BREAKUP OF STREAMS IN THE CANADIAN HIGH ARCTIC

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ABSTRACT

River valleys in the High Arctic are choked with deep snow at the time of breakup. This contrasts with river breakup in more southerly latitudes where ice is a critical factor. In the High Arctic, about three-quarters of annual runoff leaves the basins in two weeks following the initiation of flow, but such peak runoff is confined or obstructed by snow jams.

Recent studies in the vicinity of Resolute, Northwest Territories, show that snow distribution in the valleys strongly influences the sequence of flow events. Initial runoff occurs as slush flow, sheet flow over snow or subsurface flow in the snow. Subsequently, streamflow follows channels carved through the snowpack or tunnels formed inside the snow. In certain valleys, snowdrifts impound substantial amount of water to create a series of ponds. The bursting of these ponds generate flash floods of short duration which rapidly inundate the snow-filled valleys downstream.

Problems associated with these breakup events have implications on the planning of pipe-line crossings, culvert design and even the field measurement of flood discharge.

INTRODUCTION

In the High Arctic, streams usually dry up completely before the arrival of winter so that the valleys are free of river ice. In winter, the valleys are infilled with a substantial amount of snow. During the breakup periods, the valley snowpacks retard snowmelt runoff and jam up the downstream movement of flow.

Despite considerable attention paid to ice jams in Canadian rivers (e.g. Michel, 1971) little information is available regarding snow jams, though they are recurrent and prevalent in most parts of Arctic Canada (Pissart,1967; Sauriol,1978). A study of snow jams enables better understanding of snowmelt runoff relationship and hence finds applications in the prediction of melt-generated peakflows. It is therefore the purpose of this paper to describe the sequences of breakup in valleys where snow jams are frequent, and to discuss the possibility of predicting breakup events.

STUDY AREA

This study was carried out in an area near Resolute, Cornwallis Island, Northwest Territories (74°55'N, $94^{\circ}50'$W). Elevation of this area ranges from sea level to 200 m and the topography includes gently rolling to moderately steep slopes. Recent glaciation has left behind many topographic depressions some of which are occupied by lakes and ponds in summer (Fig. 1). Postglacial uplift has enhanced rapid incision of coastal streams, though many valleys remain non-incised at their upper courses.

Besides occasional presence of tundra vegetation, the ground surfaces are barren. The lack of natural obstacles enables snowdrifts to sweep over extensive areas throughout

