The hydrology of small runoff plots in an area of continuous permafrost, Banks Island, N.W.T.

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Hydrologic studies of four small runoff plots were conducted in the continuous permafrost zone of north-central Banks Island between 1977 and 1979. One plot was located on an interfluve while the other three where on slopes where snowbanks develop. The plots ranged in size from 27 to 525 m^2. For two to three months of each summer field season, all the major inputs and outputs of the hydrologic cycle were measured at each plot.

The results of the study indicate a high degree of variability in the proportions of water losses from the plots, attributable to surface and subsurface flow. This variability is evident both in inter-year comparisons for a single site and inter-site comparisons for a single year. Inter-year variability is controlled largely by the winter snow distribution and by meteorological conditions during the melt season. Inter-site variability is influenced by snowbank size, with the largest snow accumulation site exhibiting the highest percentage loss to surface flow, and the smallest loss to subsurface flow and evapotranspiration.

Surface-flow hydrographs of snowmelt runoff recorded at the plots are explicable within the context of accepted snowmelt theory. Surface flow generated by rainfall was much less important and occurred only twice in the three years of measurement. On these occasions, only areas downslope of existing snowbanks, or those areas from which snow had recently disappeared, produced surface flow. These observations support the validity of the partial and variable concepts of runoff generation in the high Arctic. Areas producing surface flow are dependent on topographically controlled snowbank distribution, rather than, as in temperate areas, on the location of streams.

Une étude hydrologique du ruissellement a été effectuée sur quatre petites parcelles situées dans la zone de pergélisol continu de la partie centrale du nord de l'île Banks entre 1977 et 1979. Une des parcelles était située dans l'interfluve et les trois autres sur les pentes où apparaissent les bancs de neige. La superficie des parcelles variait de 27 à 525 m^2. Pendant deux ou trois mois de l'été, saison du travail sur le terrain, chaque année, toutes les principales données d'entrée et de sortie du cycle hydrologique ont été mesurées pour chacune des parcelles.

Les résultats de l'étude révèlent une forte variabilité des proportions des pertes d'eau attribuables au ruissellement en surface et à l'infiltration. Cette variabilité se manifeste tant au niveau des résultats obtenus d'une année à l'autre pour une même parcelle qu'au niveau des résultats obtenus pour des parcelles différentes pendant une même année. La variabilité d'une année à l'autre dépend en grande partie de la répartition des chutes de neige en hiver et des conditions météorologiques pendant la saison de fonte. La variabilité d'une parcelle à une autre dépend de la taille des bancs de neige; les parcelles où les bancs de neige étaient les plus gros présentant les proportions de pertes par ruissellement les plus élevées et les pertes par infiltration et par évapotranspiration les moins importantes.

Les hydrogrammes de l'écoulement en surface de l'eau de fonte des neiges, obtenus pour chacune des parcelles s'expliquent dans le contexte de la théorie acceptée concernant la fonte des neiges. L'écoulement en surface attribuable aux pluies était beaucoup moins important et n'a été mesuré que deux fois pendant les trois années qu'a duré l'étude. En ces occasions un écoulement en surface n'a été observé que dans les secteurs situés en aval de bancs de neige existants ou dans les secteurs d'où la neige n'était disparue que depuis peu. Ces observations appuient la validité de la théorie du ruissellement partiel et variable dans le haut-arctique, les endroits où s'effectue l'écoulement en surface dépendant plutôt de la répartition topographique des bancs de neige que de la localisation des cours d'eau comme c'est le cas dans les régions tempérées.

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Introduction

Only a few studies of slope hydrology have been undertaken in the permafrost areas of Arctic Canada (e.g. Ballantyne 1978; Landals and Gill 1973; Soulis and Reid 1978; Wilkinson and Bunting 1975). This paper describes a field study of slopewash and other hydrologic processes in central Banks Island. The study methodology involved evaluation of the spatial distribution and movement of water at four small runoff plots. The results

