Downslope water movement and solute concentrations within the active layer, Banks Island, N.W.T.

A.G. Lewkowicz
EBA Engineering Consultants Ltd., 5664 Burleigh Crescent S.E., Calgary, Alberta, Canada T2H 1Z8
and
H.M. French
Departments of Geography and Geology, University of Ottawa, Ottawa, Ontario, Canada K1N 6N5

Subsurface water movement and solute concentrations were measured during the summers of 1977, 1978, and 1979 on two slopes with small runoff plots, located in the vicinity of the Thomsen River, north-central Banks Island. At two other instrumented plots, subsurface-flow volumes were estimated from water-balance studies.

The results show that the relative importance of subsurface flow in the water balance of individual plots varied both at daily and seasonal time scales. On all slopes, however, snowmelt was the major source of water supply, and flow declined very rapidly after the end of snow ablation.

In general, the values of solute concentrations in subsurface wash were high. Concentrations tended to increase with depth within the active layer. Seasonal trends in concentrations at any one depth included relatively low values during most of the snowmelt period, an increase in the ten days that followed, and a "plateau" concentration attained at very low discharges.

The total weights of solutes removed from the plots by subsurface flow during the snowmelt season were large, with a maximum of 43 g/m^2 in 1978 at the site of the largest snowbank. Using a dry bulk density of 1.5 Mg/m^3, this figure corresponds to a denudation rate of 29 mm/1000 years. The removal of materials in solution by subsurface flow is thus regarded as an important geomorphological process in this area of the Arctic.

La circulation des eaux souterraines et leur concentration en solutés ont été mesurées pendant les étés de 1977, de 1978, et de 1979 sur deux versants occupés par de petites parcelles d'étude du ruissellement aux environs de la rivière Thomsen dans la partie centrale du nord de l'île Banks. En deux autres parcelles de mesure, les volumes de l'écoulement souterrain ont été estimés à partir d'études du bilan hydrique.

Les résultats obtenus indiquent que l'importance relative de l'écoulement souterrain quant au bilan hydrique de parcelles individuelles varie d'une manière quotidienne et saisonnière. Sur toutes les pentes toutefois la fonte des neiges constituait la principale source d'eau et l'écoulement diminuait très rapidement après la disparition de la neige.

En général, les concentrations de solutés de l'écoulement souterrain étaient élevées. Les concentrations avaient tendance à augmenter en fonction de la profondeur à l'intérieur de la couche active. Les tendances saisonnières de la concentration pour une profondeur donnée révèlent des valeurs relativement faibles pendant la plus grande partie de la période de la fonte et une augmentation pendant les 10 jours qui suivent; cette concentration atteint un "plateau" pour des débits très faibles.

La masse totale de solutée retirée des parcelles par l'écoulement souterrain pendant la période de la fonte est élevée et on a mesuré un maximum de 43 g/m^2 à l'emplacement du plus gros banc de neige. Basée sur une densité apparente à sec de 1,5 Mg/m^3 cette valeur correspond à une érosion de 29 mm/1000 années. Il s'ensuit que la disparition de matériaux en solution dans l'écoulement souterrain doit être considérée comme un important processus géomorphologique dans cette région de l'Arctique.

Proc. 4th Can. Permafrost Conf. (1982)

Introduction

Although hillslope hydrology is now a recognised field of study in both humid and hot, semi-arid environments (Kirkby 1978), relatively little attention has been paid to the movement of water through the active layer in permafrost regions. The hydrologic role of this subsurface flow, which is derived mainly from snowmelt, is not clearly understood. The few field studies that have been undertaken (e.g. Dingman 1971; Landals and Gill 1973; Soulis and Reid 1978; Wilkinson and Bunting 1975) provide useful but limited information. For example, in the discontinuous permafrost zone, Landals and Gill (1973) calculated runoff coefficients for eight plots which varied between 1.0 and 81.7 per cent. In areas of continuous permafrost, the potential importance of snowbanks in forcing subsurface flow to the surface through the maintenance of frozen ground has been noted by several investigators (e.g. Ballantyne 1978; Dutkiewicz 1967) but not quantified in detail.