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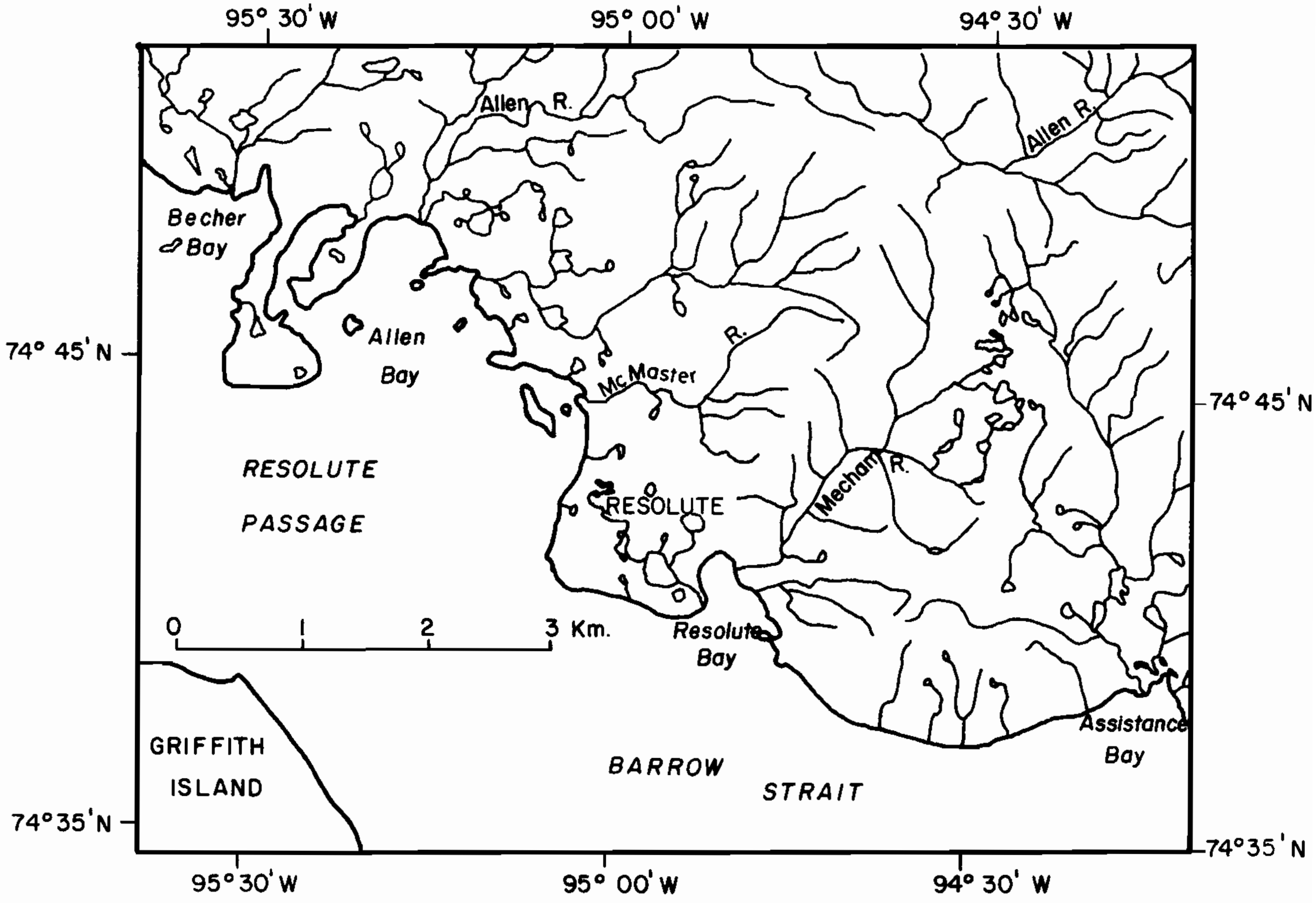

Fig. 1. Distribution of major river valleys and lakes in the vicinity of Resolute, Cornwallis Island, Northwest Territories.

winter, resulting in snowpacks of high density (over 350 kg m^{-3}) and hardness (exceeding 50,000 kg m^{-2}). Snow is an integral part of the landscape for over eight months each year. Melting does not occur in the long polar winters which experience radiation losses from the ground and the snow surfaces. With such energy losses, the snowpack is often very cold (below -15°C at the end of May) and the permafrost is very close to the ground.

FIELD METHOD

Field observations were made during the breakup periods of 1976 to 1978. Immediately before breakup, profiles of snow jams were surveyed at selected sites. Whenever possible, snow depths and densities were obtained using a steel pole and a Meteorological Service of Canada snow sampler. Time lapse photography was then taken at several valley segments to record the breakup processes. Some valley profiles were re-surveyed repeatedly throughout the melt season to show conditions of the snow jams as they disintegrated.

At three sites, water stage was recorded by Leupold-Stevens type F water-level recorders. In addition, staff gauges were set up to provide supplementary data. Discharge was obtained by velocity-area method, with velocity determined using a Price-type current meter.

FORMATION OF SNOW JAMS

In the High Arctic, the snow does not undergo any melting in winter, but drifting redistributes and compacts the snow. An interaction between topography and local winds produces snowpacks of varying depths and hardness. In valley locations, drifting usually accumulates a snow cover whose thickness exceeds those on hilltops and on the basin slopes (Woo and Marsh,1978).

Topographically, stream valleys can be generally described as incised or non-incised. Incised valleys are lined by steep slopes and are usually infilled with a large amount of snow. Non-incised valleys are more open and their floors are consequently more exposed, usually holding a thinner snow cover. The disposition of snow in the valleys gives variety to the form of snow jam.

