 1994 | 1995 | ave. | 1993 | 1994 | 1995 | ave. |
| SWEQ | $P_{sn}$ (cm) | na | na | na | na | 12.5 | 8.0 | 14.2 | 11.6 |
| Summer Pcp. | $P_s$ (cm) | 20.8 | 27.1 | 20.9 | 22.9 | 20.8 | 27.1 | 20.9 | 22.9 |
| Total Pcp. | $P_t$ (cm) | na | na | na | na | 33.3 | 35.1 | 35.1 | 34.5 |
| $P_{sn}/P_t$ | | na | na | na | na | 0.38 | 0.23 | 0.41 | 0.34 |
| Snow runoff | $R_{sn}$ (cm) | 0.5 | 0.5 | 3.6 | 1.5 | 10.0 | 5.2 | 9.8 | 8.3 |
| Summer runoff | $R_s$ (cm) | 10.5 | 14.2 | 15.2 | 13.3 | 11.7 | 10.0 | 13.9 | 11.9 |
| Total runoff [a] | $R_t$ (cm) | 11.0 | 14.7 | 18.8 | 14.8 | 21.8 | 15.2 | 23.7 | 20.2 |
| $R_{sn}/R_t$ | | na | na | 0.19 | na | 0.46 | 0.34 | 0.41 | 0.41 |
| Max summer storm (cm) | | 5.2 | 2.6 | 3.5 | 3.8 | 3.3 | 0.9 | 2.0 | 2.1 |
| Runoff ratio | $R_t/P_t$ | na | na | na | na | 0.65 | 0.43 | 0.67 | 0.59 |
| Snow run. rat. | $R_{sn}/P_{sn}$ | na | na | na | na | 0.80 | 0.65 | 0.69 | 0.71 |
| Summer run. rat. | $R_s/P_s$ | 0.51 | 0.52 | 0.73 | 0.59 | 0.56 | 0.37 | 0.67 | 0.53 |
| | | Upper Kuparuk River | | | | Kuparuk River | | | |
| | | 1993 | 1994 | 1995 | ave. | 1993 | 1994 | 1995 | ave. |
| SWEQ | $P_{sn}$ (cm) | 13.2 | 10.6 | 15.0 | 12.9 | 13.5 | 7.4 | 13.9 | 11.6 |
| Summer Pcp. | $P_s$ (cm) | 22.4 | 27.8 | 27.4 | 25.9 | 11.0 | 15.1 | 13.9 | 13.3 |
| Total Pcp. | $P_t$ (cm) | 35.6 | 38.4 | 42.4 | 38.8 | 24.6 | 25.7 | 28.4 | 26.2 |
| $P_{sn}/P_t$ | | 0.37 | 0.28 | 0.35 | 0.33 | 0.55 | 0.29 | 0.49 | 0.44 |
| Snow runoff | $R_{sn}$ (cm) | 6.2 | 6.6 | 7.9 | 6.9 | 11.3 | 6.1 | 11.0 | 9.5 |
| Summer runoff | $R_s$ (cm) | 14.2 | 17.3 | 21.3 | 17.6 | 2.8 | 5.7 | 4.9 | 4.4 |
| Total runoff [a] | $R_t$ (cm) | 20.5 | 23.9 | 29.2 | 24.5 | 14.1 | 11.8 | 15.9 | 13.9 |
| $R_{sn}/R_t$ | | 0.30 | 0.28 | 0.17 | 0.25 | 0.80 | 0.52 | 0.69 | 0.67 |
| Max summer storm (cm) | | 3.5 | 2.7 | 5.3 | 3.8 | 2.4 | 5.4 | 1.1 | 2.9 |
| Runoff ratio | $R_t/P_t$ | 0.58 | 0.62 | 0.69 | 0.63 | 0.57 | 0.46 | 0.56 | 0.53 |
| Snow run. rat. | $R_{sn}/P_{sn}$ | 0.47 | 0.62 | 0.53 | 0.54 | 0.84 | 0.82 | 0.79 | 0.82 |
| Summer run. rat. | $R_s/P_s$ | 0.64 | 0.62 | 0.78 | 0.68 | 0.25 | 0.38 | 0.35 | 0.33 |

na, not available
[a] Includes flow between breakup and September 7.

runoff ratios and summer runoff ratios for the entire basin, which is consistent with the high $R_{sn}/R_t$ values. When the ground is completely frozen during snowmelt, runoff is essentially the only outlet for melting snow. However, precipitation that falls during the summer on the flat coastal regions largely get stored in ponds and surface depressions and eventually evaporates. The snowmelt period is the only time that significant runoff occurs from the coastal wetlands (Rovansek et al., 1996). Average total runoff ratios were above 0.5 for each basin. Using data taken from Baumgartner and Reichel (1975), we obtained a global runoff ratio of 0.36. The high runoff ratios in the Kuparuk River basin are consistent with other studies in permafrost-dominated basins (Woo et al., 1996), and are due to two factors. First, the subsurface storage capacity is limited by permafrost in the Kuparuk River basin and essentially no precipitation enters long term subsurface storage. Second, potential evapotranspiration is reduced at high latitudes due to cooler climates.

The ratio of snowfall to total annual precipitation ($P_{sn}/P_t$) was lower than the ratio of snowmelt runoff to total runoff ($R_{sn}/R_t$) in Imnavait Creek, with averages of 0.34 and 0.41 respectively. In the Upper Kuparuk basin, the $P_{sn}/P_t$ ratio was higher than the $R_{sn}/R_t$ ratio,

Table 2
Summer precipitation at each station (mm) in the Kuparuk River basin study

| Year | Prudhoe Bay | Franklin Bluffs | Sagwon Bluffs | West Kuparuk | Upper Kuparuk | Imnavait Creek | Basin average |
|---|---|---|---|---|---|---|---|
| 1993 | 59 | 72 | 71 | na | 225 | 208 | 110 |
| 1994 | 136 | 94 | 117 | 126 | 275 | 271 | 151 |
| 1995 | 79 | 82 | 147 | 122 | 274 | 209 | 140 |
| average | 91 | 83 | 112 | 124 | 258 | 229 | 134 |
| Nine year average | 61 | 82 | 106 | na | na | 183 | 109 |

with averages of 0.33 and 0.25 respectively. This was probably due to delayed snowmelt in the higher elevations of the foothills that did not get incorporated into the initial snowmelt runoff peak. In the entire Kuparuk basin, $P_{sn}/P_t$ was considerably lower than $R_{sn}/R_t$ with averages of 0.44 and 0.67, respectively. This could be a result of three possible contributing factors. First, rain events in the upstream regions contribute flow while snowmelt may be still occurring downstream. Hence, the snowmelt hydrograph at the mouth of the river may be a mixture of a spatial distribution of rain and snowmelt events. However, there was very little rain throughout the basin immediately after snowmelt in 1993 when 80% of the annual flow occurred during the snowmelt period. One small storm appeared in the falling limb of the entire Kuparuk River hydrograph in 1993 (Fig. 2(a)), but it was insignificant in the total volume of flow during the snowmelt period. Second, snow is transported by wind and redeposited into topographic depressions such as river channels and water tracks. Consequently, water that would have evaporated from

