Hydrometeorological Relationships in a Glacierized Catchment in the Canadian High Arctic

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ABSTRACT

Runoff from a small glacierized catchment in the Canadian high Arctic was monitored throughout one melt season. The stream discharge record is one aspect of a larger project involving glacier mass balance, superimposed ice formation, and local climate on a glacier in the Sawtooth Range, Ellesmere Island, Northwest Territories, Canada.

In order to better understand the main factors influencing the production of runoff on the glacier during the period of main summer melt, regression analyses are performed relating daily air temperature, shortwave incoming and net radiation, absorptivity and wind speed to daily glacier discharge. Air temperature at the glacier meteorological station on rain-free days is the element with the greatest correlation with runoff (r^2=0.57; n=34). A multiple regression of discharge with air temperature, shortwave incoming radiation, net radiation hours and wind speed, achieved the best fit (r^2=0.84; n=34). Rain events (>10 mm day^{-1}) can dominate daily discharge when they occur during the period of ice melt, creating more runoff per unit area than can be produced due to melt alone, and significantly reduce the accuracy of runoff predictions.

Key words: Arctic glaciers, glacial runoff, hydrometeorologic correlations.

INTRODUCTION

Glacierized catchments comprise the majority of watersheds in mountainous Arctic regions, and due to the enhancement of streamflow by glacier ice melt, supply the bulk of runoff to the Arctic Ocean and surrounding waters. However, very few records of runoff from Arctic glacierized basins exist and the relationships between meteorological elements and runoff on Arctic glaciers are not well understood. Studies by Adams (1966) on Axel Heiberg and Wendler et al. (1972) in northern Alaska, obtained partial stream discharge records in proglacial basins for two consecutive seasons. Studies in the late 1960s in the Decade and the Lewis glacier basins, both on Baffin Island, also obtained records of runoff from glacierized watersheds (Østrem et al. 1967; Church 1972). These studies included traditional glacier mass balance measurements (Østrem and Brugman 1991) and some correlations were made between discharge and meteorological elements. Although several annual discharge records exist from Ellesmere Island catchments without glaciers (Ambler 1974; Woo 1976; Lewkowicz and Wolfe 1994), and from proglacial catchments without glacier measurements (Cogley and McCann 1976), this study presents the first complete discharge record from a Canadian high Arctic glacier basin with simultaneous glacier measurements of ablation and climate, covering the entire length of the melt season. This paper will examine the discharge record of Quviagivaa Creek, discuss the hydrological processes acting in the basin throughout the melt season, and will investigate statistical relationships between runoff and several meteorological variables for the main period of glacier melt (June 29-August 3, 1993). This preliminary study is presented as a first step in the eventual construction of a more comprehensive physically-based hydrometeorological model, which will be applied to high Arctic glacierized catchments.

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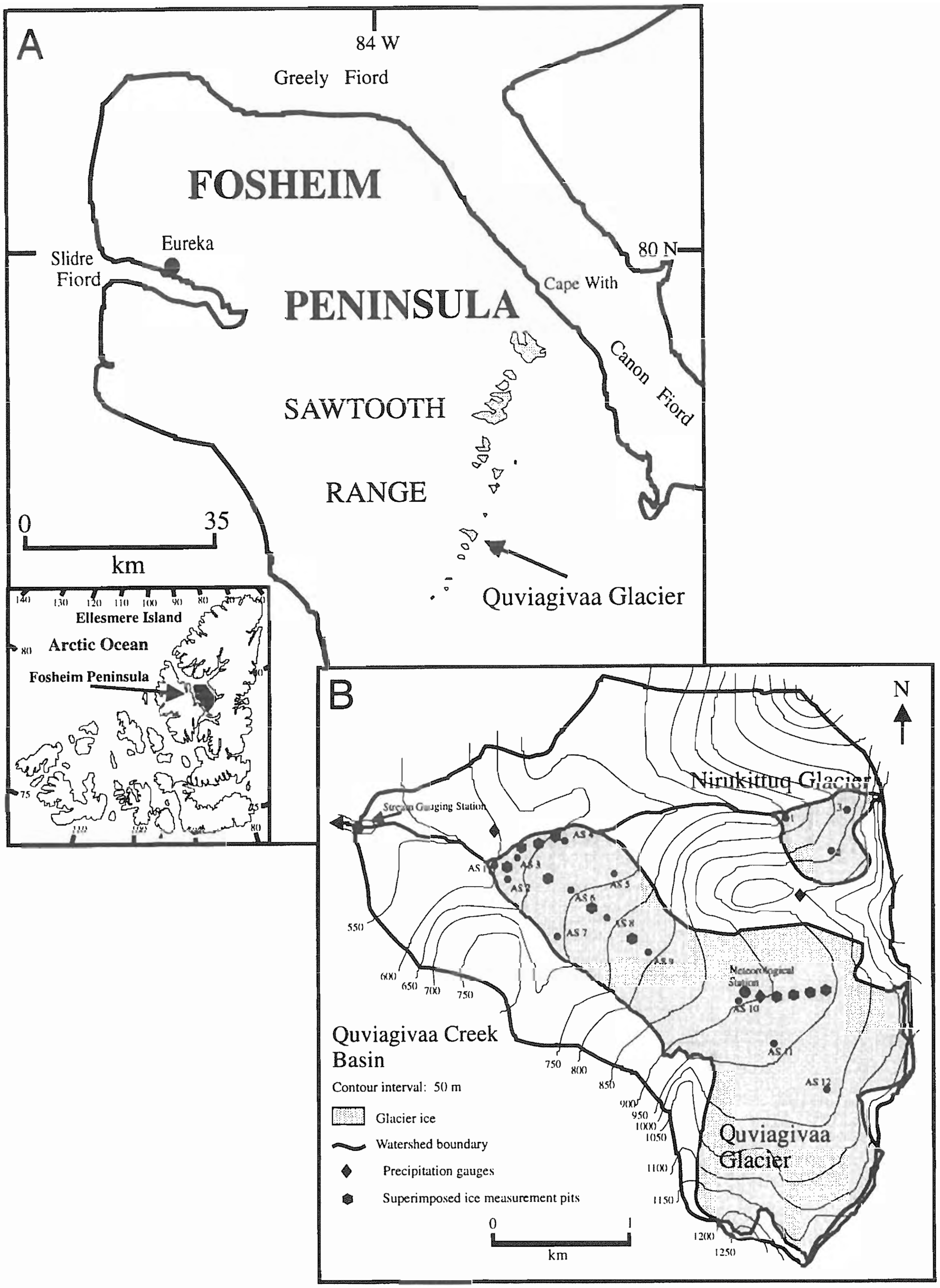