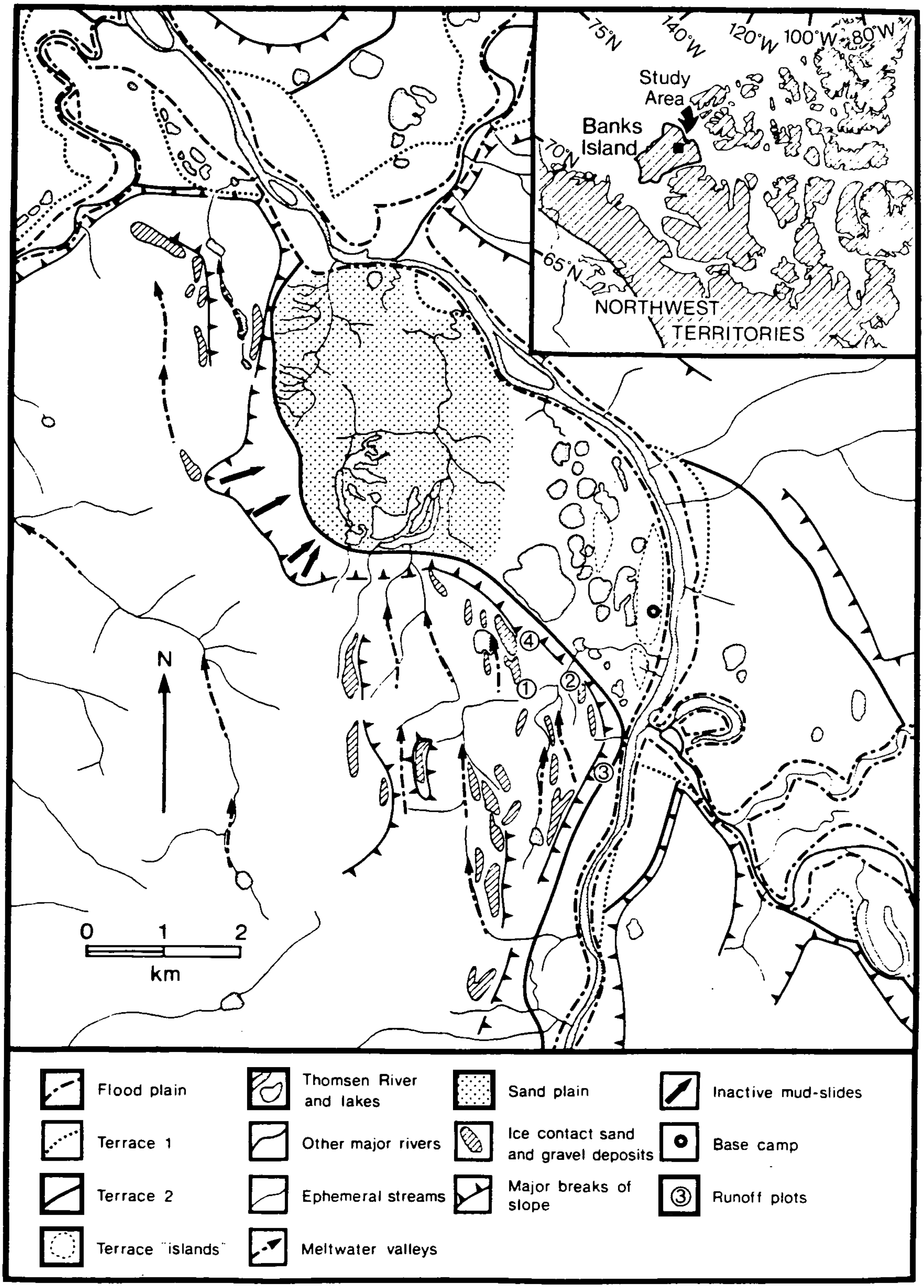


FIGURE 1. Morphogenetic map of the study area (*from* field observations and air-photo interpretation).

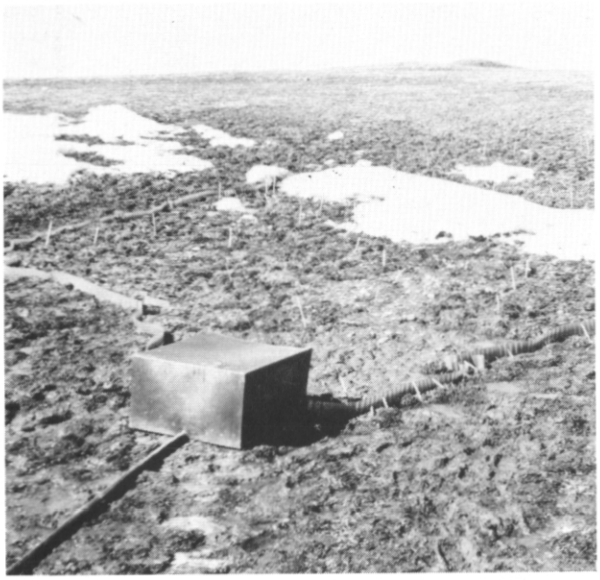


FIGURE 2. Plot 1, June 2, 1979. *Note* break-up of thin snowpack into discrete pieces and use of edging to divert surface flow to collector. Interfluve site has low vegetation cover.

allow a consideration of the applicability of models of stream runoff generation to the continuous permafrost zone.

Study Area and Runoff Plot Characteristics

The study was conducted in the tundra lowlands of the Thomsen River, north-central Banks Island at latitude 73° 14′ N. and longitude 119° 32′ W. (Figure 1) during the summers of 1977, 1978, and 1979. The area is underlain by poorly lithified Cretaceous shales and sands. Slope angles exceeding 15 to 20° are rare and relative relief is typically 50 to 100 m. Veneers of surficial materials, mainly silty clayey till and sandy ice-contact and outwash deposits, related to a pre-Wisconsin ice advance, are widespread. The climate is polar continental. The mean January air temperature drops below -30°C while the mean July temperature is +6°C. Precipitation amounts are small, averaging 114 mm/a, and show a high degree of variability. Records from Sachs Harbour for the month of June, for example, show that the mean monthly precipitation is 7.6 mm, but that the standard deviation is 6.6 mm.

Investigations were concentrated at four sites, each instrumented with a small runoff plot. Site selection was influenced by two factors. First, design of the monitoring equipment precluded its use on very hummocky terrain or on slopes of less than 3 degrees; and secondly, it was appropriate for the sites to be representative of significant portions of the area. Since ridges and interfluves form a high proportion of the slopes, an interfluve location was chosen for plot 1 (Figure 2). The remaining three plots were located at snowbank sites which were presumed to be particularly important both in hydrologic and geomorphological terms.

On each slope the plot was defined by a combination of surface-flow observations, detailed topographic surveying, and the use of polyurethane edging to channel surface flow to the collector. The positions of the plots on the slopes remained the same throughout the study at sites 2 and 4, but varied between years at sites 1 and 3. The plot was moved at site 1 as a result of terrain disturbance during monitoring in 1977. The relocation at site 3 was the result of the late commencement of measurements in 1977 by which time much of the snowbank had ablated. In the other two years, runoff collection began at the start of the ablation season and, due to the size of the snowbank, equipment had to be located farther downslope. Plot characteristics and hydrologic monitoring equipment are summarized in Table 1.