Snowpack in a non-incised, narrow valley usually covers the entire floor, producing a uniform, smooth snow surface across the valley (Fig. 2a). For a non-incised but broad valley, snow distribution is asymmetrical across the valley, depending on the direction of snowdrift. In most cases, the lowest point on the snow surface seldom corresponds with the lowest point of the valley floor (Fig. 2b). Similarly, snow may accumulate quite uniformly across an incised, narrow valley (Fig. 2c), but not so for an incised valley with a broad floor (Fig. 2d). In addition, the distribution of snow along the length of incised valleys is often uneven, sometimes producing transverse ridges which span across the valleys to enclose snow troughs.

With the arrival of spring, the Arctic snowpack warms up and then melts differentially according to location and the characteristics of the pack. When runoff occurs, the presence of snow jams hinders the flow of water along the streams.

COMMENCEMENT OF RUNOFF

The energy available for snowmelt (Q_M) can be considered in terms of the energy balance equation

$$Q_M = Q^* - H - LE - G \qquad (1)$$

where Q* is net radiation at the snow surface, H is sensible heat flux, LE is latent heat flux and G is heat consumed to warm up the snow. In the High Arctic, net radiation remains negative throughout winter. When spring comes, net radiation increases but the bulk of it is first consumed in heating the ambient air, and then to raise the temperature of the snow to 0°C as well as to sustain sublimation from the snow surface. Figure 3 shows how the air and the snowpack warmed up gradually before snowmelt began at Resolute. This demonstrates a delay in appreciable snowmelt long after the net radiation has become positive.