Figure 1. A: Location map of the Fosheim Peninsula, Ellesmere Island. B: Topographic map of the Quviagivaa Creek basin, showing Nirukittuq and Quviagivaa glaciers and locations of measurement sites.

STUDY AREA AND METHODS

An 8.7 km^2 glacierized catchment in the central Sawtooth Range, Fosheim Peninsula, Ellesmere Island (79° 33.98' N, 83° 20.48' W) was selected for study. The basin contains two small glaciers: "Quviagivaa" (4.7 km^2) and "Nirukittuq" (0.4 km^2), and is 59% glacierized (Fig. 1).

Prior to melt, a gauging station was set up in Quviagivaa Creek (the only outlet from the basin), approximately 900 m downstream from the glacier portal. In a stilling well, stage was recorded using a potentiometer connected to a float and a counterweight. From June 17 to July 21 a Campbell Scientific CR21 datalogger recorded the stage every 30 minutes. Because the datalogger malfunctioned on July 21, a battery-operated Stevens Type F water level recorder was used until the flow became too low to measure on August 8. Standard stream gauging techniques were used to measure stream discharge. High flows on July 21 due to a rain event resulted in the aggradation of the streambed, necessitating two separate stage-discharge curves: one for the period of June 14 to July 21 (A), and one for the period of July 22 to August 10 (B) (A: r^2=0.98, n=15; B: r^2=0.99, n=13). The main melt period was delineated from the hydrograph as the period in which daily average discharge values were above 0.5 $m^3 s^{-1}$ and in which strong diurnal variations in stream discharge were evident. Daily discharge values were taken as the sum of hourly values from trough to trough on the hydrograph. This method accounts for the lag (<1 day) for most melt in the catchment to travel through the glacier system to the gauging station.

Meteorological data were collected at a station on the glacier at 875 m a.s.l. (Fig. 1). Instruments were mounted on masts supported by guy wires and were connected to a Campbell Scientific CR21X datalogger housed in a water-tight box. Hourly values of air temperature, wind speed and direction, incoming shortwave radiation (0.4-1.1 μm), and net radiation (0.25-60 μm) were recorded. Albedo measurements were made at each of 12 ablation stations every other day using a portable solarimeter, mounted on a 75 cm long wooden rod, from which voltage was read using a multimeter. Precipitation was measured with Atmospheric Environment Service standard rain gauges at four sites within the basin: the camp meteorological station (550 m); the glacier terminus (590 m); the glacier meteorological station (875 m); and a ridge top between the two glaciers (1000 m).

RESULTS

General observations of discharge

The complete annual runoff record from the 8.7 km^2 Quviagivaa Creek drainage basin, and average daily meteorological elements for the same time period, are shown in Figure 2. Using the characteristics of the hydrograph and taking into account the procession of melt in the glacier catchment, the discharge record can be separated into three periods: early melt, main melt, and recession (Jensen and Lang 1972). This paper will deal only with the main melt period, which is the only period in which the bulk of runoff was glacier-derived.