Methods

Measurement of a number of parameters was undertaken, usually on a daily basis. The water equivalent of the snow on each of the runoff plots was calculated after measurement of snow depths, density, and areal extent. Depths were assessed

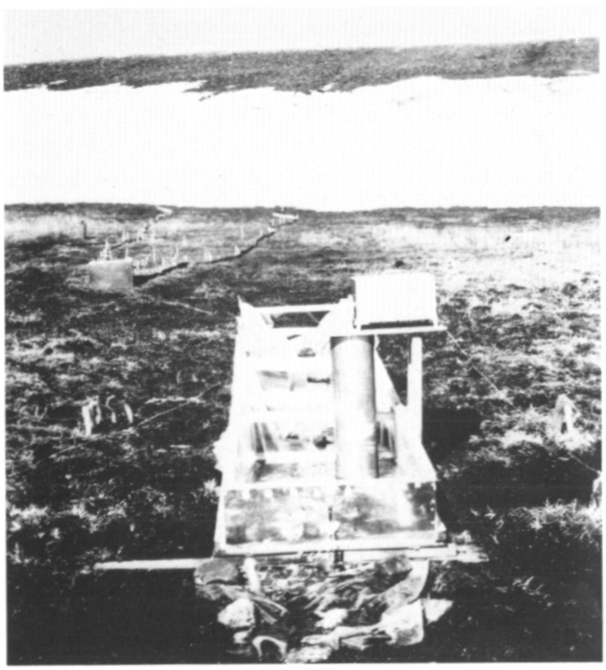


FIGURE 3. Plot 3, June 30, 1978. *Note* operating weir and water-level recorder in foreground. Plot ends at slope crest.

TABLE 1. Plot characteristics and hydrologic monitoring equipment

Plot No.	Type	Mean slope of plot	Aspect	Area m^2	Surface flow collector	Subsurface flow collector	Soil lysimeters	Rain gauge
1	Interfluve	5°	125°	1977: 149.6 1979: 437.7	Yes	No	Yes	Yes
2	Snowbank	5°	315°	1977-1979: 524.7	Yes	No	Yes	Yes
3	Snowbank	12°	125°	1977: 26.6 1978–1979: 262.3	Yes	1) 0.06 m level in plot 2) 0.06, 0.16, 0.31 m levels 130 m downslope of plot	Yes	Yes
4	Snowbank	13°	70°	1978–1979: 67.0	Yes	0.06, 0.16, 0.31, 0.46 m levels at exit of plot	Yes	Yes

using a combination of snow-course measurements, probing with a steel rod, and measuring from a fixed line to the snow surface. Densities were measured in 1977 and 1978 with CRREL 0.5-L snow tubes, while in 1979 a Mount Rose snow sampler also was employed. The areal extent of each snowbank was recorded by marking the snow edge with coloured pegs and surveying these after the cessation of melt. Summer precipitation, when it occurred, was measured with a Weathermeasure tipping-bucket rain-gauge and recorder at plot 1, and with a number of manual rain-gauges located at the other plots and at the base camp.

Sublimation losses from the plots were evaluated using white polyurethane lysimeters containing snow and embedded in the snowbank. Small cans with reconstructed or undisturbed soil cores were used to monitor evapotranspiration. At each plot, two soil lysimeters were kept near saturation through the daily addition of water equal to the previous day's loss, while a third was allowed to dry out. This procedure was followed in order to represent areas of the plot respectively downslope and upslope of melting snow.

Surface flow leaving the plots was collected using a copper box, open upslope and sealed to the ground with silicone sealant, with a pipe leading to flow-monitoring apparatus. In 1977, surface-flow recording was manual and regression analysis of discharge against net radiation, with allowance for time-lag effects, was used to fill in gaps in the record (Lewkowicz 1978, pp. 73-76). In the two later years, monitoring was accomplished using small V-notch weirs and water-level recorders (Figure 3). Each weir was individually calibrated with a stage-discharge curve, enabling continuous and simultaneous recording of surface flow at the plots. Subsurface flow leaving the plots was monitored manually and intermittently using Whipkey-type guttering at plots 3 and 4 (*see* Lewkowicz and French 1982).

In addition to these measurements, net radiation, air temperature, and wind run were recorded at the base camp, 1.5 km north of the plots.

Seasonal Water Balance Studies

The year to year variability of water balance components is best exemplified using the data from plot 2 where the records are most complete. Calculations based on the amount of water present on the plot at the time the snow became isothermal are shown in

TABLE 2. Water balance during isothermal period, plot 2, 1977–1979

Isothermal date and date of complete snow ablation	Inputs: Snow on plot mm	%	Rain mm	%	Losses: Snow evaporation mm	%	Unsaturated evapotranspiration mm	%	Saturated evapotranspiration mm	%	Flow through snow mm	%	Surface flow mm	%	Residual mm	%
1977 5/6 - 19/6	260.2	98	6.5	2	4.0	1	5.7	2	4.6	2	0.0	0	67.5	26	184.9	69
1978 25/6 - 4/7	198.0	99	1.2	1	2.3	1	3.5	2	5.0	3	0.0	0	22.4	11	166.0	83
1979 30/6 - 13/7	285.1	99	3.6	1	3.7	1	5.2	2	4.9	2	201.0	69	7.4	3	66.5	23