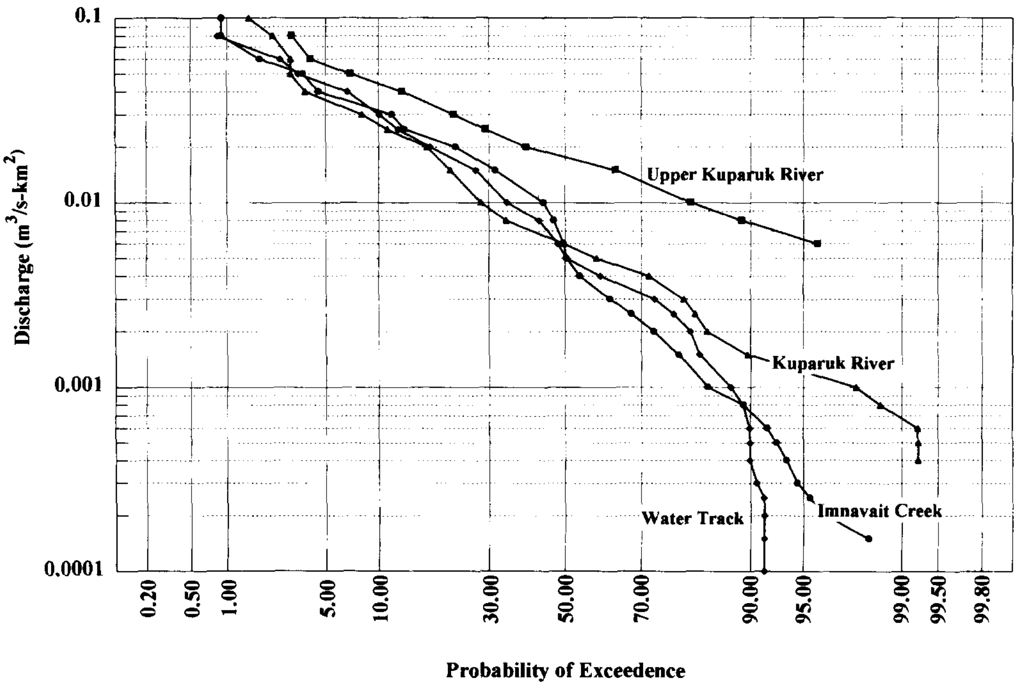


Fig. 3. Flow duration curves for each basin in 1994. Specific discharge (log scale) is plotted against probability of exceedence (normal probability axis).

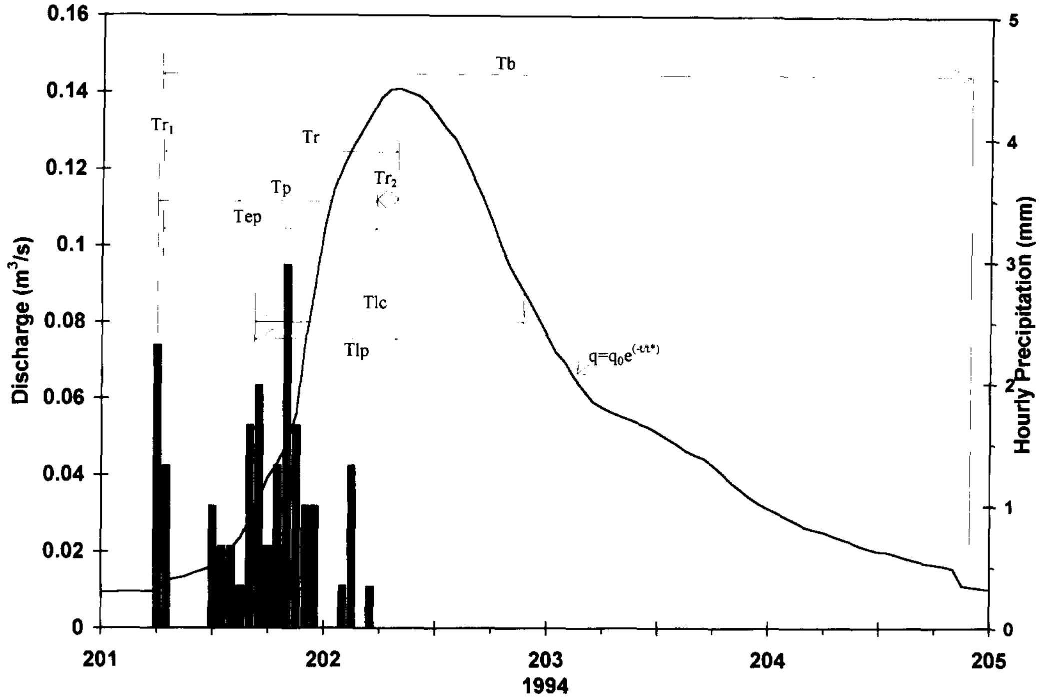


Fig. 4. A storm hydrograph and hyetograph from Imnavait Creek in mid-July, 1994 illustrating the variables used in Table 3.

flat regions is melted directly into the channel network and exported as runoff causing high $R_{sn}/P_{sn}$ values and subsequent high $R_{sn}/R_{t}$ values. Third, very little precipitation that falls on the low gradient coastal plain during the summer is exported as runoff; instead it is lost to evapotranspiration.

Flow duration curves for each basin in 1994 are shown in Fig. 3. The slope of a flow duration curve is an indication of the temporal variability of discharge. Steep curves result when the variability is high (Searcy, 1959). Flow duration curves for the water track, Imnavait Creek, and the Kuparuk River mouth have consistently steep slopes throughout most of the range of flows excluding the low flows, indicating that the variability is approximately the same across scales. At low flows the water track curve becomes more steep, the Imnavait Creek curve becomes more steep to a lesser extent, and the Kupurak River curve continues at approximately the same slope. Searcy (1959) states that steep slopes at low flows result from minimal basin storage. Thus, there is an increasing influence of baseflow with drainage area between the water track, Imnavait Creek, and the Kuparuk River. The flow duration curve for the Upper Kuparuk River possesses a less steep slope indicating lower temporal variability throughout the entire range of flows. This feature can be credited to a spring in the headwater basin that flows through the summer and contributes substantial baseflow to the river. Flow duration curves for 1993 and 1995 possess similar characteristics to those for 1994.

### 4.2. Storm hydrographs

Presented here are quantitative descriptions of hydrograph timing for Imnavait Creek and cross-scale comparisons on other hydrograph characteristics, including response factors, recession constants, and storm peak downstream travel times. The high spatial variability of precipitation in drainage areas greater than a few square kilometers prevents accurate rainfall–runoff timing analysis for the larger basins. Significant conclusions of this section are that streams respond rapidly to precipitation, have extended recessions, and high storm runoff/precipitation ratios. We attribute all of these features to the controls that permafrost exerts on runoff generation and channel network structure.