The main melt period was characterized by strong diurnal fluctuations in discharge, daily peaks ranging between 0.5 and 3.0 $m^3 s^{-1}$. This period, lasting from June 29-August 3, comprised 94% of all flow measured in 1993. Synchronous discharge measurements at the glacier terminus and at the gauging station at the beginning of the main melt period (June 29), revealed that approximately 50% of flow was derived from snowmelt on the non-glacierized slopes downslope from the glacier. Late on 29 June a large slush flow (Fig. 3) occurred on the lower snout of the glacier. This flow made a pathway for flow from the northern glacier ice margin to Quviagivaa Creek and moved a large mass of saturated snow off the glacier. From June 29 onwards the high temperatures and radiation values caused rapid melting. On July 5 a large slush pool that had been forming near the glacier meteorological station burst, creating numerous slush flows (Fig. 4), and opening flow pathways from the upper portions of the glacier. Comparisons of discharge measurements made at the glacier terminus and gauging station on July 9 showed that the percentage of total flow derived from snowmelt on the non-glacierized slopes downslope from the glacier terminus had been reduced to 10%. Consistently warm temperatures in early July meant that by the middle of July surfaces with no ice in the basin were predominantly snow-free. The seasonal peak discharge of 3.0 $m^3 s^{-1}$ on July 21 occurred during a prolonged rainy period in which up to 40 mm of rain fell on the largely snow-free glacier. Reduced discharge due to low air temperatures, solar radiation and wind speed persisted for a week after July 21, but was followed by high melt rates and discharge values from July 30-August 1 (see Fig. 2). By the beginning of August the drainage network extended over the entire glacier, some supraglacial channels reaching depths of 2 m. Temperatures dropped below 0°C on August 3 and ended melting in the catchment.

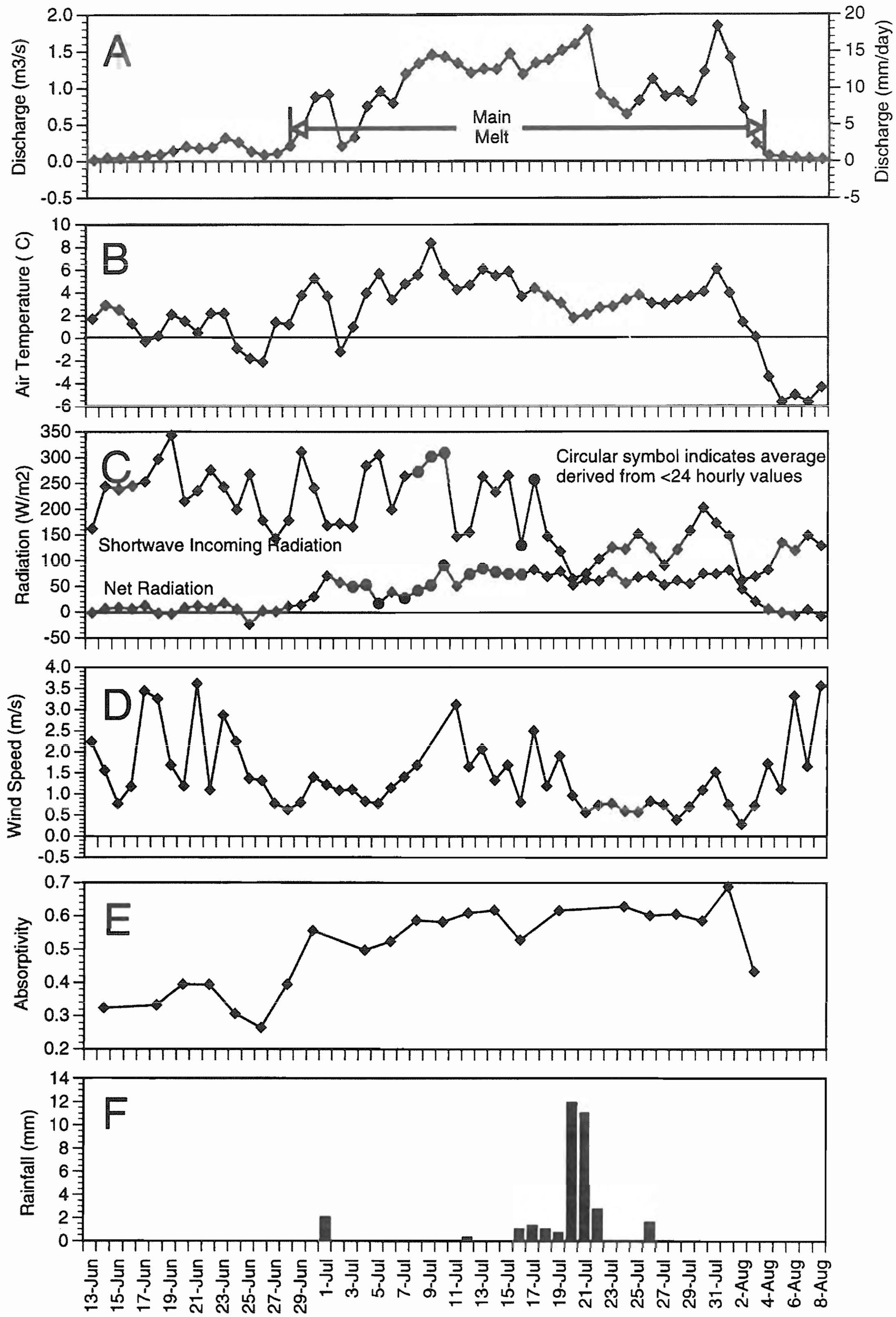

Figure 2. Plots of discharge and meteorological elements for the period of streamflow. A: Average daily discharge expressed in m^3/s and mm day^{-1}. B: Average daily air temperature. C: Average daily incoming shortwave radiation and net radiation. D: Average daily wind speed. E: Average glacier absorptivity. F: Daily rainfall.