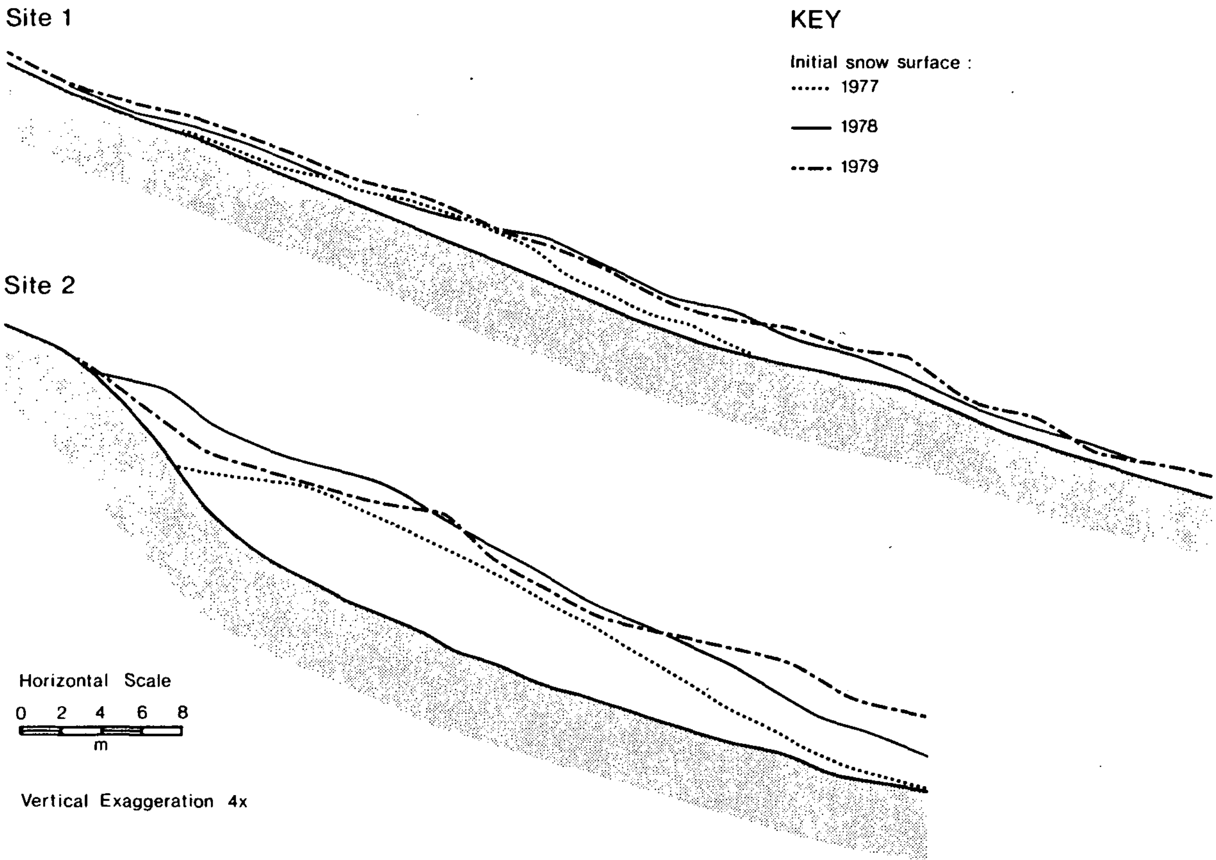


FIGURE 4. *Slope profiles and snow depths at sites 1 and 2, 1977 to 1979.*

Table 2. Losses at this location were dominated either by flow through the snow, or by surface flow together with a large residual. Surface flow over three years averaged only 13 per cent of the post-isothermal losses despite its apparent significance in visual terms at the runoff plot. The large residuals are attributed to a combination of subsurface flow and active-layer storage which subsequently could contribute to evapotranspiration.

While the hydrologic inputs of snow and rainfall (*see* Table 2) changed little during the three years, there is a striking amount of variation in the relative proportions of water losses. In 1977, for example, surface flow constituted 26 per cent of the losses from the plot. In 1978, this value fell to 11 per cent, and in 1979 it was only 3 per cent. This variability is thought to result from differences in both initial snow distribution and meteorological conditions during the melt season.

A particularly early thaw occurred in 1977, and at that time the snowbank was thin, both at the crest and base of the slope (Figure 4). Between June 9 and June 14, above-average air temperatures and nearly continuous sunshine caused rapid ablation and the highest, seasonal, surface runoff coefficient of 26 per cent. In contrast, the 1978 and 1979 thaw seasons commenced late and with different snow distributions. Snow depths of 0.4 and 0.9 m existed at the location of the surface flow collector in 1978 and 1979 respectively (*see* Figure 4) and these amounts of ablation were necessary before the collector position was clear of snow. In 1978, this was accomplished by evaporation and settling during the pre-isothermal period (Figure 5), but in 1979, a large volume of water is thought to have left the plot as downslope flow through the snow (*see* Table 2).

Not only is the water equivalent of the winter snow accumulated in a snowbank important, but also its distribution. In the limiting case, a uniform thickness of snow will produce no surface or subsurface flow *per se*, but will be depleted solely by evaporation and flow through the snow.

The results obtained at plot 2 can be contrasted with those from the interfluve site (plot 1). In both 1977 and 1979, the snowpack was of variable thick-

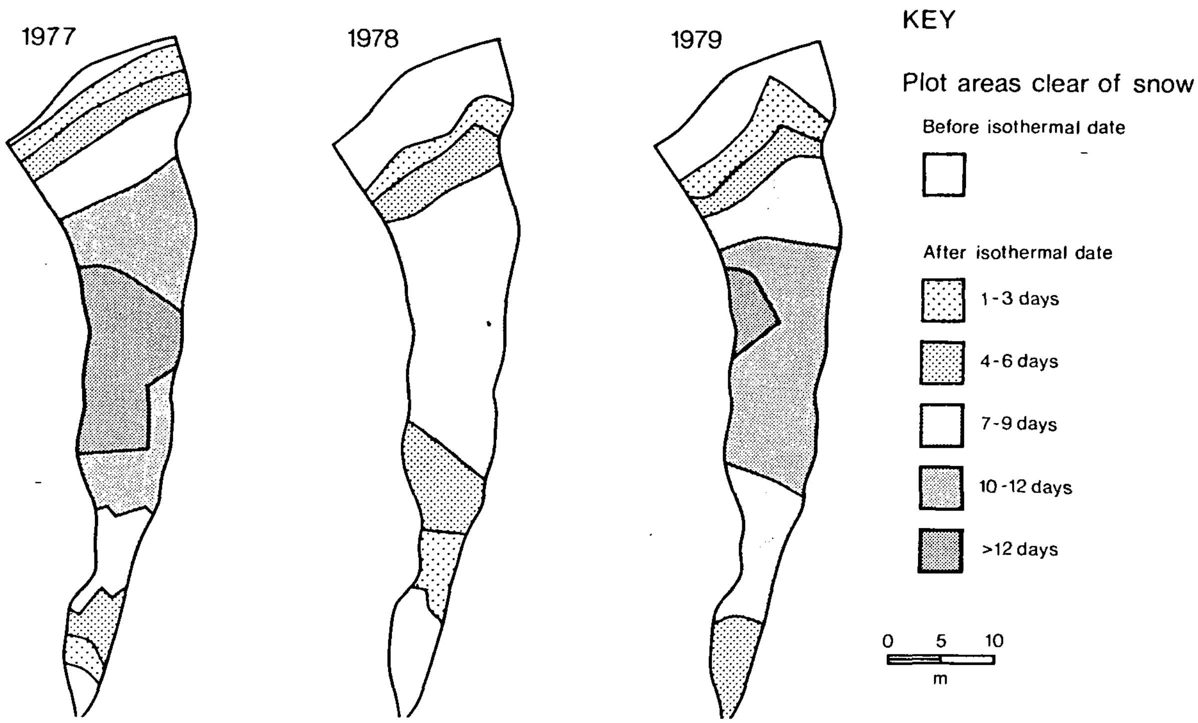


FIGURE 5. Changes in snow distribution and ablation at plot 2, 1977 to 1979.