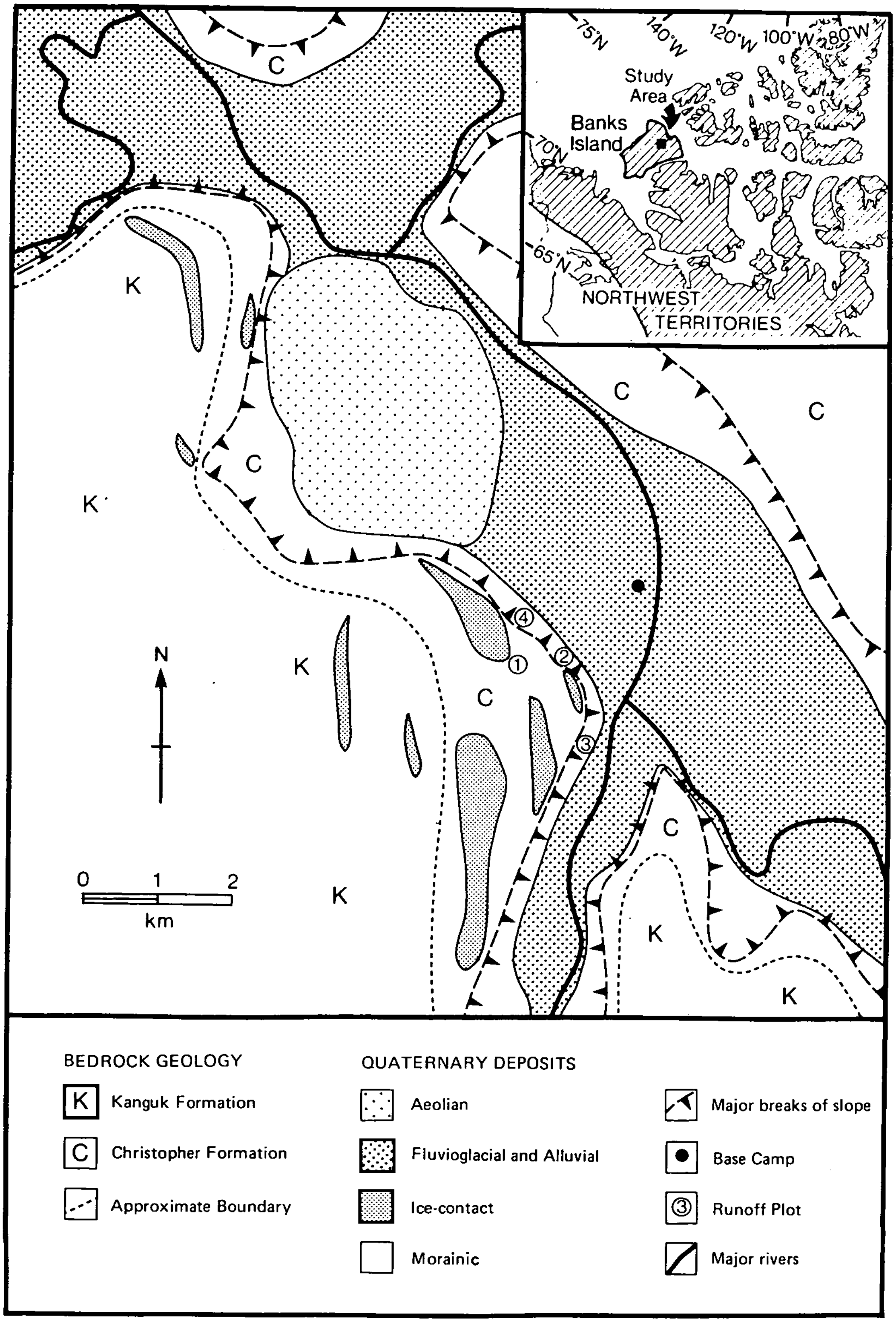

FIGURE 1. Bedrock and surficial geology of the study area (*after* Miall 1979, and Vincent 1978).

FIGURE 2. Upland terrain unit, July 15, 1979. On this date all snow had ablated at the interfluve site, but large accumulations remained at the snowbank plots (e.g. plot 2, *arrowed*).

Measurements of solute concentrations in both surface and subsurface flow in permafrost regions also are limited in number. The overall importance of solution as a geomorphological process was emphasised by Rapp (1960), but later work suggests that this conclusion may not be universally applicable (e.g. Chyurlia 1978; Guibault and Chacko 1978; Wedel *et al.* 1978). In the Canadian Arctic Islands, McCann and Cogley (1971) noted downslope increases in solute concentrations in rillflow derived from snowbanks. Woo and Marsh (1977) emphasised the effects of biogenic CO_2 production, and Wilkinson and Bunting (1975) noted a diurnal regime in solute concentrations in rills which they attributed to varying contributions by solute-charged talus interflow.

Within this context the present paper describes field observations undertaken on four slopes, each instrumented with a runoff plot, in north-central Banks Island. The aim of the study was to assess the geomorphic and hydrologic significance of water movement through the active layer in this part of the western Canadian Arctic. Here, attention is focused upon seasonal variations in subsurface water movement and solute concentrations. The derivation of estimates of average rates of denudation achieved by solution then becomes possible.

Study Area

Field work was undertaken during the summers of 1977, 1978, and 1979 in north-central Banks Island in the vicinity of the Thomsen River (latitude 73° 14′ N., longitude 119° 32′ W.). All the runoff plots were situated within an area of 2 km^2 (Figure 1).

The terrain in the study area consists of the wide valley of the Thomsen River and its major tributaries, and a series of gently rolling hills drained by numerous small nival streams (Figure 2). Relative relief is approximately 50 to 100 m and slope profiles are typically smooth convex-rectilinear-concave in form. Bedrock consists of poorly lithified sands and shales of Cretaceous age (Miall 1979). Few exposures exist, however, since veneers of surficial materials (silty clayey till, sandy ice-contact and outwash deposits) related to a pre-Wisconsin ice advance (Vincent 1978) cover much of the area.

The climate of Banks Island is characterised by long, cold winters and short, cool summers. Mean monthly air temperatures drop below -30°C in January and February and rise to a maximum of +6°C in July. Precipitation amounts are small, averaging 114 mm/a, approximately half of which falls as snow during the winter months. Soils and vegetation are transitional between tundra and polar desert. On south-facing slopes and in valley bottoms supplied with adequate moisture, meadow-tundra vegetation develops, while on interfluves and ridges polar-desert conditions prevail.