Figure 3. Remnants of a large slush flow at the terminus of Quviagivaa Glacier, June 30, 1993.

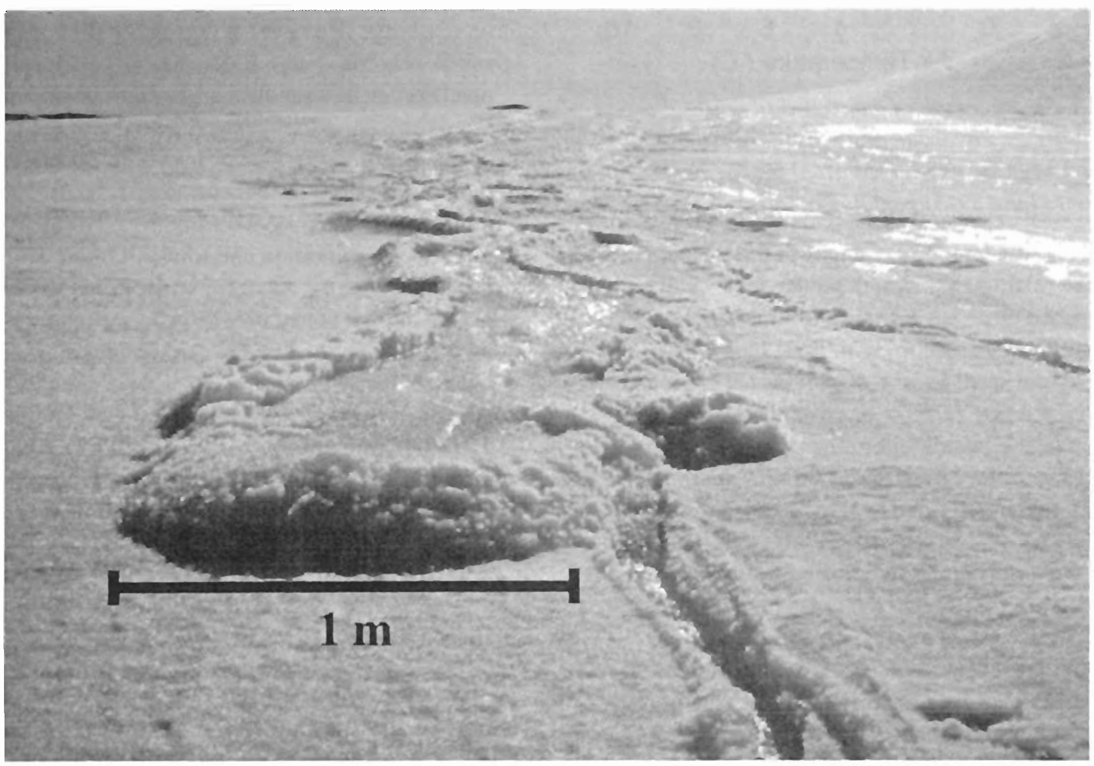

Figure 4. Slush flows advancing down-glacier on the central snout of Quviagivaa Glacier, July 5, 1993.

Hydrometeorological conditions and runoff- air temperature

We used the period of main melt (June 29-Aug 3) to study the relationships between runoff and individual meteorological parameters. Because of the overwhelming signal the large precipitation event on July 20-21 had on flow, data from those dates were not included in the statistical analyses.

A scattergraph of average daily air temperature versus average daily discharge (expressed as mm of runoff averaged over the catchment area) was produced for the main melt period (Fig. 5).

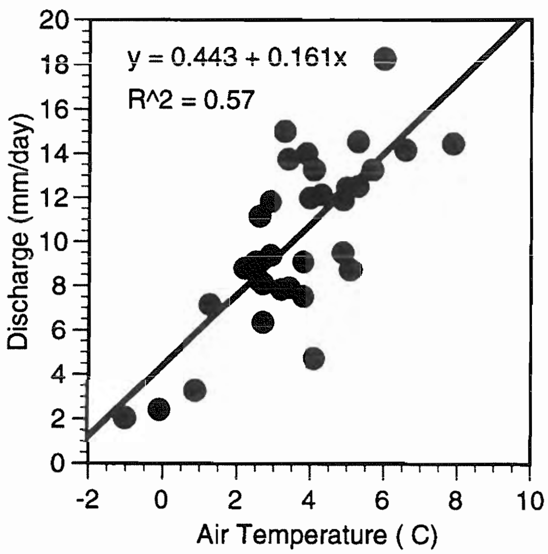

Figure 5. Scattergraph of average daily air temperature and average daily discharge (mm day^{-1} averaged over the catchment area) for the period of main melt (June 29-August 3, 1993.