ness (*see* Figure 4) and disintegrated into discrete units as it ablated. This led to relatively large values for evapotranspiration since much of the snow-free ground on the plot was kept near saturation by snow melting upslope (Table 3). The major influences on the percentage losses at this site were meteorological conditions during the ablation season.

In both years, surface flow was generated during a period of three to four days, but in contrast to plot 2, more surface flow was produced in 1979. In 1977, surface-flow generation commenced three days after the pack became isothermal. During this period, air temperatures were positive but radiation inputs were low. Snowmelt did not exceed subsurface and evaporative losses, and surface flow was not generated. When weather conditions ameliorated and sunshine became continous, between June 1 and June 3, little snow was left. In contrast, water loss from the snow on the plot in 1979, was limited by heat deficits that developed as air temperatures dropped below 0°C at "night". As in 1977, however, surface flow was generated finally during a period of high radiation inputs coincident with increased air temperatures. In both years, had antecedent conditions of positive air temperatures and overcast skies persisted, it is possible that all the meltwater produced at this location would have left the plot as subsurface flow. The latter is thought to be largely responsible for the residuals in Table 3.

Comparisons among the three snowbank sites support the concept of threshold melt values required to generate surface flow. In 1978, for example, plot 3, the site with the largest snowbank, also had the highest value for surface flow (81 per cent of the losses, 525.7 mm) while plot 2 showed the

TABLE 3. Water balance during isothermal period, plot 1, 1977 and 1979

Isothermal date and date of complete snow ablation	Inputs: Snow on plot		Inputs: Rain		Losses: Snow evaporation		Losses: Unsaturated evapotranspiration		Losses: Saturated evapotranspiration		Losses: Flow through snow		Losses: Surface flow		Residual	
	mm	%	mm	%	mm	%	mm	%	mm	%	mm	%	mm	%	mm	%
1977 29/5 - 4/6	56.2	100	0.0	0	1.4	2	3.3	6	4.6	8	0.0	0	6.4	12	40.5	72
1979 28/6 - 5/7	39.1	100	0.0	0	2.0	5	1.8	4	5.3	14	0.0	0	19.0	49	11.0	28

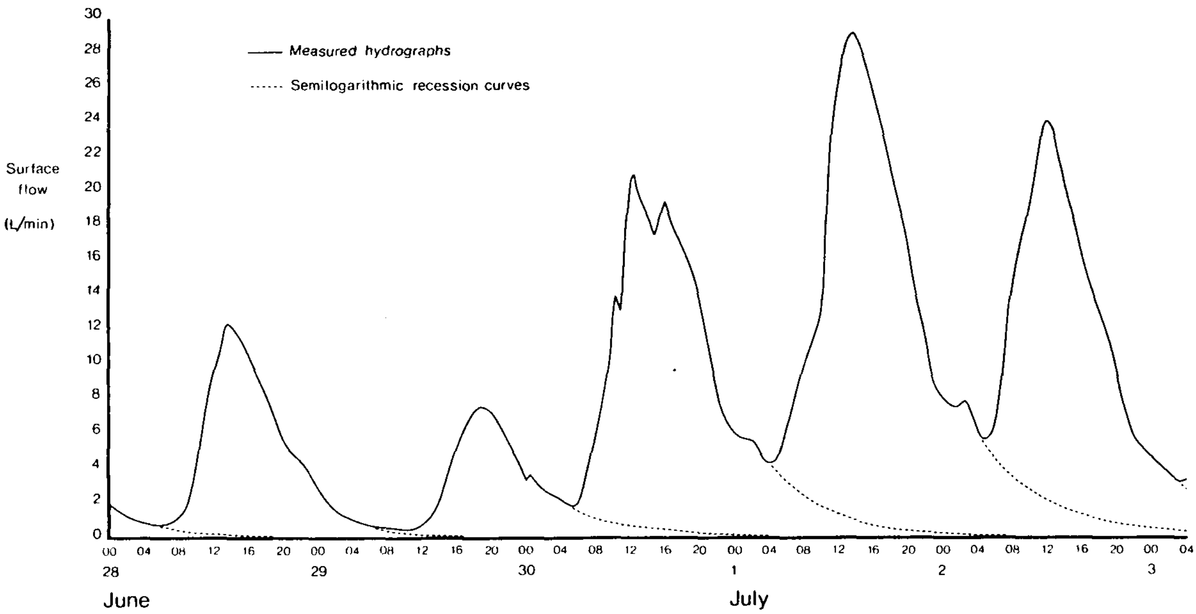


FIGURE 6. Surface-flow hydrographs for plot 3, from June 28 to July 3, 1978.

lowest figure (11 per cent of the losses, 22.4 mm). Conversely, evaporation and residual percentages were highest at plot 2 (combined total, 88 per cent, 174.5 mm) and lowest at plot 3 (combined total, 18 per cent, 112.0 mm).

Calculations indicate that all four plots contribute above-average percentages of runoff (surface and subsurface flow combined) to streams in the study area. As expected, the largest snowbank site produced the highest proportion of runoff (up to 96 per cent of the water equivalent of the snow available) while plot 1 produced the lowest value (as low as 68 per cent). The average coefficient of stream runoff for the upland area containing the plots is estimated to have been between 60 and 69 per cent. These data suggest that some parts of the upland surfaces contribute little or no water to stream runoff and that their snow cover is lost directly to the atmosphere.