Table 3
Rainfall-runoff analysis for Imnavait Creek

| Storm date | $T_p$ (h) | $T_{ep}$ (h) | $P_{pk}$ (mm) | $P_t$ (mm) | $P_{abst}$ (mm) | $P_{5ant}$ (mm) | $I$ (mm h$^{-1}$) | $I_{max}$ (mm h$^{-1}$) | |
|---|---|---|---|---|---|---|---|---|---|
| Hyetograph | | | | | | | | | |
| 17/06/94 | 54.0 | 51.0 | 13.5 | 17.1 | 2.3 | 10.5 | 0.2 | 2.3 | |
| 24/06/94 | 37.0 | 42.0 | 16.1 | 19.7 | 0.0 | 8.2 | 0.4 | 3.6 | |
| 04/07/94 | 18.0 | 18.0 | 18.4 | 21.3 | 0.0 | 6.6 | 0.9 | 3.3 | |
| 12/07/94 | 10.0 | 9.0 | 21.7 | 21.7 | 0.3 | 0.7 | 2.0 | 8.2 | |
| 19/07/94 | 23.0 | 23.0 | 20.3 | 20.3 | 1.6 | 5.6 | 0.5 | 3.0 | |
| 29/07/94 | 7.0 | 6.0 | 34.8 | 36.0 | 1.6 | 0.3 | 4.3 | 22.0 | |
| 06/08/94 | 28.7 | 16.0 | 9.5 | 9.5 | 0.7 | 0.7 | 0.6 | 3.0 | |
| 10/06/95 | 19.9 | 19.0 | 5.3 | 7.2 | 0.5 | 5.5 | 0.3 | 1.7 | |
| 15/06/95 | 10.1 | 8.1 | 17.8 | 17.8 | 2.4 | 7.2 | 1.8 | 2.7 | |
| 01/07/95 | 16.1 | 10.1 | 15.7 | 18.0 | 6.5 | 3.6 | 0.9 | 3.1 | |
| 18/07/95 | 89.0 | 87.1 | 39.8 | 45.8 | 0.7 | 12.5 | 0.5 | 2.7 | |
| Average | 28.4 | 26.3 | 19.3 | 21.3 | 1.5 | 5.6 | 1.1 | 5.0 | |
| Storm date | $T_{r1}$ (h) | $T_{r2}$ (h) | $T_r$ (h) | $T_{lp}$ (h) | $T_{lc}$ (h) | $T_b$ (days) | $q_{ant}$ (m$^3$ s$^{-1}$ × 10$^3$) | $q_{pk}$ (m$^3$ s$^{-1}$ × 10$^3$) | $R$ (mm) |
| Hydrograph | | | | | | | | | |
| 17/06/94 | 3.0 | 2.0 | 53.0 | 14.0 | 24.8 | 4.0 | 6.6 | 92.3 | 6.1 |
| 24/06/94 | -5.0 | 1.0 | 43.0 | 24.4 | 41.6 | 4.1 | 4.5 | 94.2 | 5.8 |
| 04/07/94 | 0.0 | 3.0 | 21.0 | 13.6 | 34.2 | 5.4 | 3.1 | 121.7 | 6.3 |
| 12/07/94 | 1.01 | 2.0 | 21.0 | 17.0 | 33.3 | 4.3 | 1.8 | 100.7 | 5.5 |
| 19/07/94 | 0.0 | 1.0 | 24.0 | 11.6 | 25.0 | 2.9 | 9.5 | 95.0 | 6.8 |
| 29/07/94 | 1.0 | 10.0 | 16.0 | 12.1 | 35.1 | 7.0 | 1.4 | 9.5 | 5.3 |
| 06/08/94 | 12.7 | 15.2 | 31.2 | 25.8 | 49.3 | 3.8 | 1.5 | 5.6 | 0.5 |
| 10/06/95 | 1.0 | 7.0 | 26.0 | 22.8 | 20.8 | 1.5 | 14.0 | 96.8 | 3.8 |
| 15/06/95 | 2.0 | 3.9 | 12.0 | 9.1 | 22.8 | 3.3 | 16.4 | 219.2 | 10.8 |
| 01/07/95 | 6.0 | 4.9 | 15.0 | 11.8 | 51.7 | 8.6 | 5.6 | 99.3 | 6.1 |
| 18/07/95 | 2.0 | -1.1 | 86.0 | 33.8 | 44.6 | 3.2 | 22.0 | 351.8 | 21.1 |
| Average | 2.9 | 5.4 | 31.7 | 17.8 | 34.8 | 4.4 | | | |

$T_p$, Duration of precipitation; $q_0$, antecedent discharge; $T_{ep}$, duration of effective precipitation; $q_{pk}$, peak discharge; $P_{pk}$, precipitation prior to hydrograph peak; $R$, total runoff volume; $P_t$, total precipitation during storm; $P_{abst}$, precipitation prior to initial rise in hydrograph; $P_{5ant}$, precipitation during 5 days prior to storm; $I$, rainfall intensity averaged over storm; $I_{max}$, maximum hourly intensity; $T_{r1}$, time from first rainfall to first rise in hydrograph; $T_{r2}$, time from end of rainfall to hydrograph peak; $T_r$, duration of hydrograph rise; $T_{lp}$, time from hyetograph centroid to hydrograph peak; $T_{lc}$, time from hyetograph centroid to hydrograph centroid; $T_b$, time from initial rise to antecedent discharge.

### *4.2.1. Hydrograph timing*

Analysis was restricted to simple hydrographs in 1994 and 1995 with clearly defined precipitation pulses that caused the initial rises and had minimal precipitation during the recession; seven storms in 1994 and four storms in 1995 were selected. Table 3 summarizes the rainfall–runoff characteristics of those storms selected for analysis. Fig. 4 illustrates the variables in Table 3.

The duration of the precipitation that contributed to the rise in the hydrograph is labeled $T_{pk}$. The duration of effective precipitation, $T_{ep}$, is time between the initial rise in the hydrograph and the end of the contributing precipitation. One cannot actually identify the actual effective precipitation, but it is common to assume the duration of effective precipitation is the same as the duration of the total precipitation. The initial abstraction, $P_{abst}$, is the precipitation that fell prior to the initial rise in the hydrograph. The total precipitation that fell during $T_{pk}$ is labeled $P_{pk}$. Precipitation that did not last at least three continuous hours before the rise in the stream hydrograph was disregarded, as was minor precipitation that occurred during the falling limb of a storm hydrograph. Significant precipitation fell during the falling limbs of some storm hydrographs. This precipitation was

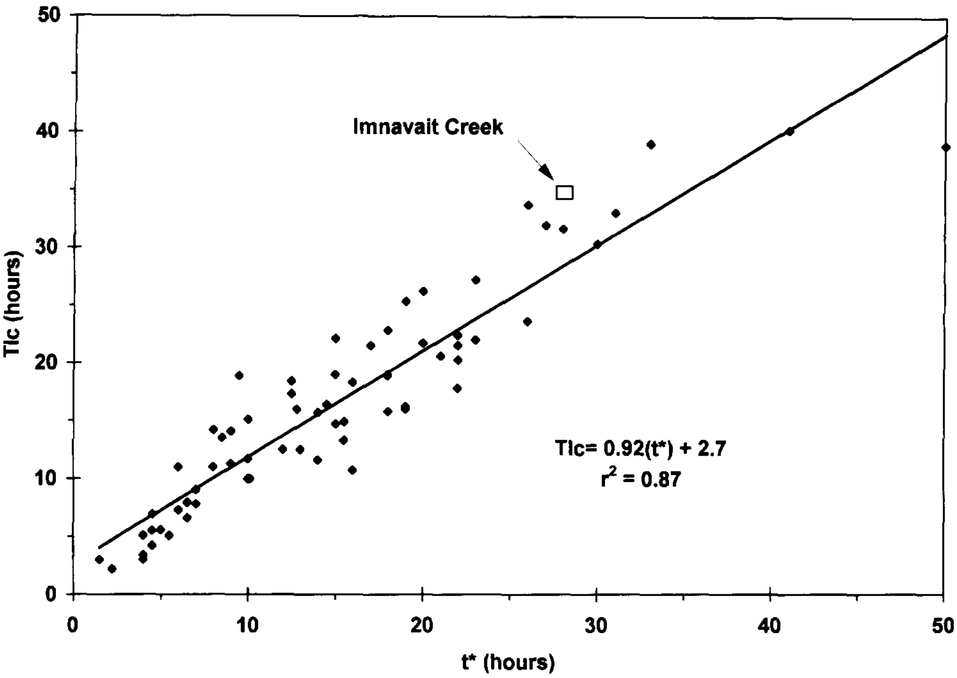


Fig. 5. Relationship between the centroid lag and the hydrograph recession ($t^*$) from a study of 40 streams in the conterminous US by Holtan and Overton (1963). The mean value for Imnavait Creek is shown as an open square.

included in $P_t$, the total precipitation that fell during the time base, $T_b$, of the hydrograph. These two precipitation variables were separated so that the initial response of the streams and the total runoff/precipitation ratios could be analyzed separately.