In Figure 2, the temporal changes in the temperature-discharge relationship, which reduce the r^2 value in Figure 5, are more easily seen. Although melt is occurring throughout the basin from June 12 onwards, a significant lag effect (>1 day) is produced primarily because of snow dams in the stream bed, retention of meltwater within the snowpack and crevasses, and the formation of superimposed ice on the glacier. Primarily due to snowdams in the creekbed and a thick snowpack at the terminus of the glacier, flow during the first week of measurement (see Fig. 2) is confined to the non-glacierized slopes below the glacier, thereby restricting the area of contribution of flow to <10% of the drainage basin. Runoff generated from melt in the upper sections of the glacier is initially impeded (early July) by numerous transverse crevasses until they fill with water. Storage of runoff as superimposed ice is likely a major cause of low discharge values on days such as June 30 and July 5 when high temperatures did not result in peaks in discharge as high as for days with similar temperatures in late July. The formation of superimposed ice is widespread early in the melt season, when meltwater percolating through the winter snowpack refreezes immediately as it reaches the still-cold glacier surface (-5 to -10°C), and is less common when the snow has disappeared and the glacier surface has warmed to 0°C. The formation of superimposed ice varies in time and space on the glacier surface, occurring progressively later at the higher elevations and in areas with deeper snowpacks (>1 m). Superimposed ice reached thicknesses >30 cm in some of the deep snow areas on the glacier snout. In the ablation zone, this ice melted and contributed to runoff some 2-4 weeks after it was formed. In regions of net accumulation, the formation of superimposed ice may create a lag which lasts into the next melt season or longer.

Precipitation

During periods of rainfall, fog and low cloud are often present over the glacier and reduce the influence of solar radiation on melt and runoff. The r^2 value for the discharge-temperature regression is reduced to 0.35 when the single July 20-21 rain event is included, revealing the importance of such events on discharge. However, a regression plot of daily rainfall and discharge shows a poor relationship. A much better fit with discharge might be expected with hourly precipitation values due to the quick response of the mid-summer glacier hydrological system to rain events. With the exception of July 20-21, most of the precipitation events during the 1993 melt season were short in duration and totaled<3 mm. Although producing small rises in the hydrograph, these minor events did not constitute the primary contribution to daily discharge and therefore do not explain the average discharge during the days in question. However, the largest precipitation event on July 20-21 (30-40 mm of rain in 48 h), resulted in the highest instantaneous discharge of the season in Quviagivaa Creek (3.0 m^3 s^{-1}) despite low air temperatures.

Solar radiation

Studies of glacier ablation and runoff in the high Arctic have shown the importance of solar radiation on melt and runoff (e.g. Keeler 1964; Braithwaite 1981). However, we found no statistically significant relationship between discharge and shortwave incoming radiation. This is primarily because of the timing of peak solar radiation inputs around the summer solstice (depending on cloud conditions), at which time the high glacier surface albedo results in a loss of 60-85% of the radiation. Runoff on high Arctic glaciers with altitudinal ranges such as Quviagivaa is usually just beginning in late June, with maximum runoff commonly occurring in July, often a full month after the peak in incoming shortwave radiation (Adams 1966).

Although statistically significant at the 99% confidence interval, net radiation hours (the daily sum of positive hourly net radiation values) displays a rather weak relationship with average daily discharge (Fig. 6). Compared with incoming shortwave

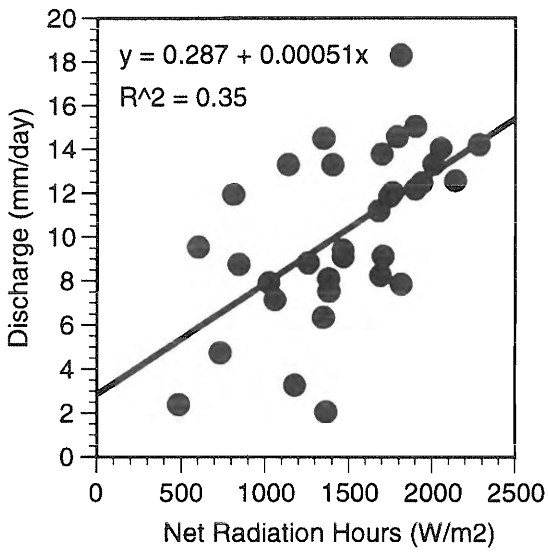

Figure 6. Scattergraph of daily net radiation hours and average daily discharge (mm day^{-1} averaged over the catchment area) for the period of main melt (June 29-August 3, 1993).

radiation, net radiation should more closely approximate runoff, as maximum net radiation and discharge values occur during July. The weak relationship is likely caused by the unrepresentativeness of the net radiation site measurements compared with the large variance in net radiation across the glacier surface caused by variations in aspect, shading, and albedo.

Absorptivity

Average glacier surface absorptivity (1-albedo) is second only to air temperature in explaining average daily discharge for the glacier basin, and the relationship is significant at the 99% confidence interval (Fig. 7). The glacier absorptivity values were arrived at by averaging daily values measured at 8-12 ablation stations on the glacier. Absorptivity is a spatially-averaged value, resulting in a higher r^2 value than that obtained using the single site net radiation data.