Coefficients of surface runoff for the plots can be

TABLE 4. Comparison of coefficients of surface runoff for Thomsen River and Yellowknife, N.W.T.

Thomsen River[1]	Plot characteristics						
Plot No.	1	1	2	2	2	3	4
Year	1977	1979	1977	1978	1979	1978	1978
Initial pack water equivalent (mm)	71.0	85.2	260.2	233.9	217.6	710.2	912.0
Surface runoff coefficient (%)	9	22	26	10	2	74	33

Yellowknife[2]	Plot characteristics: Bare rock		Vegetated ridges		Muskeg depressions		Compound sites	
Plot No.	1	2	3	4	5	6	7	8
Initial pack water equivalent (mm)	46.0	79.5	79.5	74.0	79.5	61.0	66.0	94.5
Surface runoff coefficient (%)	1	82	68	72	37	56	77	50

[1]*Note:* Data not presented from plots 3 and 4 in 1979 as snow ablation was incomplete when monitoring ended.
[2]*Source:* Landals and Gill (1973)

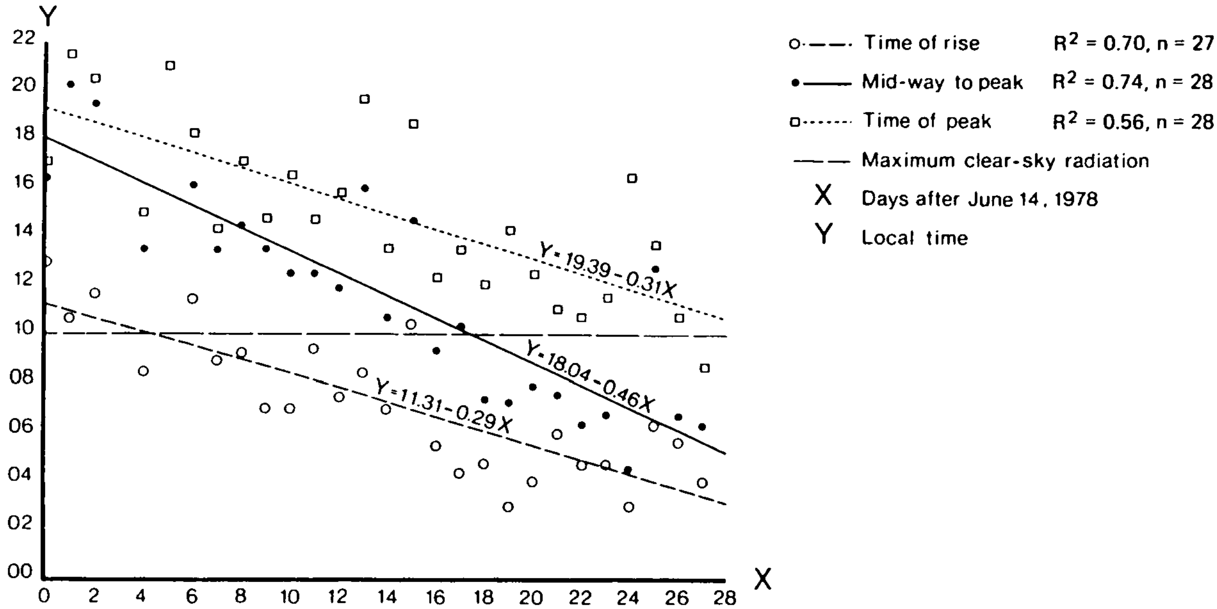


FIGURE 7. Changes in timing of surface-flow hydrographs from plot 3, 1978.

compared with those obtained by Landals and Gill (1973) from the Yellowknife area in the discontinuous permafrost zone. A wide range of values were obtained in both areas, but those from Banks Island are generally lower than those from farther south (Table 4), in spite of higher snowpack water-equivalents. This trend probably results from more-rapid rates of melt in the Yellowknife area, which allow greater exceedance of value of threshold saturation. For example, Landals and Gill (1973) recorded more than 30 per cent of the total annual surface flow in a single day at long-lasting snowbank sites. In contrast, the maximum runoff recorded in one day at a snowbank in the present study represented only 16 per cent of the annual total.