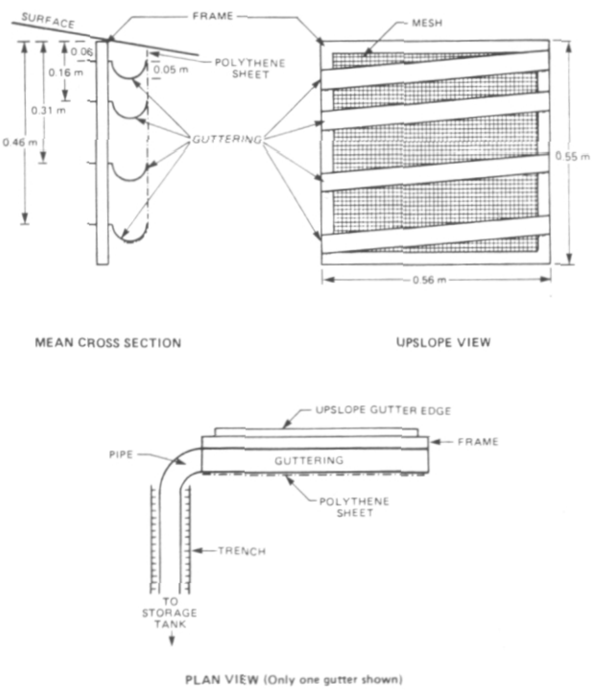

FIGURE 3. Subsurface-flow collection apparatus.

TABLE 1. Summary of collection site and characteristics of runoff plots

Plot No.	Type	Mean slope of plot	Aspect	Surficial materials	Subsurface flow collection
1	Interfluve	5°	125°	Gravelly sand	No
2	Snowbank	5°	315°	Sandy silt	No
3	Snowbank	12°	125°	Silty sand	(1) 0.06 m level within plot (2) 0.06, 0.16, 0.31 m levels 130 m downslope of plot
4	Snowbank	13°	70°	Silty sand	0.06, 0.16, 0.31, 0.46 m levels at exit of plot

Methods

The instrumentation used to monitor subsurface water movement was located on two of the slopes possessing runoff plots. Using Whipkey-type guttering (Figure 3), water was collected at four depths in the active layer (0.06, 0.16, 0.31, and 0.46 m). Two collection positions were at the margins of snowbanks while a third was approximately 130 m downslope of a very large snowbank (Table 1). The collection guttering was inserted during the summer of 1977 and results presented here are mainly from 1978 and 1979.

Subsurface flow was monitored during the snowmelt season by recording instantaneous discharges from pipes attached to the guttering. When discharges declined after the end of the ablation period, all flow was collected and measured, usually two to five times per day. In addition, for the snowmelt period, subsurface-flow volumes at all four runoff plots were calculated as residuals of the runoff-plot water balances (assuming permafrost to be an impermeable barrier). Comparison of these calculated values and the volumes actually collected suggests that contributory slope widths to the guttering were two to four times the width of the collectors themselves.

Samples of subsurface flow were subjected to field titration for total calcium and magnesium hardness (Schwarzenbach method) and/or to measurement of specific conductance. All measurements were undertaken within 24 hours of sampling and a strong positive relationship was established between the two methods. Solute concentrations in mg/L were estimated after multiplying the recorded specific conductance value (μs/cm) by 0.65, the middle value of the range given by Rainwater and Thatcher (1960).

Subsurface Water Movement

Results indicate a high degree of variability in the proportion of the water balance represented by subsurface flow, comparable to that recorded by Landals and Gill (1973). On a daily time scale, the percentage of snowmelt water taking the subsurface route to the stream ranges from near zero to almost 100 per cent. This is to be expected as the corollary of the threshold concept of surface-flow generation. In general, the higher the rate of meltwater production on a particular day, the lower the percentage of water leaving the plot as subsurface flow.

The results of two periods of 24-hour monitoring of the subsurface guttering (Figure 4), if typical, suggest the existence of two distinct subsurface-flow regimes downslope of an ablating snowbank. During most of the ablation period, surface flow is continuous and subsurface discharge rates at any particular level exhibit little variation. In periods of discontinuous surface flow, which usually occur at the beginning and end of the ablation period, subsurface-flow rates parallel the variation in surface flow, presumably an indication of active-layer desaturation.

At the annual time scale, variations in subsurface flow result mainly from the effects of two factors. First, meteorological conditions during the thaw season influence successive coefficients of daily runoff. Secondly, the snow distribution effected in winter alters the proportion of water that is lost to *in situ* ablation and to flow downslope within the snowpack. For example, subsurface-flow residuals at plot 2 vary from 23 per cent in 1979 to 83 per cent in 1978 with a three-year average (1977 to 1979) of 58 per cent.

Differences among the plots are thought to result mainly from the general variation in snowbank form. The greater the dimension of the snowbank orthogonal to the slope contours, the higher the meltwater production per unit width of slope. Since the regolith is unable to absorb this water, most leaves the plot as surface flow with a consequent reduction in the importance of subsurface discharge (Lewkowicz and French 1982).