Figure 8 shows the surface conditions of the glacier for four dates through the melt season, mapped from daily photographs and traverses of the

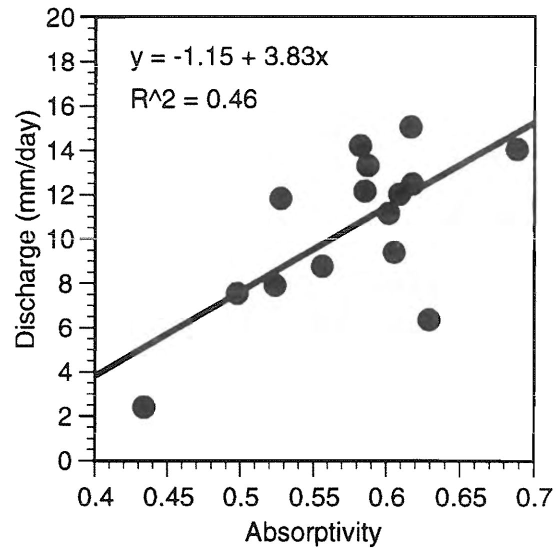

Figure 7. Scattergraph of average glacier absorptivity (1-albedo) and average daily discharge (mm day^{-1} averaged over the catchment area) for the period of main melt (June 29-August 3, 1993).

glacier on alternate days. The average glacier albedo is reduced from 0.69 on June 24, when the glacier was still predominantly snow-covered, to 0.31 on August 1 when the glacier was largely dust-encrusted, ablating glacier ice. Most of the superimposed ice exposed on August 1 was formed in previous years, and has the effect of increasing the average glacier albedo. Melt and runoff proceed much more efficiently for a given radiation heat input when the snow and superimposed ice have ablated, and darker glacier ice is exposed. The lower albedos in late July and early August compensate for the lower values of incoming shortwave radiation at this time. This effect is demonstrated by comparing discharge and weather conditions on July 8 and 31. Although both days have similar mean temperatures, the average glacier albedo decreases from 0.41 on July 8 to 0.31 on July 31. The darker surface on July 31 results in a greater percentage of solar radiation being absorbed by the
glacier, and a slightly higher average discharge, although average incoming shortwave radiation is

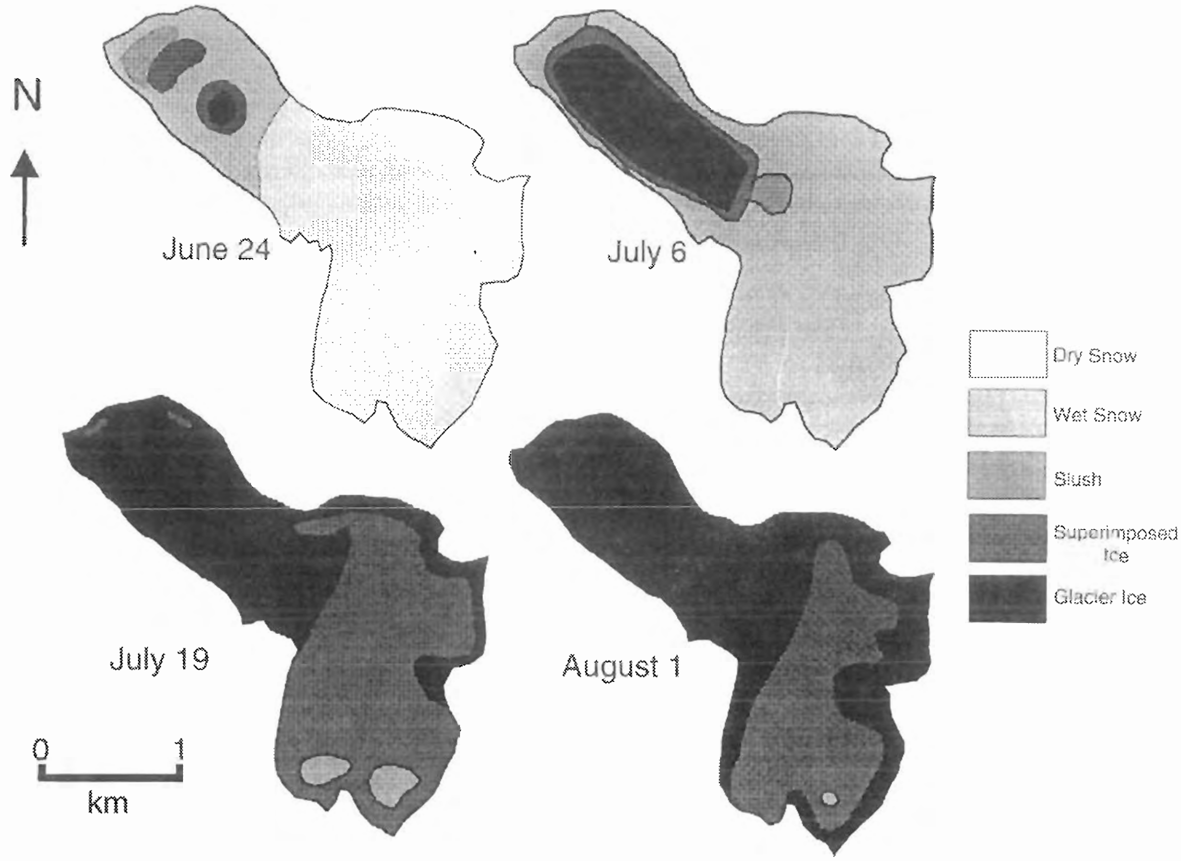

Figure 8. Surface conditions for Quviagivaa Glacier on four dates during the 1993 ablation season.