Initial abstractions were quite low, ranging between 0 and 6.50 mm with an average of 1.52 mm. In many watersheds, the initial abstraction depends on watershed wetness, with high soil moisture leading to low initial abstractions. However, no significant correlations existed at a 95% confidence level between the initial abstraction and various indices of watershed wetness, including the five day antecedent precipitation ($P_{5day}$) and the antecedent discharge ($q_{ant}$). The low initial abstractions and lack of correlation with watershed wetness were most probably results of the diminished subsurface storage capacity due to the presence of permafrost. Essentially, the watershed appears wet with very little precipitation. Kane et al. (1989) reported that an average of 15 mm of precipitation were required to initiate runoff in Imnavait Creek following dry antecedent conditions in surface organic soils. They found a similar value for storage in the active layer prior to ablation. Thus, surface storage in the organic soils and tundra vegetation can be significant, and the relations between hydrologic response and the indices of watershed wetness can be quite different between dry and wet periods.

The initial-response time in Imnavait Creek was fast, and ranged between 0 and 6 h with an average of 2.15 h. This is largely determined by the time required to fill the soil water deficit and depression storage (Dingman, 1994). Church (1974) compiled response times from permafrost basins and also concluded that rapid response times are characteristic of northern rivers. The rapid response can be credited to the network of water tracks that exist on the slopes (Kane et al., 1989). The water tracks remain saturated for much of the summer except during extreme dry times. Thus, the water tracks respond immediately to precipitation and a relatively constant saturated area exists to convey saturation overland flow to the creek. Dingman (1970, 1973) attributed the rapid response found in a basin with permafrost near Fairbanks, AK to moisture conditions in the valley bottom. Water tracks in the Kuparuk River basin are extensions of

Table 4

Response factors ($R/P$) and recession constants ($t^*$) for several storms in each basin. Storm date refers to the day of the initial rise in the hydrograph. Missing values occur because of complex hydrographs

| Water Track | | | Upper Kuparuk River | | |
|---|---|---|---|---|---|
| Storm date | $R/P$ | $t^*$ (h) | Storm date | $R/P$ | $t^*$ (h) |
| | | | 17/06/94 | | 61.44 |
| 24/06/94 | 0.47 | 29.28 | 25/06/94 | 0.38 | 136.56 |
| 04/07/94 | 0.29 | 17.04 | 04/07/94 | 0.37 | 76.08 |
| 12/07/94 | 0.36 | 25.92 | 12/07/94 | 0.33 | 63.84 |
| 18/07/94 | 0.49 | 23.76 | | | |
| 29/07/94 | 0.29 | 20.64 | 29/07/94 | 0.11 | 84.96 |
| 06/08/94 | 0.30 | 6.96 | 07/08/94 | 0.23 | 40.56 |
| | | | 11/06/95 | 0.36 | 42.00 |
| | | | 15/06/95 | 0.43 | 69.60 |
| | | | 01/07/95 | 0.20 | 95.04 |
| | | | 17/07/95 | 0.61 | |
| Average | 0.37 | 20.60 | Average | 0.33 | 74.45 |
| Imnavait Creek | | | Kuparuk River | | |
| 17/06/94 | 0.35 | 28.56 | 20/06/94 | | 213.60 |
| 24/06/94 | 0.29 | 25.68 | 28/06/94 | | 176.16 |
| 04/07/94 | 0.30 | 27.36 | 07/07/94 | | 159.36 |
| 12/07/94 | 0.25 | 24.72 | 18/07/94 | | 185.52 |
| 19/07/94 | 0.29 | 27.12 | 22/07/94 | | 202.32 |
| 29/07/94 | 0.15 | | | | |
| 06/08/94 | 0.05 | | | | |
| 10/06/95 | 0.53 | 32.16 | | | |
| 15/06/95 | 0.61 | 32.13 | 16/06/95 | | 95.04 |
| 01/07/95 | 0.34 | 44.16 | 02/07/95 | | 131.04 |
| 18/07/95 | 0.46 | | 20/07/95 | | 99.60 |
| | | | 02/08/95 | | 194.64 |
| | | | 12/08/95 | | 214.56 |
| Average | 0.33 | 30.24 | Average | | 167.18 |

the saturated valley bottom. Thus, the explanation presented above is similar to that proposed by Dingman (1970, 1973). The storm of June 25th 1994 had a negative initial response time, and the duration of effective precipitation ($T_{ep}$) was longer than the duration of precipitation ($T_p$). Both situations are impossible and are probably the result of the spatial variability of rainfall. These values were not included in the averages. The Imnavait Creek basin is small enough that precipitation is generally uniform over the basin. However, small convective storms can occur over portions of the basin remote from the precipitation gauge.

Recession began soon after the cessation of rainfall for all storms. $T_{r2}$ ranged between −1.08 and 115.2 h with an average of 5.36 h. The negative value was included in the average for $T_{r2}$ because during a storm of diminishing rainfall intensity it is possible for a hydrograph to peak before the end of the rainfall.

The lag to peak ($T_{lp}$) and the lag to centroid ($T_{lc}$) were surprisingly long, with averages of 17.8 and 34.8 h. Holtan and Overton (1963) reported an average $T_{lc}$ of 19.5 h in a study of 40 streams in the conterminous United States, ranging in drainage area between 76 km$^2$ and 4200 km$^2$. The drainage area of Imnavait Creek is over an order of magnitude smaller than the smallest basin in Holtan and Overton's study, yet the mean $T_{lc}$ was nearly twice as long. Dunne and Leopold (1978) summarized data from rural, temperate regions and produced much better correlations between both lag variables and drainage area. Imnavait Creek produced a mean $T_{lc}$ and $T_{lp}$ approximately