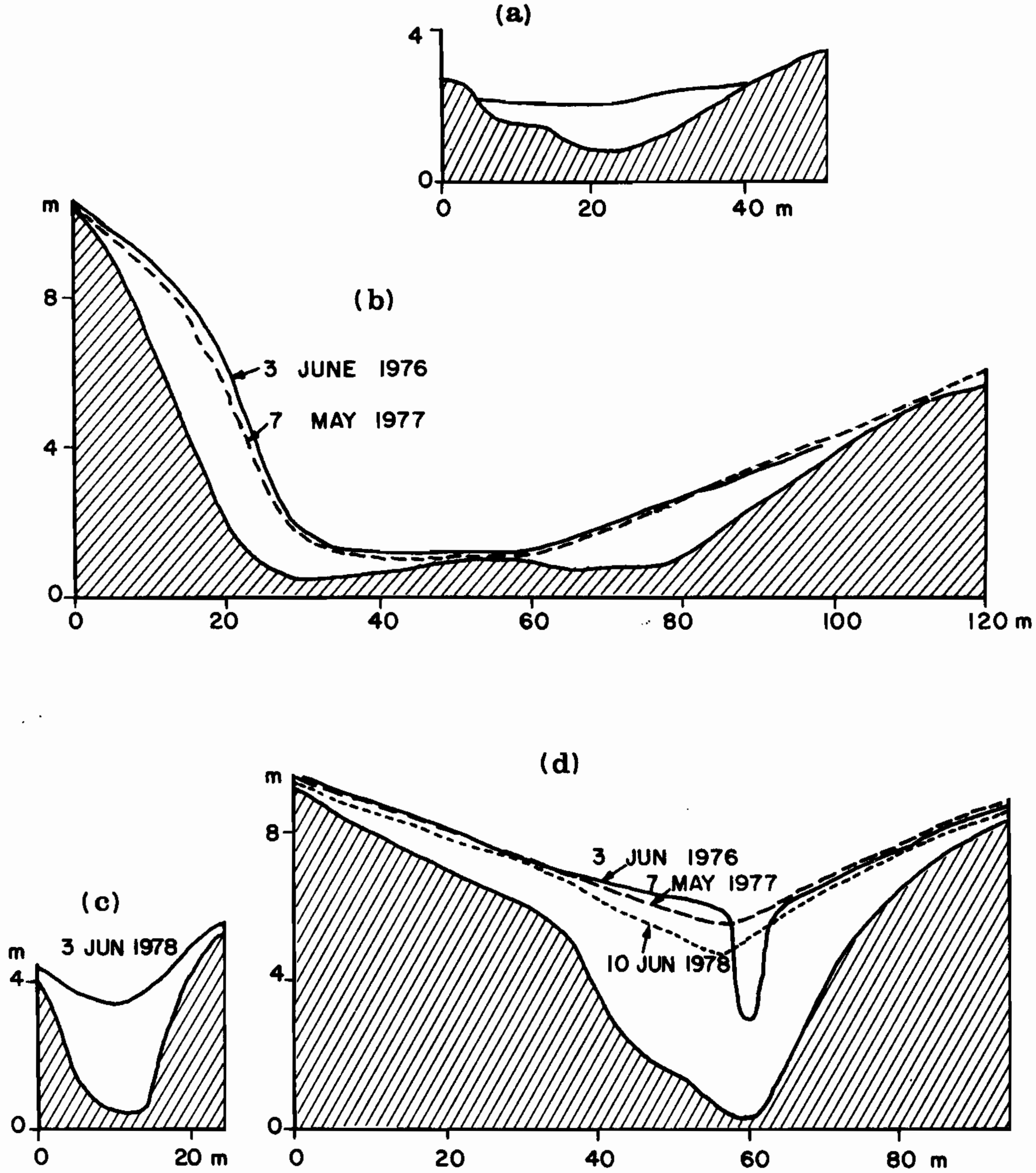

Fig. 2. Cross-sections of valleys showing the distribution of snow in
(a) a non-incised valley with narrow floor
(b) a non-incised valley with broad floor
(c) an incised valley with narrow floor
(d) an incised valley with broad floor.