Measurements show that subsurface flow de-

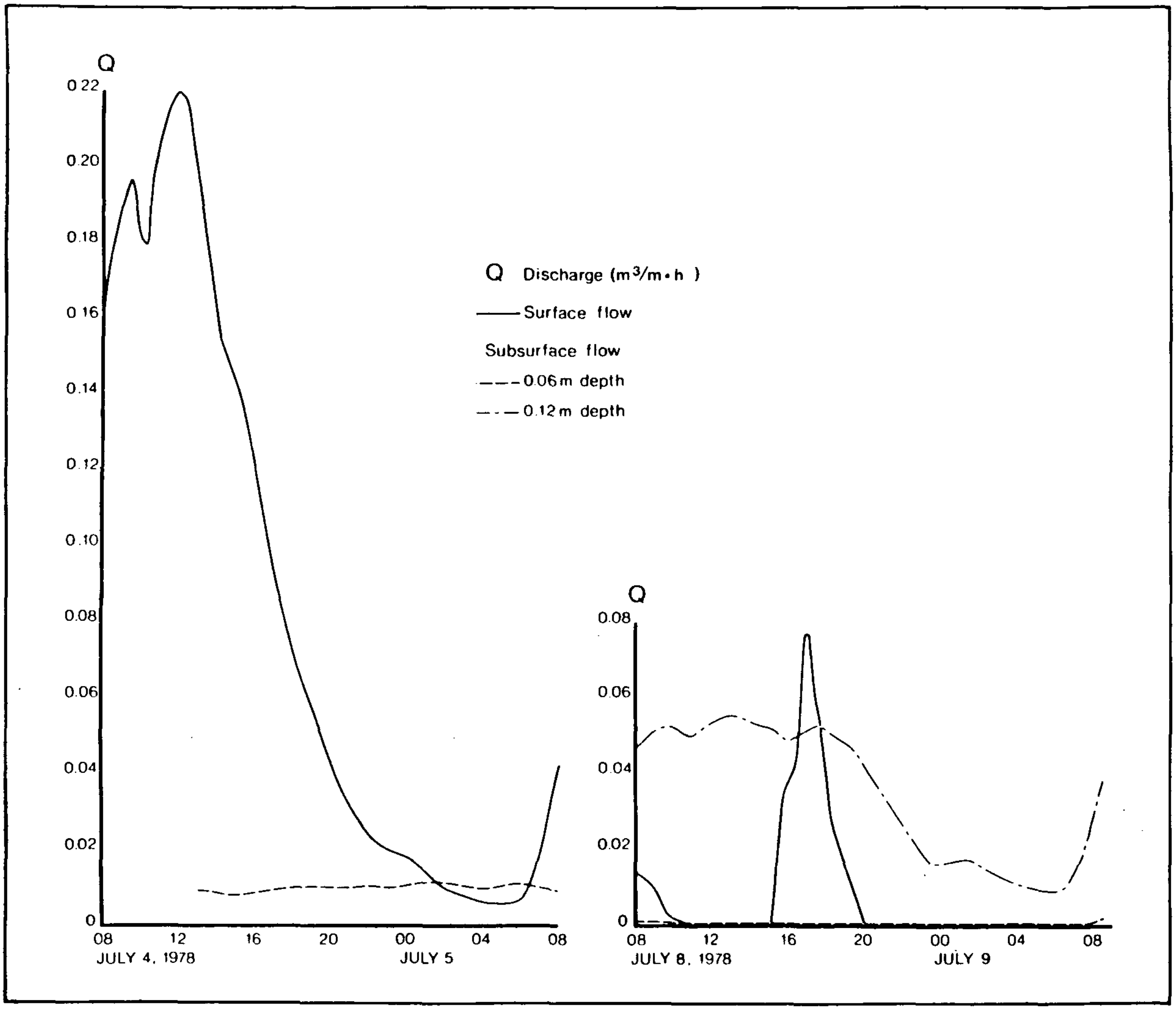

FIGURE 4. Comparison of surface and subsurface discharge rates for plot 4, 1978.

clines very rapidly following the complete ablation of snow (Figure 5). Flow ceases progressively from the higher collection levels downwards, and, during subsequent summer precipitation events, returns in the opposite manner. After the end of melt and following flow revitalisation by summer precipitation, recession is faster at site 4 and than at site 3, probably because the latter collector is located at the base of a longer slope. Although the possibility exists that thawing of ground ice is responsible for sustaining low levels of flow close to the frost table, in general, flow after the cessation of snowmelt is unimportant. For example, in the 30 days following the end of melt in 1978, only 0.132 m^3 and 0.075 m^3 of water were collected at all gutter levels from sites 3 and 4 respectively. In both cases, this discharge was equivalent to less than a single day's flow during the ablation period. The insignificance of subsurface flow following the cessation of snow ablation probably is linked to the rapid decline in nival stream discharge.

Solute Concentrations

The best record of seasonal solute concentrations in subsurface flow was obtained in 1978 when 250 samples were collected over a period of 45 days. A clear pattern can be observed in the values over this period (Figure 6) and is exemplified using data from the 0.16-m collection level at site 3. There are several points of note.