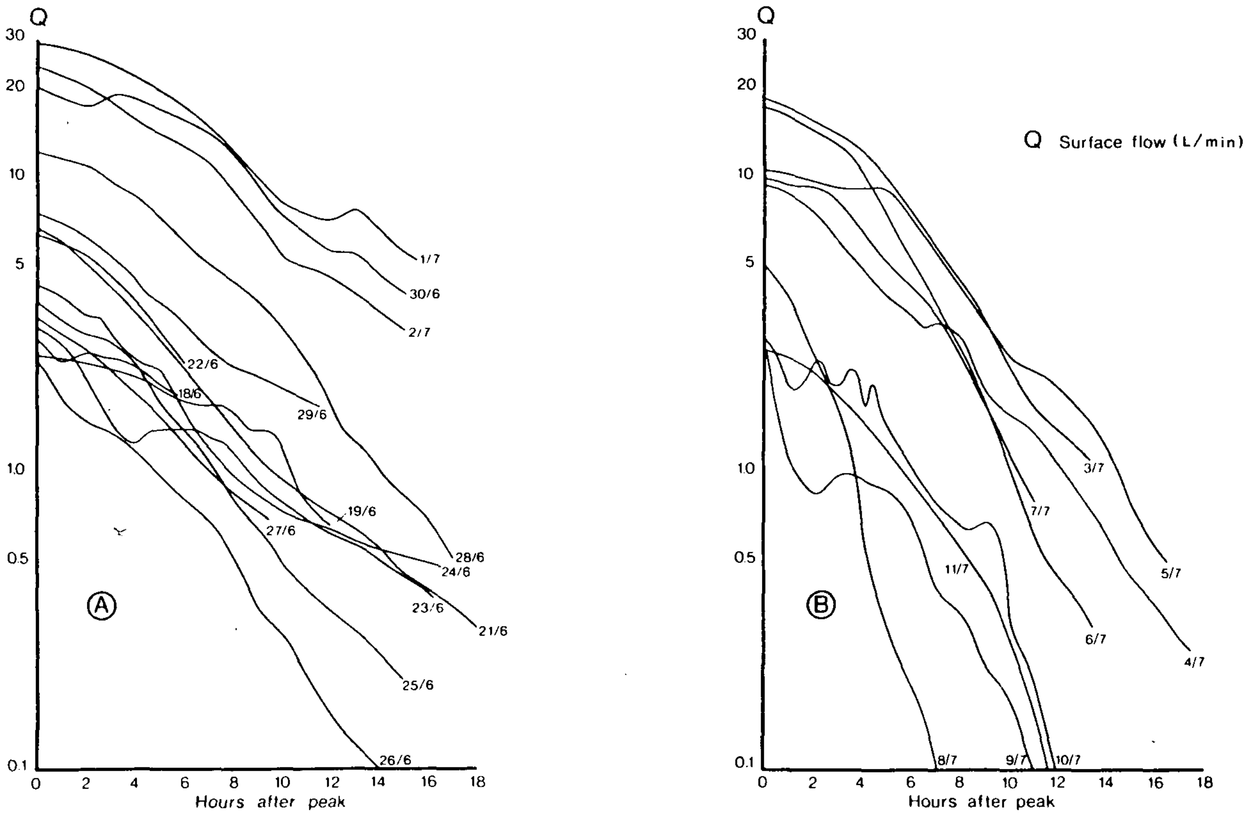
Diurnal Snowmelt Hydrographs

Eighty-five daily hydrographs of surface flow were recorded at the plots during the three field seasons. No two hydrographs are identical but a number of recurrent characteristics exist.

A typical hydrograph (Figure 6) is made up of (1) a steeply sloping rising limb, (2) a peak, and (3) a more gently sloping falling limb. On a day with cloudless skies, the limbs are relatively smooth curves, but the peak is sharp (e.g. July 1 and 2, Figure 6). Similar smooth curves are produced on a day with overcast skies (e.g. June 29, Figure 6) but snowmelt rates are lower and a smaller volume of surface runoff is produced. Moreover, the maximum surface-flow rate occurs several hours later in the day and the hydrograph is less sharply peaked. On intermittently cloudy days, changes in energy inputs are reflected in a variable hydrograph shape. The double peak on June 30, for example (*see* Figure 6), represents the response to a double peak in net radiation produced by the passage of a bank of altostratus clouds.

Continuous surface flow prevailed at the snowbank locations during the middle part of the ablation season when recession curves extended into the following day. Discontinuous flow was usual first, at the interfluve site where the snow was thin, and secondly, at the snowbank sites at the beginning of the ablation season when melt rates were low, and at the end, when snow thicknesses were much reduced. These observations are consistent with both current snowmelt-hydrology theory (Colbeck 1972, 1974, 1977) and measurements made in subarctic and alpine areas (Dunne *et al.* 1976; Jordan 1979).

Lag times between energy inputs and surface-flow responses are least at locations with thin snowpacks. In addition, as the ablation season progresses, lag times tend to decrease as a result of diminishing snow thickness and increasing size of snow crystals. The longest recorded succession of hydrographs (plot 3, 1978), shows that the times of (1) hydrograph rise, (2) the point mid-way to the peak, and (3) the hydrograph peak, all occur progressively earlier in the day as the melt season advances (Figure 7). There is little change in the average elapsed time between rise and peak, but the



RECESSION CURVES, JUNE 18 - JULY 2 **RECESSION CURVES, JULY 3 - JULY 11**

FIGURE 8. Surface-flow hydrograph recession curves, for plot 3, 1978.

lag time between the time of maximum clear-sky incoming radiation and the peak discharge, decreases from 9.25 hours at the beginning of the ablation season to only 0.60 hours on the last day of surface-flow generation. In addition, the steeper slope of the mid-point regression line indicates that the shape of the hydrograph changes as the ablation season advances, to a steeper initial limb and a broader peak. The dispersion about the regression lines arises mainly from varying meteorological conditions which influence both the time of peak energy input and through the surface melt rate, the speed of the shock-front in the unsaturated and saturated zones of the snow.

The recession limbs of diurnal hydrographs of surface flow represent the emergence of slow-moving melt fluxes developed after the time of peak surface melt. Slow drainage of the pack continues until the arrival of the following day's shock-front. Recession limbs tend to become steeper during the ablation season as horizontal and vertical flow paths decrease and snow permeabilities increase. This trend is exemplified by the 1978 data set from plot 3 (Figure 8) when obvious steepening of the recession limbs began after July 2 following a number of days of particularly rapid ablation.

Effects of Summer Precipitation

Surface-flow hydrographs were affected by rainfall only twice during the three field seasons, illustrating the relative unimportance of rainfall compared with snowmelt in generating surface flow. Moreover, in both cases it is probable that, without antecedent snowmelt to maintain high moisture contents in the active layer, surface flow would not have been produced.