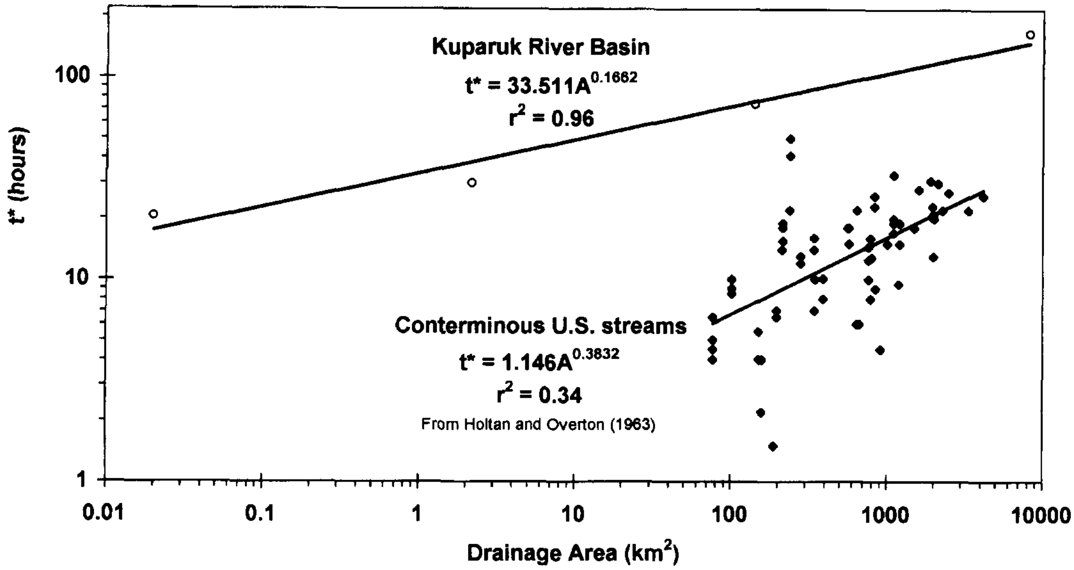


Fig. 6. Relation between the hydrograph recession ($t^*$) and drainage area for the Kuparuk River basin and for 40 streams studied by Holtan and Overton (1963).

twice as high as the values reported by Dunne and Leopold (1978) for its basin size. The Holtan and Overton (1963) data show a relationship between $T_{1c}$ and the recession constant of the falling limb of the hydrograph, $t^*$ (Fig. 5). Long recessions induce later hydrograph centroids, which create higher time lags. The relationship between mean $T_{1c}$ and mean $t^*$ from Imnavait Creek fits nicely on the trendline in Fig. 5. Thus, we would expect long hydrograph recession for Imnavait Creek.

*4.2.2. Recession analysis*

The falling limbs of storm hydrographs typically approximate exponential decays according to

$$q = q_0 e^{(-t/t^*)} \tag{1}$$

where $q$ is the streamflow rate $t$ hours after the beginning of the recession, $q_0$ is the streamflow rate at the beginning of recession, and $t^*$ is the recession constant (in hours). In this representation, $t^*$ is the time lapse between the occurrence of a given flow rate, $q_0$, and the occurrence of 1/e times that rate. To determine $t^*$, a correlation of $\ln(q)$ vs. $t$ was performed for points on the falling limb of each storm hydrograph; with the regression coefficient taken as $1/t^*$.

Recession constants are given in Table 4 for several storms in each basin. Fig. 6 shows that a positive log–linear relationship exists between the average recession constant in each basin and drainage area, and that relationship plots much higher than a similar relationship from the Holtan and Overton (1963) data discussed above. This indicates that, for similar drainage areas, the recession constants in the Kuparuk River basin are higher than those reported by Holtan and Overton (1963).

Other studies have also documented extended recessions in basins with permafrost. Dingman (1973) reported an average $t^*$ of 39 h for a 1.8 km$^2$ basin near Fairbanks, AK. Likes (1966) reported a $t^*$ of 35 h for a 98 km$^2$ basin in the Cape Thompson region of Alaska. Brown et al. (1968) reported recession constants up to 160 h for a small basin in Barrow, AK. Likes (1966)explained the high recession time as a result of infiltration of water into a highly absorptive surface layer and subsequent slow release. Dingman (1973) showed that recession constants decrease as evapotranspiration increases, and suggested that low evapotranspiration rates in arctic and sub-arctic regions are responsible for long hydrograph recessions. An alternative explanation may be that essentially zero precipitation goes into long-term storage in basins with permafrost, and a greater proportion of the input precipitation makes it to the stream during the response hydrograph. All event water is exported either as runoff or as evapotranspiration. Slaughter and Kane (1979) showed that basins with permafrost have higher peak flows and lower baseflows than basins without permafrost. Consequently, the falling limbs of hydrographs have greater distances to fall and the recessions are extended. In basins without permafrost, some precipitation infiltrates into the soil and enters into long term storage as groundwater. This water may ultimately reach the stream, but not during the storm from which it originated. This is essentially a difference in accounting. The entire recession is visible in hydrographs from basins with permafrost, while the tail end of recessions in basins without permafrost are masked by baseflow.

#### *4.2.3. Response factors*

Hewlett and Hibbert (1967) called the ratio of direct runoff to precipitation the response factor (*R*/*P*), where direct runoff is the total runoff minus the baseflow. Note that the response factors are different from the runoff ratios reported in Table 1, as those included total streamflow. Several graphical techniques exist to separate baseflow from direct runoff, none of which is more physically justifiable than the others. Hewlett and Hibbert (1967) projected a line from the initial hydrograph rise across to the falling limb at a slope of $0.000547\ m^3\ s^{-1}\ km^{-2}\ h^{-1}$ and called the volume of water above that line direct runoff. Baseflow is minimal in the Kuparuk River basin, and streamflows drop to very low levels between storms. The method of Hewlett and Hibbert (1967) overestimates baseflow contributions in regions with minimal baseflow. In such regions, it is reasonable to simply project a straight line across the hydrograph from the point of initial rise to the point where the discharge returns to its antecedent value. However, to avoid possible overestimation of direct runoff and to allow more favorable comparisons to the extensive data of Hewlett and Hibbert (1967) and Woodruff and Hewlett (1970), a method closer to theirs was used. A line was projected from the initial rise in the hydrograph to the point on the falling limb where a break in slope occurred on a semi-logarithmic plot (Linsley et al., 1982). The volume of water above that line is the direct runoff. The method is subjective, but most likely underestimates direct runoff and response factors.

The average response factors for all storms in the water track, Imnavait Creek, and the Upper Kuparuk River were 0.37, 0.33, and 0.33, respectively (Table 4). Dingman (1994) stated that response factors are often less than 0.10. Woodruff and Hewlett (1970) studied long term averages of response factors for basins in the southeastern US and reported values around 0.08, and Colonell and Higgins (1973) reported similar results for basins in New England. Hewlett and Hibbert (1967) found response factors ranging between 0.02 and 0.34, with an average of 0.10, in several small watersheds in the eastern US. Although the ranges overlap slightly, response factors in the Kuparuk River basin are clearly higher than those reported in the studies above. Newbury (1974) compared runoff ratios between permafrost and non-permafrost basins and also found that permafrost basins produce higher runoff ratios. Dingman (1973) reported an average value of 0.18 for the Glenn Creek basin near Fairbanks, AK. It is interesting to note that 60% of the Glenn Creek basin is underlain by permafrost, and the response factors are intermediate between those reported in the permafrost free temperate basins and the 100% permafrost Kuparuk basins. However, more case studies are required to document such a trend. Slaughter et al. (1983) compared three basins in interior Alaska with differing percentages of their areas underlain by permafrost, and showed that the basins with more permafrost generated higher flows per unit area, regardless of the moisture conditions of the basins.