100 W m^{-2} lower. It follows that the early ablation of newly formed superimposed ice and the exposure of glacier ice early in the melt season increases the likelihood of a high runoff year.

Wind

A melting glacier cools the air directly above it, and this negative feedback slows melting. However, winds work to mix the cold surface layer of air with warmer air which has not been in contact with the glacier ice. Higher wind speeds increase the mixing of warm air heated by the surrounding ice-free land, with the colder glacier air and increase melt and runoff. The correlation between average discharge and average wind speed on the glacier, significant at the 99% confidence interval, is relatively low (r^2=0.31; n=34), but the nearly continuous presence of wind on the glacier during the melt season (99% of all measurements), suggests the important role of wind during melt.

Multiple variable prediction of runoff

The best prediction of average daily discharge during the main melt period was achieved using a multiple regression of discharge with average daily air temperature, shortwave incoming radiation, net radiation hours and wind speed (variables are listed in order of decreasing importance to the multiple regression). The resulting equation, significant at the 99% confidence interval (r^2=0.84), is:

$$y = 0.315\ (T) - 0.00248\ (K) + 0.000217\ (NRH) + 0.11767\ (W)$$

where: T = average daily air temperature (°C)
K = average daily shortwave incoming radiation (W m^{-2})
NRH = daily net radiation hours (W m^{-2})
W = average daily wind speed (m s^{-1}).

Using the four variables the resulting standard error is ±0.165 m^3 s^{-1}.

DISCUSSION

The extrapolation of hydrometeorological values across a glacier

In any study of the natural environment, where site measurements are the basis of quantitative comparisons, one must determine how representative these measurements are of the system. In this study, daily discharge is regressed with air temperature, incoming shortwave radiation, net radiation, absorptivity, and wind speed, with the assumption that the aforementioned elements are reasonably representative of conditions on the glacier as a whole.

Air temperature varies mainly with elevation across the glacier with the exception of a border tens of metres wide around the glacier which is affected by the advection of warmer air from non-ice surfaces. The meteorological station was placed near the median elevational range of the glacier to more accurately represent the average of the total temperature range. The good fit of the air temperature-discharge relationship can be anticipated, considering the high correlation between ablation and melting degree hours (a function of air temperature) obtained at the glacier meteorological station during the period of main melt (r^2=0.93; n=16).

Shortwave incoming radiation cannot be properly extrapolated across a glacier surface without the construction of a terrain model to take into account the effects of shading by adjacent mountains and the range of aspects and slope angles. In addition, differences in incoming radiation between the upper glacier and snout of Quviagivaa are often heightened on clear days through the local formation of low clouds at the top of the glacier, while the glacier snout is in partial or total sunshine (conditions experienced on approximately 30% of all days in the 1993 field season).

The highly variable absorptivity of the surface must be accounted for in the extrapolation of radiation values across the glacier. The better fit achieved in the discharge-absorptivity regression (Fig. 7), compared with net radiation hours, is primarily because of the spatially-averaged albedo value.

Attempts to choose a representative location to measure wind speed must always take into account the predominance of glacier-generated winds, which commonly develop on even the smallest glaciers (Ohata 1989). The average wind speed will likely be found at the location of average fetch. Wind speed at the suitably-located meteorological station is likely to be close to the mean for the entire glacier.

Comparisons with other glacier basins

The record of discharge presented in this paper adds to a meager set of glacier runoff data from the Canadian Arctic islands. Reasons for the small number of studies include the logistical constraints and high costs of reaching study sites, and the many difficulties involved with hydrology data collection in the high Arctic. These include snow-filled streams, and extreme summer flows caused by rain events and high melt periods which tend to rearrange channel geometry, wash away weirs, stilling wells, and recording devices. The only complete season glacier discharge records from the Arctic islands are from two Baffin Island glaciers; the Lewis Glacier in 1963 and the Decade Glacier in 1965 (Anonymous 1967; Østrem et al. 1967).

Over the entire melt season, runoff from glacier basins is not correlated well with meteorological data. Complexity in the relationship is caused by the partial areas of the basin which contribute to flow at the outset of melt, and by a melt-runoff lag which varies spatially and temporally. Working in a glacierized basin in the Swiss Alps, Jensen and Lang (1972) successfully used separate regression equations to forecast discharge by subdividing the melt season into three intervals (Main snowmelt, Main ablation season, and Reduced ablation). For this study, the relationships between discharge and meteorological elements, were analyzed for the period of main melt, in which almost the entire basin was contributing to runoff. In a study on Mikkaglaciaren in Arctic Sweden, Stenborg (1970) estimated that 25% of the total summer discharge was delayed from the early to the middle part of the summer. Factors which create this lag are given by Stenborg (1970), and are listed in the order of their approximate quantitative importance on Quviagivaa Glacier for the summer of 1993:

1. The formation of superimposed ice in June and early July,
2. Slush pools above 875 m a.s.l.; formed by rapid melting of the snowpack in early July,
3. Snowdams in the glacier marginal streams and in the streambed below the glacier, which caused partial to total restriction of flow in June,
4. Storage of meltwater in crevasses which do not drain to the bed,
5. The limited development of supraglacial channels at the beginning of the melt season, forcing the meltwater to move across the rough glacier surface,
6. Capillary storage of meltwater in the spring snowpack and firn.