First, relatively low solute concentrations existed during most of the melt season. At this depth, con-

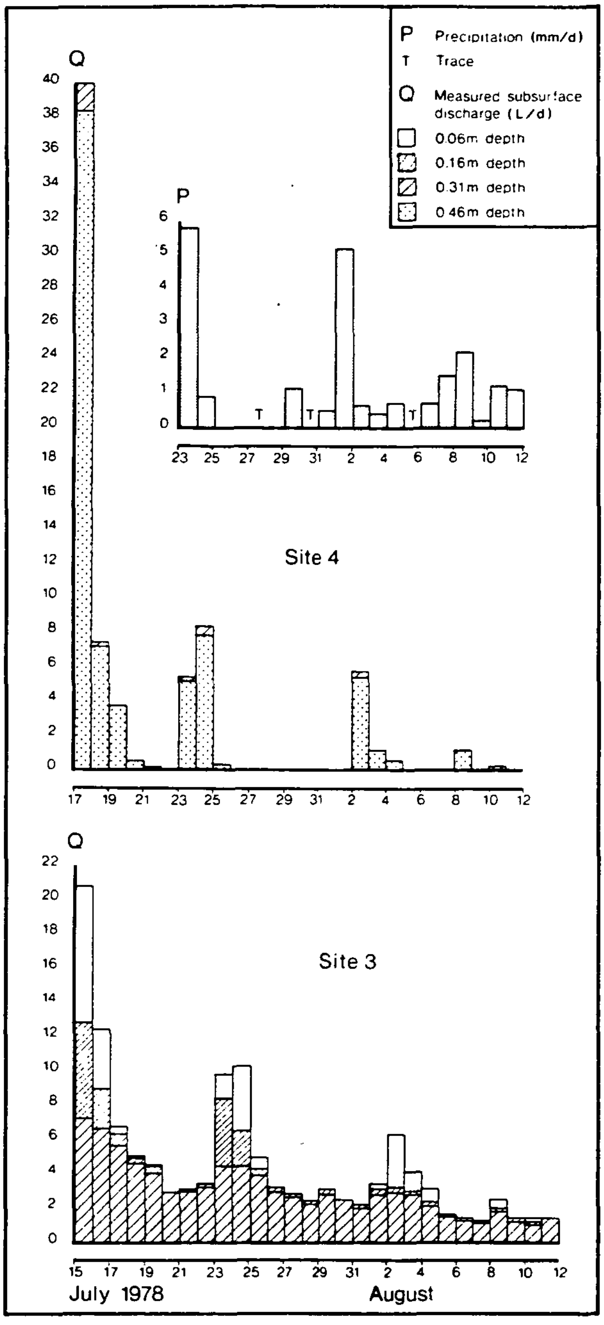

FIGURE 5. Decline in subsurface flow following snowbank ablation at sites 3 and 4, 1978.

centrations were 200 to 240 mg/L. Secondly, increases in concentrations occurred during the final two or three days of melt. Thirdly, a "plateau" concentration level with minor fluctuations developed in the very low discharges following the end of ablation; in this case, typical solute concentrations were 400 to 500 mg/L.

Explanation of these seasonal trends is thought to lie partly in changes of discharge with time (Figure 7). The relatively low concentrations evident during the majority of the snowmelt period correspond to discharge values that vary little and, by inference, to flow velocities and residence times that are almost constant. The moisture supply from upslope snowmelt is continuous so that water is moved through the active layer and is prevented from achieving high solute concentrations. Towards the end of melt, the duration of diurnal recession flow from the snowbank becomes shorter and the moisture supply becomes intermittent. Discharges decline progressively from the surface downwards and, as an increasing proportion of the flow occurs through soil pores rather than through fissures and larger voids, residence times and solute concentrations increase. When the last of the snow ablates, the moisture supply is cut off. If there is no precipitation, it can be inferred that all water samples subsequently collected have residence times equal to or greater than the time since the cessation of melt. Ten or more days after the end of melt, solutes in the subsurface flow reach an apparent equilibrium with the soil minerals and further increases in solute concentrations do not occur.

When precipitation events occur in the post-snowmelt period, some decline in solute concentrations may be induced (e.g. July 23; *see* Figure 6) as discharges increase (*see* Figure 5). Since concentrations do not decline to the values extant during the snowmelt period, it is probable that some of the discharge is soil water displaced by precipitation.

A further trend in the data is that solute values tend to increase with depth at any particular time. For example, correlation analysis of the relationship between 31 pairs of samples from the 0.06- and 0.16-m levels at site 3 and 36 pairs from the 0.16- and 0.36-m levels (Figure 8) reveals differences between the sample means of 28 and 182 mg/L respectively. Correlation coefficients are +0.97 and +0.91 respectively, illustrating the consistency of the trend. These differences in concentrations are thought to result mainly from longer flow paths and/or greater residence times at depth within the active layer.

Downslope changes in concentrations at particular depths can be inferred from the observations outlined above. During most of the snowmelt period, residence times and solute concentrations increase downslope. As flow becomes intermittent, however, the slope drains from the top first. With lower discharges in these upper areas, higher concentrations may occur temporarily upslope. Eventually, when all residence times are large, little or no