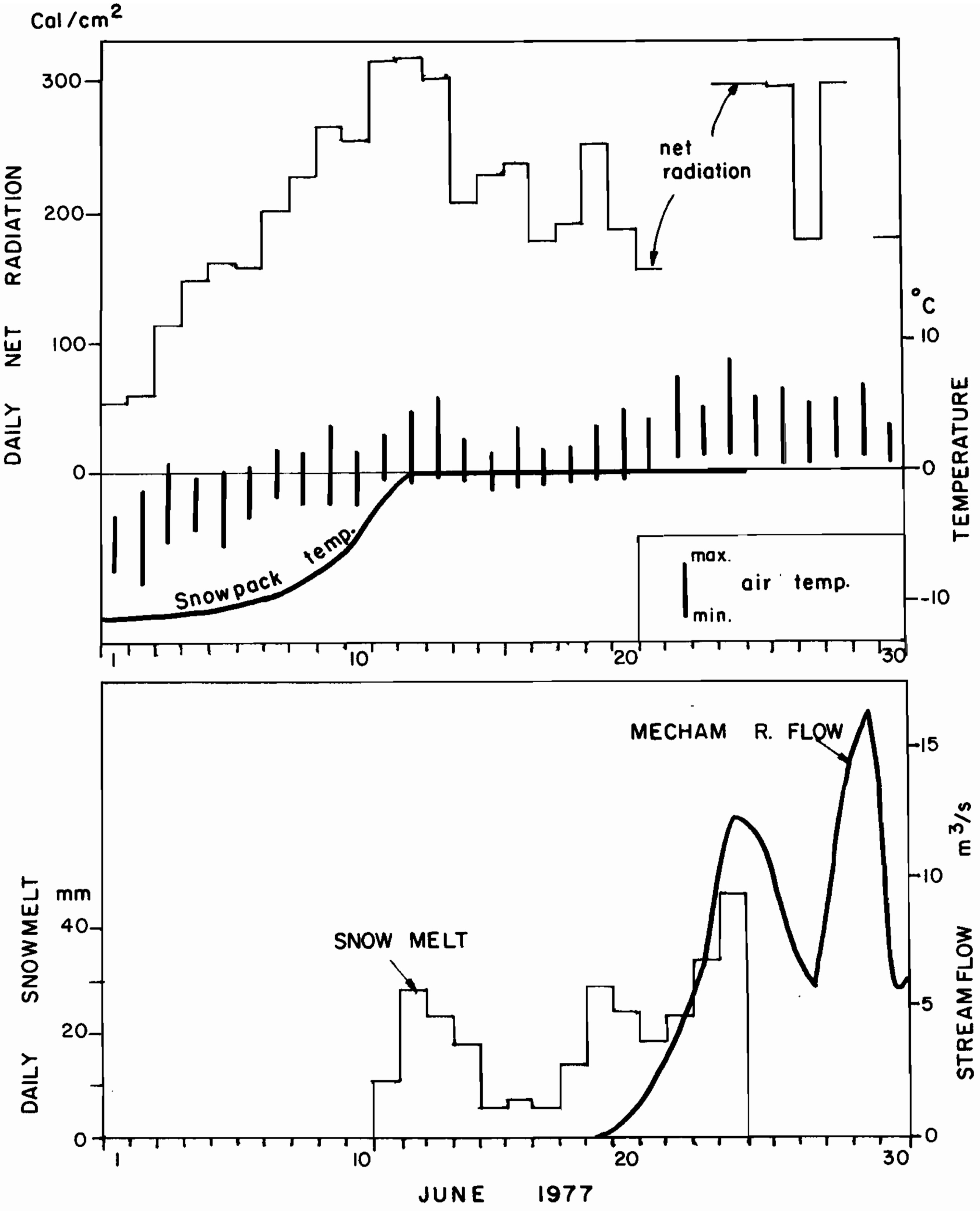

Fig. 3. Daily net radiation over snow, air temperature, snowpack temperature, snowmelt and streamflow rates at Resolute, June 1977. (Data from Atmospheric Environment Service, Water Survey of Canada and Heron and Woo, 1978).

The computation of snowmelt at a High Arctic site can be accomplished using an energy balance approach (Heron and Woo, 1978) but it is complicated by the fact that snow is unevenly distributed in the basins (Woo and Marsh, 1978). Thus, by the time the deep valley snowpack is totally ripened, some of the thinner snow cover would have disappeared on the hilltops and on some slopes. As meltwater continues to reach the valley snowpack from adjacent hillslopes, the pack becomes more saturated. Downstream movement of water commences by (1) seepage of water within the snowpack, (2) a slush flow of water and snow mixture, (3) sheet flow of water over snow surface. Eventually, these several forms of flow carve out channels in the snowpack and the flow of water then becomes confined.

DESTRUCTION OF SNOW JAMS

From the commencement of runoff, the streams have a tendency to carve their channels towards the lowest points on the valley floors. During the breakup period, water continues to cut through the snow until the channel is stabilized. In so doing, the snow jams are destroyed.

Figure 4 summarizes the different breakup sequences observed in the study area. For non-incised valleys, snowpacks are thin and through downcutting in the snow, the stream soon establishes its channel on the valley floor. However, where the initial channel position does not correspond with the lowest part of the valley, lateral shifting occurs as the stream undercuts the snowbank. When a stable channel is established, the residual snowpack is left to decay by melting.

In incised valleys, uneven distribution of snow produces ridges and troughs, the latter are filled with water drained from adjacent hillslopes and from upstream. The snow ridges become temporary dams until seepage or overflow ruptures the snow dams (Fig. 5). When this happens, a large volume of impounded water is released and a sequence of minor snow dams located downstream can be rapidly destroyed.

Snow jams in incised valleys can be quickly dissected by a large supply of water from upstream. The result is the creation of steep vertical snow walls fringing the channel (Fig. 6). If water reaches the valley snowpack slowly it will percolate through the deep snowpack. Should the hydrostatic water level in the snow fall below the surface, tunnelling will occur instead. The tunnel in the snow will continue to enlarge as snowmelt progresses, and fractures on the tunnel roof will accelerate its destruction.

For non-incised valleys and if the initial channel established in an incised valley is not located at the lowest points of the valley floor, the stream will continue to shift laterally by undercutting the snowbank. In several instances, the stream can suddenly divert its flow to an alternative channel carved elsewhere in the snowpack, and the residual snow jam then decays by melting.

STREAMFLOW DURING THE BREAKUP

Over half of the annual flow in High Arctic streams passes out of the basins during the breakup period (McCann and Cogley, 1972). The time of breakup varies slightly from year to year, but the annual peakflow is very often related to the breakup. Figure 7 shows the streamflow mass curves for a basin in the study area. Also graphed is a typical hydrograph for this stream showing prominent diurnal cycles related to the snowmelt regime.