The first rain-induced event occurred on June 15, 1977, when 6.25 mm of precipitation fell in 5 hours, with a maximum intensity of 2.5 mm/h. The hydrograph recorded at plot 2 can be separated by regression against lagged net radiation into a peak attributable to rainfall and "baseflow" attributable to snowmelt (Figure 9) (Lewkowicz *et al.* 1978). The response to rainfall is almost immediate and there is an equally rapid recession as the intensity decreases. These points suggest that the surface flow was de-

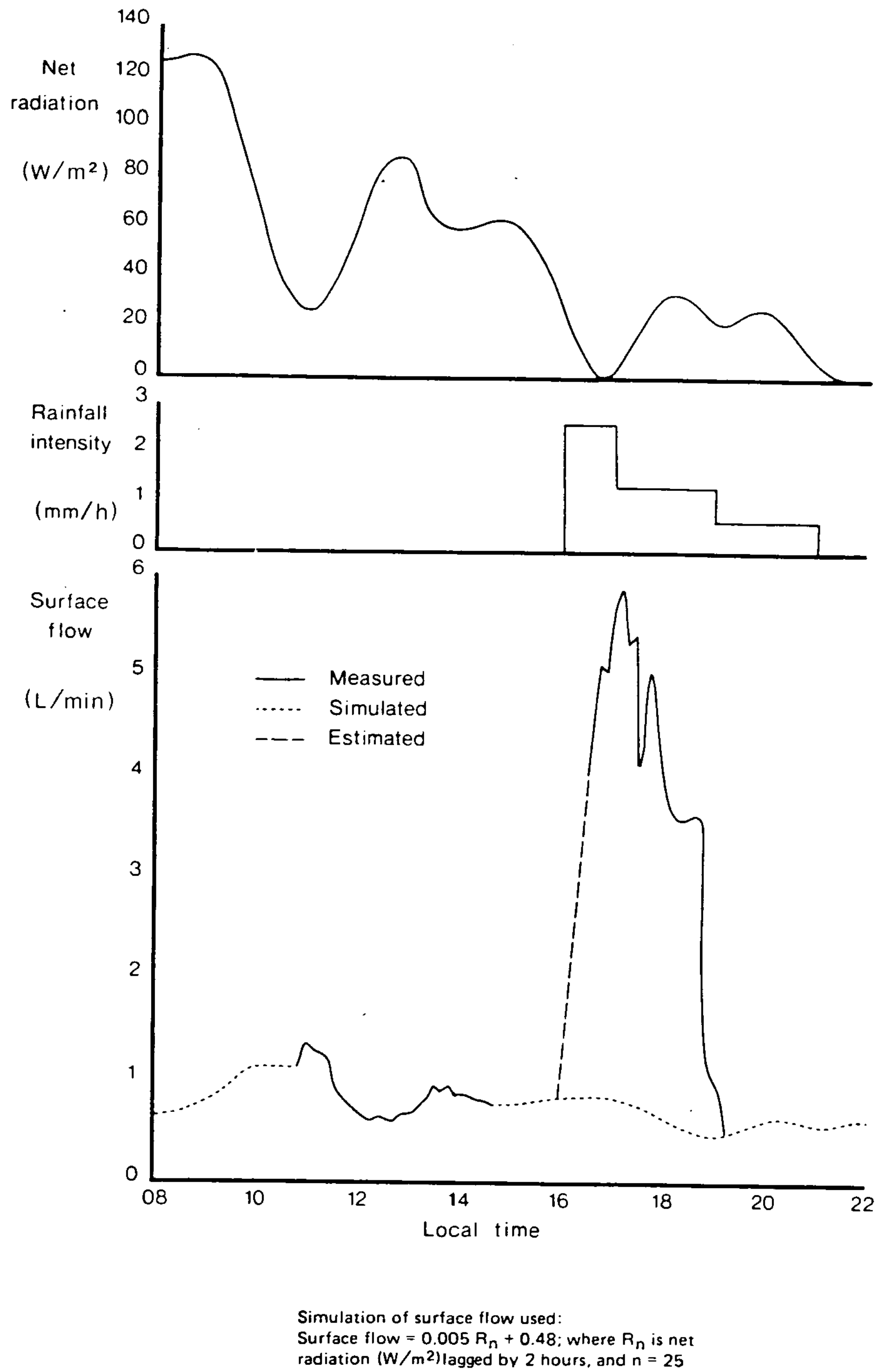


FIGURE 9. Rainfall and surface flow at plot 2, June 15, 1977.

rived from areas only a short distance away from the collector. The volume of rain falling on the saturated area of the runoff plot downslope of the snowbank can account for 92 per cent of the hydrograph peak. However, the peak represents only 20 per cent of the rain falling on the whole of the plot. Thus, most precipitation is thought to have been lost by infiltration into the unsaturated areas of the plot and to water storage within the snowbank.

During the second major storm (7.5 mm of rain in 3 hours) on June 23, 1977, surface flow was again generated at plot 2, although all snow on the plot had ablated three days earlier. In contrast, neither this storm nor the earlier one on June 15 generated surface flow at plot 1. No other precipitation event during the three field seasons, including a 7.2-mm storm on July 23 - 24, 1978, produced surface flow at any of the four runoff plots.

The explanation of the varied response to similar rainfall inputs is thought to be related to antecedent conditions. In most cases, rainfall appears to be able to generate surface flow only on an area saturated by snowmelt or on one very recently saturated. Consequently, the low-magnitude rainfall events typical of the high Arctic have the greatest probability of generating surface flow in those areas subjected to snowmelt inputs for the longest periods (i.e. snowbanks themselves and the areas downslope of them). Clearly, it would be rare for rainfall-induced surface flow to be produced at interfluve locations where snowmelt lasts for only four or five days of the year.

It follows that the partial-area contribution theory is the most relevant conceptual model for the western high Arctic. During the majority of summer precipitation events, the only parts of the catchment to produce surface flow are those where snowbanks still exist, or where they have recently existed. The areas contributing to stream runoff vary from one storm to another, depending on the timing of the storm relative to the progress of snow ablation in the catchment. Only during very exceptional storm events (e.g. Cogley and McCann 1976) aided by the presence of impermeable permafrost, are other areas of the catchment likely to produce surface flow.

Conclusions

This study has a number of implications concerning the hydrology of slopes in permafrost areas. The visual importance of snowmelt *versus* summer precipitation in high Arctic areas is confirmed by field measurements. Except at large snowbank sites, however, the subsurface flow route through the active layer appears more important than surface flow contributions to streams. During precipitation events, the partial and variable concepts of runoff generation appear valid. Because of the low magnitude of most summer storms, surface flow can only be generated during a limited time "window" during the ablation season. Moreover, the areas producing it are dependent on topographically controlled snowbank distribution rather than, as in temperate areas, on the location of streams.

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