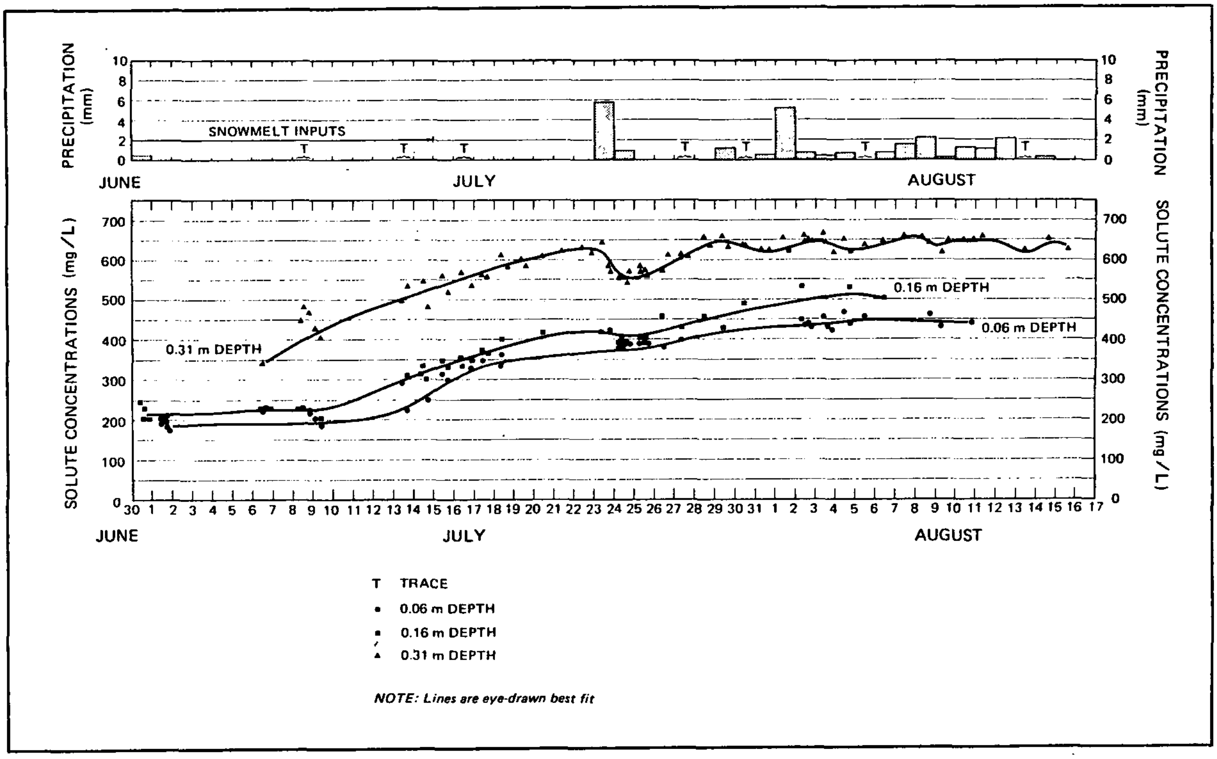

FIGURE 6. Seasonal variation of solute concentrations in subsurface flow, site 3, 1978.

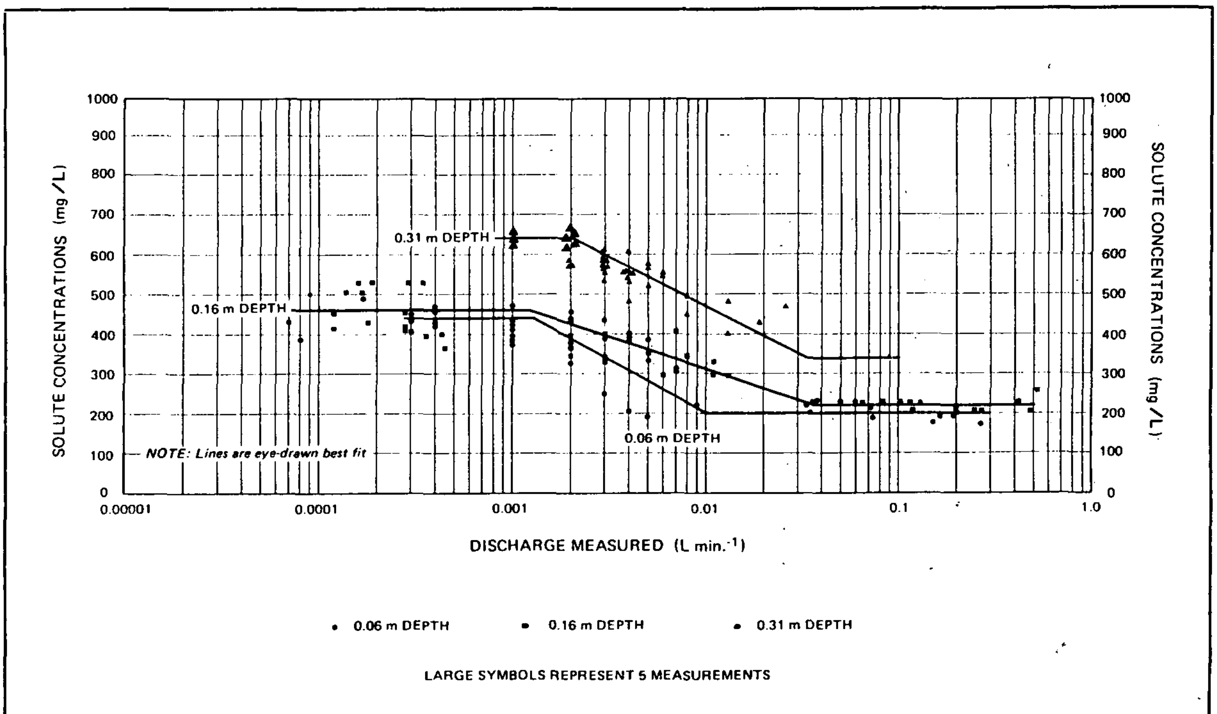

FIGURE 7. Variation of solute concentrations in subsurface flow with discharge, site 3, 1978.