Locally, the breakup of snow jams can cause the hydrograph to fluctuate irregularly. Where a snow dam ponds up meltwater, an area upstream of the dam will be flooded until a channel is created through the snow barrier. When this happens, a release of the water thus impounded will quickly increase discharge downstream of the dam. Figure 8 shows an example from the study area. In the case of "Three Mile Lake", very high flow was generated when the snow-choked outlet was broken on July 17th, 1978. In less than one day, over 70 percent of annual outflow was released and the lake settled back to its summer level. In another case, streamflow in a nearby basin was 0.3 $m^3.s^{-1}$ (July 9th,1976) at a site 1 km below a snow-dammed pond. One hour after the dam began to fail, streamflow rose to 1.0 $m^3.s^{-1}$, reaching a maximum of 1.9 $m^3.s^{-1}$ after several hours.

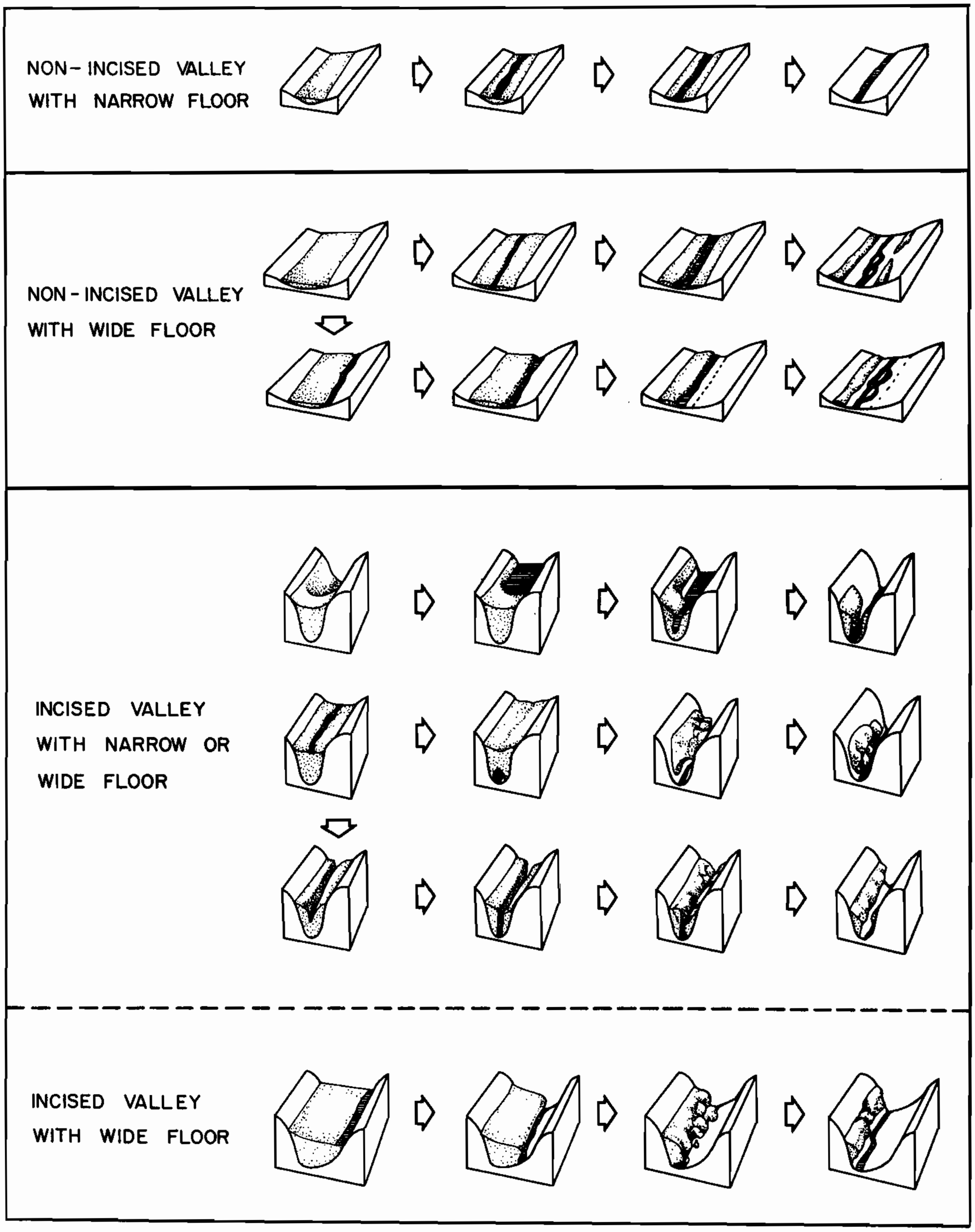

Fig. 4. Generalized sequences of breakup in snow-jammed valleys of the High Arctic.