The low response factors in temperate basins imply that large portions of precipitation do not enter the streams during the storm in which it falls, but presumably enter into long-term storage as groundwater (Dingman, 1994). This water may appear in the streams in later storms. In basins with permafrost such as the Kuparuk, higher portions of the storm precipitation reach the streams during the storm in which it falls due to the lack of storage. Hewlett and Hibbert (1967)determined that foremost among variables controlling response factors was soil-mantle depth, with shallow-soiled basins producing the highest response factors. Dingman (1970) found a positive correlation between response factors and antecedent discharge, an indicator of watershed wetness. Both watershed wetness and soil depth influence the storage capacity of a basin. Storage capacity

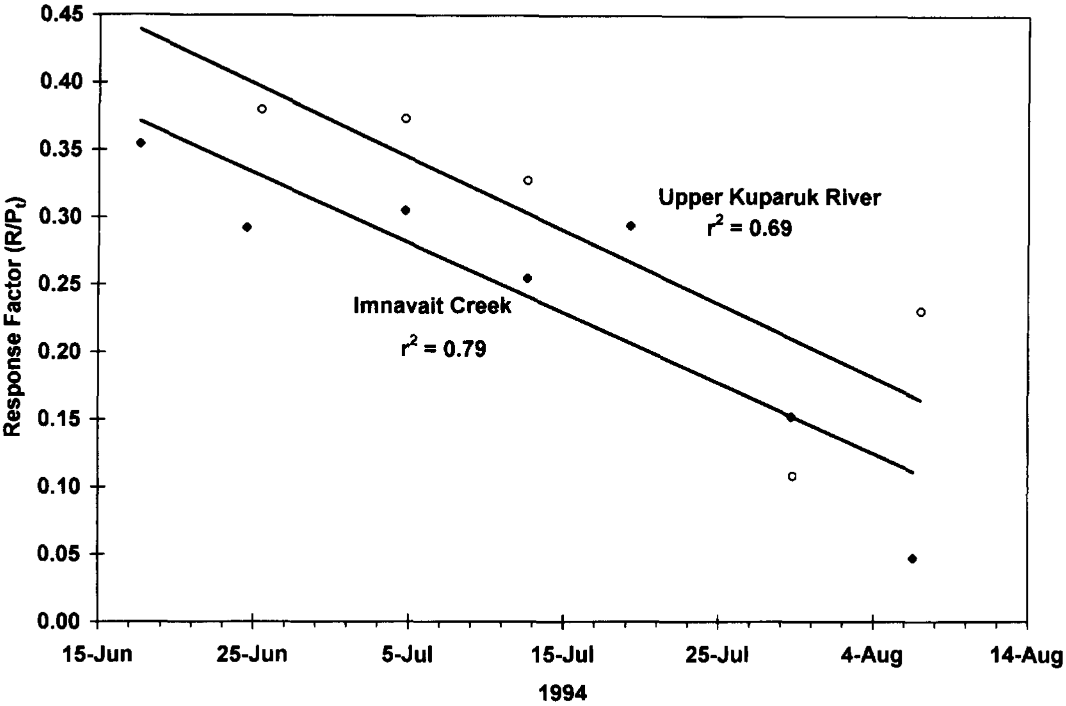


Fig. 7. The ratio of storm runoff to precipitation (*R*/*P*) decreased through the summer of 1994 for both Imnavait Creek and the Upper Kuparuk River.

controlled by soil depth dictates the spatial variability between basins, while storage capacity controlled by moisture dictates temporal variability within a basin.

Permafrost basins essentially mimic shallow-soiled, wet basins and produce high response factors due to their limited storage capacity. The variability of storage capacity in permafrost-dominated basins is subject to the same controls as in non-permafrost basins. However, in basins with permafrost the soil depth varies temporally as well as spatially. Whereas soil moisture is a stochastic variable dependent upon precipitation patterns, active layer depth is deterministic and directional, increasing as the ground thaws through the summer. Woo and Steer (1983) showed that thawing of the active layer has significant control on basin storage capacity, which in turn influences slope runoff processes. They showed that surface runoff decreased through the summer as a result of thawing of the active layer. It follows that in the absence of soil-moisture controls, increases in active layer thickness through the season may cause decreases in response factors.

Fig. 7 shows that response factors did have decreasing trends in Imnavait Creek and the Upper Kuparuk River in 1994. These trends were not observed in 1995; they may have been masked by soil-moisture conditions. Antecedent discharges ($q_{ant}$) for the storms analyzed in Imnavait Creek were typically greater for storms in 1995 than in 1994. However, it is difficult to isolate the influence of individual variables in such a dynamic system. Table 5 gives a correlation matrix of the potential influences on response factors at a 10% level of significance. Our analysis was restricted to one basin and one season so that storm date (a surrogate for active layer thickness) could be included as a variable. The sample size is small ($n$ = 7). However, the correlation matrix of these data at least provides a means to question potential relationships between controlling variables.

As suspected, $R/P$ was highly correlated to storm date and the indicators of antecedent moisture conditions ($q_{ant}$ and $P_{5ant}$.). However, $P_{5ant}$ was also highly correlated with storm date. Also, although the correlation between $q_{ant}$ and $R/P$ is low, the reader can

Table 5

Correlation matrix of potential controls on response factors ($R/P$) in Imnavait Creek, 1994. Correlations between +0.61 and -0.61 are not significant at the 5% significance level

| | $R/P$ | $q_0$ | $P_{5ant}$ | Date | $P_t$ | $I$ |
|---|---|---|---|---|---|---|
| $q_{ant}$ | 0.64 | | | | | |
| $P_{5ant}$ | 0.81 | 0.67 | | | | |
| Date | -0.89 | -0.42 | -0.88 | | | |
| $P_t$ | 0.39 | 0.49 | 0.79 | -0.63 | | |
| $I$ | -0.38 | -0.55 | -0.65 | 0.46 | -0.73 | |
| $I_{max}$ | -0.38 | -0.49 | -0.59 | 0.43 | -0.64 | 0.99 |

confirm from Table 3 that just one high value, due to an incomplete recession of the previous storm, disrupted an otherwise smooth decrease in $q_{ant}$ through the 1994 season. This suggests that storm date may not represent active layer depth, but may represent the seasonal soil-moisture pattern as dictated by precipitation. With only four storms to work with in 1995, it was difficult to decipher trends. Neither $R/P$ nor $q_{ant}$ in Imnavait Creek showed a seasonal decrease in 1995 while the active layer thickened as it always does. This suggests that the trends observed in 1994 were most likely caused by trends in antecedent moisture conditions as opposed to active layer dynamics. The seasonal influence of the thawing active layer on

Table 6

Basin interactions in the Kuparuk River drainage

| Storm date [a] | Water Track to Imnavait Creek (travel days) | Upper Kuparuk to Kuparuk Mouth (travel days) | PSCB [b] Water track to Imnavait Creek | PSCB Upper Kuparuk to Kuparuk Mouth |
|---|---|---|---|---|
| 17/06/94 | 0.75 | 3.46 | 3.28 | 4.93 |
| 25/06/94 | 0.33 | 3.46 | 1.42 | 5.86 |
| 04/07/94 | 0.42 | 2.33 | 1.01 | 7.12 |
| 12/07/94 | 0.29 | 3.71 | 1.34 | 6.75 |
| 17/07/94 | 0.13 | 4.13 | 1.42 | 14.52 |
| 29/07/94 | 0.13 | 5.50 | 1.91 | 19.13 |
| 07/08/94 | 0.50 | 6.29 | 4.62 | 21.13 |
| 17/08/94 | 0.08 | 6.33 | | |
| Mean | 0.33 | 4.40 | 2.14 | 11.35 |
| | | | | |
| 04/06/95 | | 2.92 | | |
| 11/06/95 | | 1.67 | | |
| 15/06/95 | 0.04 | 1.63 | 0.52 | |
| 22/06/95 | | 3.00 | | |
| 01/07/95 | 0.04 | 2.29 | 0.58 | |
| 08/07/95 | | 4.79 | | |
| 17/07/95 | 1.63 | 4.63 | 1.45 | 6.86 |
| 29/07/95 | | 4.75 | | |
| 12/08/95 | | 2.08 | | 2.15 |
| Mean | 0.57 | 3.08 | 0.85 | 4.51 |
| | | | | |
| Snowmelt runoff [c] | | | 0.21 | 3.09 |
| Summer runoff [c] | | | 1.32 | 6.96 |
| Total runoff [c] | | | 0.87 | 1.28 |

[a] Dates are associated with the beginning of the hydrograph rise in the Upper Kuparuk River.