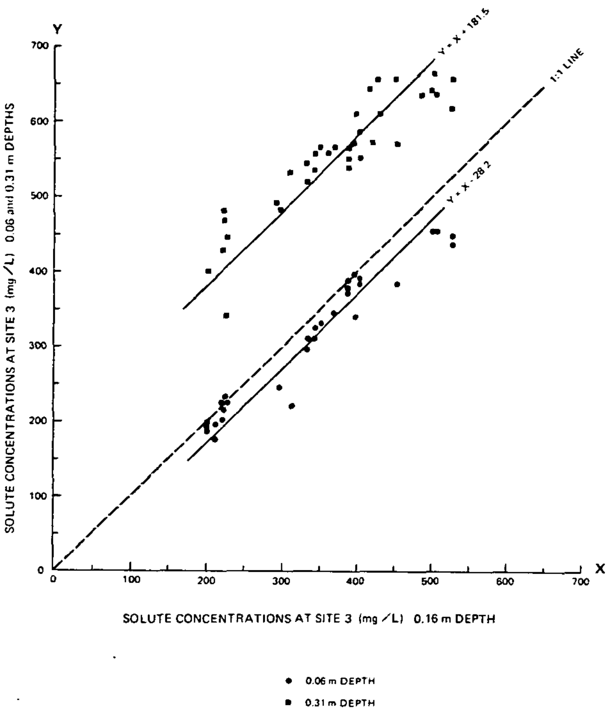

FIGURE 8. Correlations between solute concentrations in subsurface flow at three levels at site 3.

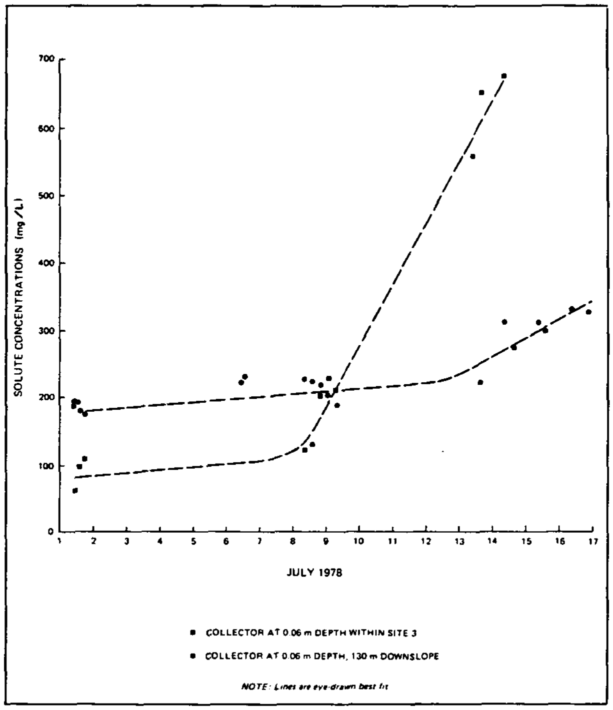

FIGURE 9. Downslope variation in solute concentrations in subsurface flow, site 3, 1978.

downslope variation in concentrations is likely. Limited data from the 0.06-m level within plot 3 and 130 m downslope from the snowbank (Figure 9) support these inferences. The first two stages are illustrated, with the crossover between downslope and upslope solute-concentration gradients apparantly occurring on July 9, 1978. Samples for the expected zero gradient were not collected as subsurface-flow volumes became too small to test.

Estimated Denudation Rates

Most subsurface flow takes place during the ablation period at high discharges and low concentrations. Estimates of the annual weight loss from the runoff plots due to solution by subsurface flow can be derived by multiplying mean solute concentrations during the ablation period by the residuals of the plot water balance equations (water inputs minus surface flow and evapotranspiration losses).

TABLE 2. Rates of weight loss and denudation due to solution by subsurface flow

Plot No.	Year	Plot area m^2	Weight loss over all the plot $g/(m^2 \cdot a)$	Area of plot affected by subsurface flow[b] %	Weight loss over affected area $g/(m^2 \cdot a)$	Denudation over all the plot[c] mm/1000 years	Denudation over affected area[c] mm/1000 years
1	1977	149.6	6	40	16	4	11
	1979	437.7[a]	4	54	8	3	5
2	1977	524.7	33	30	111	22	74
	1978	524.7	26	37	70	17	47
	1979	524.7	10	31	34	7	23
3	1978	262.3	43	30	144	29	96
4	1978	67.0	29	35	85	19	56

[a] Plot relocated on slope due to terrain disturbance in first year.
[b] Represents area of plot downslope of final position of snow.
[c] Dry bulk density assumed to be 1.5 Mg/m^3.

Weight loss values range from 4 to 43 $g/(m^2 \cdot a)$ (Table 2). Lowest values occur at the interfluve site (plot 1) and highest values occur at the plot associated with the largest snowbank (plot 3).

If one considers only those parts of the runoff plots which are downslope of the final position of the snow edge, prior to complete snow ablation (i.e. those areas actually affected by downslope water and solute movement), then rates of weight loss increase significantly. Values range from 7.6 to 143.7 $g/(m^2 \cdot a)$. Assuming a dry bulk density of 1.5 Mg/m^3, the latter values correspond to denudation rates of between 5 and 96 mm/1000 years (*see* Table 2).