When ablation of the snowpack is nearly complete capillary storage of meltwater is small, and after crevasses fill up with water they no longer create a significant lag in discharge. Superimposed ice formation is no longer widespread, and flow pathways in the basin are established. The prediction of runoff from meteorological elements in this "main melt" or "limited lag" period is then more straightforward (Colbeck 1977).

Although climate and runoff relationships are described in several Arctic glacier studies (Keeler 1964; Adams 1966), none exist which correlate unit values of stream discharge with meteorological elements in a glacierized basin. One of the most significant findings of this work is that during the main period of melt, average discharge shows a strong linear relationship with average air temperature on the glacier. Several studies have shown a positive relationship between temperature and runoff in alpine basins (Jensen and Lang 1972; Østrem 1972), however the runoff-temperature relationship is not simple, and many other factors such as albedo, radiation, wind speed, and precipitation play an important role in the production of runoff (Collins 1984).

Net radiation is in most cases the largest energy source for ablation on Arctic glaciers (Braithwaite 1981). However, as has been found on glaciers in the Arctic and in the Alps (Jensen and Lang 1972), on Quviagivaa Glacier net radiation is not correlated with ablation or discharge as well as air temperature. Konzelmann and Braithwaite (1995), while stating that net radiation is the major source of ablation energy, suggest that due to the high variability of surface albedo, spot measurements of net radiation will not give an accurate picture of the larger-scale energy balance.

The importance of the surface albedo to ablation is well known, and Van de Wal et al. (1992) have shown that variations in albedo across the snout of Hintereisferner explain most of the difference in ablation during the melt season. Since variations in the absorptivity of the surface correlate strongly with ablation it should also be the principal element determining runoff differences.

Although not showing the highest correlation with discharge in this study, wind is known to cause an increase in the vertical temperature gradient and in sensible heat transfer to the glacier surface (Ohata 1989). Working on the Greenland ice sheet margin, Duynkerke and Broeke (1994) found that the combined effect of the katabatic (down-glacier wind) and thermal wind effect (induced by the adjacent warm tundra surface), was to enhance the transport of sensible heat to the ice surface. Keeler (1964), working on the Sverdrup Glacier, Devon Island, found that the greatest ablation rates occurred due to the turbulent transfer of heat during periods of high winds, high temperatures and high humidities.

In numerous proglacial basins, rain events are related to peak annual discharges. In the White Glacier catchment in 1961, rain-induced peak flows washed out the weir, terminating stream discharge measurements for the season (Adams 1966). Similar peak flows also occurred in the Lewis and Decade glacier basins in 1965, and in the McCall Glacier basin in 1969 and 1970 (Anonymous 1967; Østrem et al. 1967; Wendler et al. 1972). Cogley and McCann (1976) describe an exceptional storm which produced peak flows in the proglacial "Sverdrup" and "Schei" rivers at Vendom Fiord, Ellesmere Island, when 54.6 mm of rain fell from July 21-23, 1973. The authors note that the storm would have gone unnoticed without measurements at research stations located away from the official high Arctic weather stations. In 1993, a similar situation occurred on July 19-22, when 9.2 mm of rain was recorded at Eureka, while 34.1 mm was measured at the terminus of Quviagivaa Glacier. This suggests that brief but significant summer precipitation events play a much greater role in runoff in glacierized catchments than would be expected from the precipitation records from the near-sea level official weather stations.

CONCLUSIONS

The characteristics of the runoff season in the Quviagivaa Creek basin were discussed, and in order to obtain a better understanding of the effect of meteorological factors on runoff from a high Arctic glacierized catchment, average daily discharge values were related with air temperature, precipitation, incoming shortwave radiation, net radiation, absorptivity and wind speed measured on Quviagivaa Glacier for the period of main melt (June 29-August 3, 1993). The main conclusions can be summarized as follows:

1. Snow dams, meltwater retention in the snowpack, slush pools, and the formation of superimposed ice produce a lag in runoff during the early melt period, and are mainly responsible for the weak temperature-discharge relationship at the outset of the runoff season,
2. Slush flows (of snow and melting superimposed ice) are an important process which result in the opening of flow pathways, the relocation of mass to lower elevations on the glacier, and in the removal of mass from the glacier,

3. For the main melt period, average daily air temperature on the glacier is the single element which shows the best relationship with average discharge on days unaffected by significant rainfall (>10 mm),
4. The best prediction of glacier runoff can be achieved using a multiple regression of average daily air temperature, wind speed, shortwave incoming radiation, and net radiation hours (r^2=0.84),
5. Rain events strongly influence the hydrograph due to the impermeable and steeply-inclined rock and ice surfaces in Quviagivaa Creek basin, and are likely responsible for peak flows in most years.

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