[b] PSCB is the percent of the volume of the storm coming from the contributing basin.

[c] Average of 3 years.

response factors may exist, but is easily dominated by precipitation patterns. McNamara et al. (1997) suggested that early in the season the increases in active layer thickness greatly influence storm flow composition, but precipitation patterns become more significant as the summer progresses.

In summary, the streams initially respond to precipitation very quickly because there is a limited reservoir to store new water in the basin. Consequently, large proportions of precipitation reach the streams as runoff, as opposed to entering long-term subsurface storage, resulting in high response factors. Baseflows are typically low since there are minimal groundwater contributions. Consequently, the falling limbs must drop from relatively high peaks to low bases. This, in addition to the slow release of water from the organic soils and tundra vegetation, accounts for the extended recessions. The high recession constants produce long time lags between the centroids of hyetographs and the centroids of hydrographs.

### 4.3. Basin interactions

The portion of stormflow coming from a contributing basin (PSCB) is obtained by dividing the volume of a storm hydrograph from one basin by the volume of the same storm from the next downstream basin. PSCBs are reported in Table 6. The Upper Kuparuk River basin drains less than 1.7% of the total Kuparuk River basin area. That PCSBs between these two basins are considerably higher suggests the upper basin was more significant than the coastal regions in contributing storm-flow to the mouth of the river. This may have been the result of greater precipitation in the headwater regions, but may also have resulted from differences in topography and the potential to produce runoff (high gradients in the headwaters versus low gradients near the coast). Rovansek et al. (1996) studied an essentially flat coastal plain wetland near Prudhoe Bay and observed that negligible surface runoff occurs from summer storms. Similar storms in regions with more relief would potentially produce runoff. Consequently, after the snowmelt period, a large portion of the basin contributes little to streamflow, and the higher foothills regions contribute to basin-scale streamflow disproportionately to their drainage areas. This effect is enhanced through the thawing season. As the active layer increases in thickness, more low gradient slopes continue to lose the ability to produce runoff while the steepest headwater basins continue to produce runoff in increasing disproportion relative to their drainage areas. Indeed, in 1994 the PSCB between the Upper Kuparuk River and the mouth of the Kuparuk River increased through the season (Table 6). The same mechanism may be responsible for the increase in the storm peak travel time between the Upper Kuparuk River and the Kuparuk River mouth through the 1994 season (Table 6).

The three-year average snowmelt, summer and total contributions from the Upper Kuparuk River to the mouth of the river were 1.3%, 7.0% and 3.0% respectively (Table 6). That the snowmelt contribution was close to the ratio of drainage areas between the two basins suggests that the entire basin contributes runoff uniformly during snowmelt. The high summer contribution further documents that the foothills region contributes flow to the mouth of the river disproportionately relative to its drainage area during the summer.

The PSCB between Imnavait Creek and the Upper Kuparuk is not reported because Imnavait Creek flows in the Kuparuk River downstream from our Upper Kuparuk River gauge. The PSCB between the water track and Imnavait Creek averaged 2.1% in 1994 and 0.9% in 1995. The three-year average snowmelt, summer and total contributions from the water track to Imnavait Creek were 0.2%, 1.3% and 0.8%. The water track drains 0.9% of the Imnavait Creek basin.

### 4.4. Runoff, permafrost, and drainage basin structure

The above results raise an interesting problem: streams respond quickly to precipitation, but have extended recessions. If a basin responds quickly, why cannot it get rid of the water quickly after the storm? Explanations were given above to account for the extended recessions including highly absorptive surface layers, low evapotranspiration, and the absence of significant baseflow. The important question is why the storage effect that extends the recession is bypassed in the initial response. Consider the structure of drainage basin in light of this problem.

The hillslopes in the Upper Kuparuk River and Imnavait Creek basins contain numerous water tracks, which are linear zones of enhanced soil moisture with wetland soils and vegetation that drain directly downslope. The water track network and the valley-bottom wetlands provide a large saturated area from which rapid saturation overland flow can occur. Walker et al. (1996) showed that 56% of the Imnavait Creek basin is covered by some form of water track or valley bottom wetland. McNamara et al. (1997) separated storm hydrographs into source components and showed that all of the storm flow derived from new water can be accounted for by precipitation directly onto the water tracks and valley bottom wetlands. Thus, the saturated water track network provides a partial source area effect for rapid response. When runoff in the water tracks declines after a storm, surface storage in mosses, peat, or depressions on parts of the hillslopes without water tracks may continue to release water and produce an extended recession. This storage effect is bypassed in the initial response due to the saturated area of the water tracks.

McNamara (1997) suggested that water tracks may comprise a rudimentary channel network that was never allowed to fully develop due to the erosional resistance of permafrost soils. Geomorphologic analysis suggest that the heads of the water tracks are positioned on the hillslopes where current models of channel formation suggest that channels should occur, but they rarely contain incised channels. Further, as a network they do not possess aggregation patterns that are characteristic of mature channel networks (McNamara, 1997). Instead, they remain as direct downslope flow paths with no bifurcation, which is characteristic of immature channel networks. Numerous water tracks remain that may have converged if permafrost had not restricted erosion. Instead of forming fully incised channels, erosion was limited enough to allow wetland soils to develop in the water tracks, which creates the large saturated area for runoff production.

## 5. Summary and conclusions

The streamflow hydrology in the Kuparuk River basin is dominated by two features: snow and permafrost. Approximately one-third to one-half of the annual precipitation over the entire basin fell as snow, and approximately 70% of the annual runoff at the mouth was due to snowmelt. No summer storm in any year of the study approached the significance of snowmelt in the annual water budget at the mouth of the river. At the smaller scales there was at least one summer storm that had peak flow rates that rivaled or exceeded the snowmelt flood. However, the volume of snowmelt runoff was always greater than that of any individual summer storm in any basin.

A typical storm hydrograph in the Kuparuk River basin shows a fast initial response time, long time lags between the hyetograph and hydrograph, an extended recession, and a high runoff/precipitation ratio. We credit these characteristics to the presence of permafrost. A network of water tracks on the hillslopes provides a large saturated area which allows rapid response to precipitation. Much higher amounts of precipitation are forced into the streams than would occur in non-permafrost basins due to diminished subsurface storage capacity. Thus, the runoff/precipitation ratios (response factors) are high. The falling limbs of storm hydrographs must then drop from relatively high peaks to the typically low base flows that result from the lack of subsurface contributions. This, in addition to the slow release of water from the organic soils and tundra vegetation, accounts for the extended recessions. The extended recessions result in long lag times between the precipitation centroids and hydrograph peaks, and between the precipitation centroids and hydrograph centroids.

Thus, the apparent conflict between fast initial responses and extended recessions can be explained by the presence of a large saturated area occupied by hillslope water tracks. This saturated area provides a partial source area for fast runoff generation that bypasses the storage capacity of organic soils and tundra vegetation.