Conclusions

Several conclusions are drawn from this study. First, subsurface flow through the active layer on slopes is a significant part of the hydrological cycle in a permafrost area. The seasonal subsurface runoff coefficient is variable, being largest at interfluve sites and smallest at the locations of large snowbanks. Secondly, decline in subsurface flow discharges is very rapid following the end of snowmelt. This is linked to a rise in solute concentrations which are relatively low during the melt period but increase after the end of ablation. Thirdly, estimates of the denudation accomplished by solution in subsurface flow support the view that solution may be an important geomorphological process in the high Arctic, particularly since the potential solutional effects of surface flow have not been included in the calculations.

Acknowledgements

Geomorphological studies on Banks Island are being supported by Natural Sciences and Engineering Research Council (NSERC) grant A-8367 (H.M. French) and by the University of Ottawa Northern Research Group (A.G. Lewkowicz). Logistical support was provided through the courtesy of G.D. Hobson, Director, Polar Continental Shelf Project, Department of Energy, Mines and Resources (Project 34-73). In addition, the Terrain Sciences Division, Geological Survey of Canada, permitted use of their tundra hut and equipment at Thomsen River, and the authors are grateful to Dr. B.G. Craig and Dr. T.J. Day for their assistance. Water-level recorders were kindly supplied through D.K. MacKay, Inland Waters Directorate, Environment Canada. A Mount Rose snow sampler was kindly loaned by the Rideau Valley Conservation Authority. The authors wish to thank EBA Engineering Consultants Ltd. for supporting some of the time spent in manuscript preparation and L. Dahl and T. Smeets who acted as draughtsman and typist respectively.

The authors also wish to acknowledge the excellent assistance of Gisele Champagne, Tom Colosimo, Joanne Lalonde, Annick LeHenaff, and Rosemary Spencer who, at various times, acted as field assistants. Without them, this study would not have been possible.

References

Ballantyne, C.K. 1978. The hydrologic significance of nivation features in permafrost areas. Geogr. Ann., vol. 60A, pp. 51-54.

Chyurlia, J.P. 1978. Snowmelt runoff, Airplane Lake Basin-June 1976. ESCOM Report No. A1-03; Environmental Social Program, Northern Pipelines. Dep. Indian Affairs and North. Develop., Ottawa, 11 p.

Dingman, S.L. 1971. Hydrology of the Glenn Creek watershed, Tanana River Basin, Central Alaska. US Army, Corps of Engineers, Cold Regions Res. and Eng. Lab. Hanover, NH, Res. Report, 297. 112 p.

Dutkiewicz, L. 1967. The distribution of periglacial phenomena in N.W. - Sorkapp, Spitsbergen. Biul. Peryglacjalny, vol. 16, pp. 37-83.

Guibault, R.A. and Chacko, Y.T. 1978. Water quality survey, Snowbird Creek Basin, Bathurst Island, preliminary report 1977. ESCOM Report No. A1-06; INA Publ. No. QS-8160-006-EE-A1. Water Quality Branch, Inland Waters Dir., Fish. and Environ. Can., 64 p.

Kirkby, M.J. (ed.). 1978. Hillslope hydrology. Wiley and Sons, New York. 389 p.

Landals, A.L. and Gill, D. 1973. Differences in volume of surface runoff during the snowmelt period: Yellowknife, Northwest Territories. *In*: The role of snow and ice in hydrology; Proc. Banff Symposia, September, 1972. UNESCO-WMO-IAHS, Geneva, pp. 927-942.

Lewkowicz, A.G. and French, H.M. 1982. The hydrology of small runoff plots in an area of continuous permafrost, Banks Island, N.W.T. Proc. 4th Can. Permafrost Conf. Calgary, Alberta, 1981, pp. 151-162.

McCann, S.B. and Cogley, J.G. 1971. Observations of water hardness from southwest Devon Island, Northwest Territories. Can. Geogr., vol. 15, pp. 173-180.

Miall, A.D. 1979. Mesozoic and Tertiary geology of Banks Island, Arctic Canada. The history of an unstable craton margin. Geol. Surv. Can., Mem., 387, 235 p.

Rainwater, F.H. and Thatcher, L.L. 1960. Methods for collection and analysis of water samples. US Geol. Surv. Water Supply Paper 1454, 297 p.

Rapp, A. 1960. Recent development of mountain slopes in Karkevagge and surroundings, northern Scandinavia. Geogr. Ann., vol. 42, pp. 71-200.

Soulis, E.D. and Reid, D.E. 1978. Impact of interrupting subsurface flow in the northern boreal forest. *In*: Proc. 3rd Int. Conf. Permafrost. Natl. Res. Council Can., vol. 1, pp. 225-231.

Vincent, J.-S. 1978. Limits of ice advance, glacial lakes, and marine transgressions on Banks Island, District of Franklin: a preliminary interpretation. Geol. Surv. Can., Paper 78-1C, Current Research, Part C, pp. 53-62.

WEDEL, J.H., THORNE, G.A., AND BARACOS, P.C. 1978. Hydrology of a small catchment on Bathurst Island, preliminary report, 1977. ESCOM Report No. A1-17; INA Publ. No. QS-8160-017-EE-A1. Water Surv. Can., Inland Waters Dir., Fish. and Environ. Can., 122 p.

WILKINSON, T.J. AND BUNTING, B.T. 1975. Overland transport of sediment by rill water in a periglacial environment in the Canadian High Arctic. Geogr. Ann., vol. 57A, pp. 106–116.

WOO, M.K. AND MARSH, P. 1977. Effect of vegetation on limestone solution in a small High Arctic basin. Can. J. Earth Sci., vol. 14, pp. 571–581.