The hydrologic response in the Kuparuk River basin is adjusted to the presence of permafrost. This implies that changes in the permafrost may induce changes in the hydrologic response. On a seasonal time scale, this may occur as streamflow characteristics such as response factors and basin interactions change systematically through the season coincident with the thawing active layer. However, it is difficult to separate the influence of the active layer from the overriding precipitation patterns. On a longer time scale, the sensitivity of streamflow hydrology to the presence of permafrost has strong implications that arctic ecosystems may experience significant changes in a changing global climate. At any time scale, the relationship between permafrost and hydrologic response may have resounding ecological impacts on processes such as the timing and magnitude of the delivery of nutrients to the aquatic system.

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## References

Baumgartner, A., Reichel, E. (1975) The World Water Balance. Elsevier Scientific Publishing Company, New York, NY.

Brown, J., Dingman, S.L., Lewellen, R.J. (1968) Hydrology of a drainage basin on the Alaskan Coastal Plain. U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH, Research Report 240.

Church, M. (1974) Hydrology and permafrost with reference to northern North America. Proc. Workshop Seminar on Permafrost Hydrology, Can. Nat. Comm., IHD, Ottawa, pp. 7–20.

Colonell, J.M., Higgins, G.R., 1973. Hydrologic response of Massachusetts watersheds, Water Resources Bulletin, 9, 793–800.

Dingman, S.L. (1970) Hydrology of the Glenn Creek watershed, Tanana River basin, central Alaska. Research Report 297, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Dingman, S.L. (1973) Effects of permafrost on stream characteristics in the discontinuous permafrost zone of central Alaska. In Permafrost: North American Contribution to the Second International Conference. Washington, DC: National Academy of Sciences, 447–453.

Dingman, S.L. (1994) Physical Hydrology. Macmillan Publishing Company, New York.

Dunne, T., Leopold, L.B. (1978) Water in Environmental Planning. W. H. Freeman and Company, San Francisco, CA.

Hamilton, T.D. (1986) Late Cenezoic glaciation of the Central Brooks Range. In: T.D. Hamilton, K.M. Reed, and R. M. Thorson (Editors), Glaciation in Alaska: the Geologic Record. Alaska Geological Society, pp. 9–49.

Hastings, S.J., Luchessa, S.A., Oechel, W.C., Tenhunen, J.D., 1989. Standing biomass and production in water drainages of the foothills of the Phillip Smith Mountains, Holarctic Ecology, 12 (3), 304–311.

Hewlett, J.D., Hibbert, A.R. (1967) Factors affecting the response of small watershed to precipitation in humid areas. International Symposium of Forest Hydrology, pp. 275–290, Permagon, Oxford.

Hinzman, L.D., Kane, D.L., Gieck, R.E., Everett, K.R., 1991. Hydrologic and thermal properties of the active layer in the Alaskan Arctic, Cold Regions Science. and Technology, 19, 95–110.

Holtan, H.N., Overton, D.E., 1963. Analyses and application of simple hydrographs, Journal of Hydrology, 2, 309–323.

Kane, D.L., Hinzman, L.D., Everett, K.R., Benson, C.S., 1989. Hydrology of Imnavait Creek, an arctic watershed, Holarctic Ecology, 12, 262–269.

Kreit, K., Peterson, B.J., Corliss, T.L., 1992. Water and sediment export of the upper Kuparuk River drainage of the North Slope of Alaska, Hydrobiologica, 240, 71–81.

Likes, E.H. (1966) Surface-water discharge of Ogoturuk Creek. Environment of the Cape Thompson Region, Alaska. US Atomic Energy Commission, Oak Ridge, TN, pp. 125–131.

Linsley, R.K. Kohler, M.A., Paulhus, J.L.H. (1982) Hydrology for Engineers. McGraw-Hill, New York.

McNamara, J.P. (1997) A nested watershed study in the Kuparuk River basin, Arctic Alaska: Streamflow, scaling and drainage basin structure. Ph.D. dissertation, University of Alaska Fairbanks, Fairbanks, AK.

McNamara, J.P., Kane, D.L., Hinzman, L.D., 1997. Hydrograph separations in an Arctic watershed using mixing model and graphical techniques, Water Resources Research, 33 (70), 1707–1720.

National Snow and Ice Data Center (1994) ARCSS/LAII Data Series Volume 1: Alaska North Slope Data Sampler.

Newbury, R.W. (1974) River hydrology in permafrost areas. Proc. Workshop Seminar on Permafrost Hydrology, Can. Nat. Comm., IHD, Ottawa, Ont., pp. 31–37.

Osterkamp, T.E., Payne, M.W., 1981. Estimates of permafrost thickness from well logs in northern Alaska, Cold Reg. Sci. and Technol., 5 (1), 13–27.

Rovansek, R.J., Hinzman, L.D., Kane, D.L., 1996. Hydrology of a tundra wetland complex on the Alaskan Arctic Coastal Plain, Arctic and Alpine Research., 28 (3), 311–317.

Searcy, J.K., (1959) Flow duration curves — Manual of hydrology, Part 2. Low flow techniques. U.S.G.S Water Supply Paper 1542-A.

Slaughter, C.W., Hilgert, J.W., Culp, E.H. (1983) Summer streamflow and sediment yield from discontinuous-permafrost headwaters catchments. Proc. Fourth International Conference on Permafrost, Fairbanks, Alaska, pp. 1172–1177.

Slaughter, C.W., Kane, D.L. (1979) Hydrologic role of shallow organic soils in cold climate. Proc. Canadian Hydrology Symposium: 79 Cold Climate Hydrology, Vancouver, B.C., pp. 380–389.

Walker, D.A., Auerbach, N.A., Lestak, L.R., Mueller, S.V., Walker, M.D. (1996) A hierarchic GIS for studies of process, pattern, and scale in an arctic ecosystem: The Arctic System Science Flux Study, Kuparuk Basin, Alaska. Presented at the 2nd circumpolar arctic vegetation mapping workshop, Arendal, Norway, May 20-23, 1996.

Walker, M.D., Walker, D.A., Everett, K.R. (1989) Wetland Soils and Vegetation, Arctic Foothills, Alaska. US Department of the Interior Biological Report 89(7).

Weller, G., Chapin, F.S., Everett, K.R., Hobbie, J.E., Kane, D., Oechel, W.C., Ping, C.L., Reeburgh, W.S., Walker, D., Walsh, J., 1995. The Arctic Flux Study: a regional view of trace gas release, Journal of Biogeography, 22, 365–374.

Woo, M.K., Heron, R., Marsh, P., Steer, P., 1983. Comparison of weather station snowfall with winter snow accumulation in High Arctic basin, Atmosphere-Ocean, 21, 312–325.

Woo, M.K., Marsh, P., 1978. Analysis of error in the determination of snow storage for small High Arctic basins, J. Applied Met., 17, 1537–1541.

Woo, M.K., Steer, P., 1982. Occurrence of surface flow on arctic slopes, southwestern Cornwallis Island, Canadian Journal of Earth Sciences, 19 (12), 2368–2377.

Woo, M.K., Steer, P., 1983. Slope hydrology as influenced by thawing of the active layer, Resolute, N.W.T. Canadian Journal of Earth Sciences, 20 (6), 978–986.

Woo, M.K., Yang, Z., Xia, Z., Yang, D., 1996. Streamflow processes in an alpine permafrost catchment, Tianshan, China, Permafrost and Periglacial Processes, 5, 71–85.

Woodruff, J.F., Hewlett, J.D., 1970. Predicting and mapping the average hydrologic response for the eastern United States, Water Resources Research, 6, 1312–1326.