Fig. 5. Rupturing of a snow dam (centre right) drains a temporary lake and generates peak flow to the valley downstream.

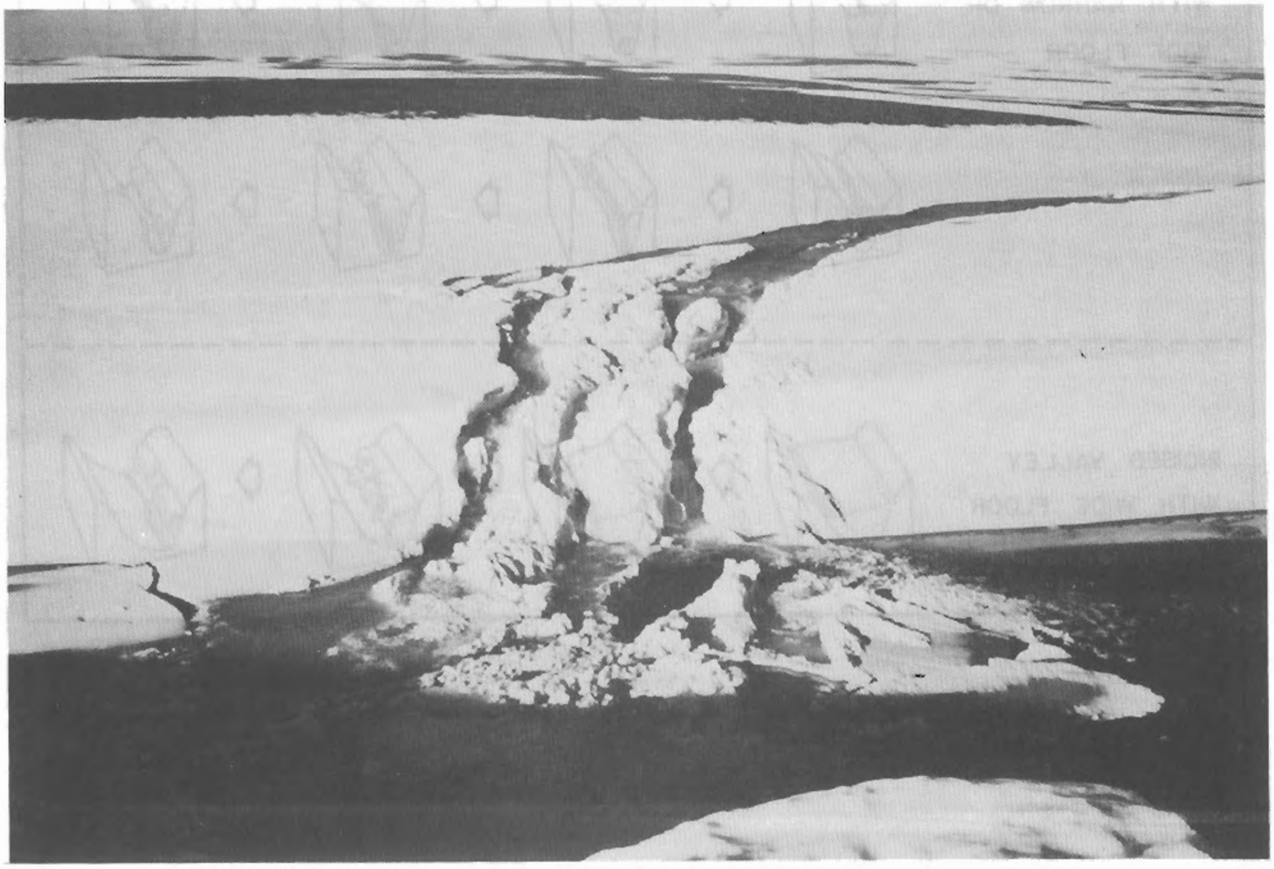

Fig. 6. Downcutting of a deep valley snowpack by slush and over-snow flow producing channels flanked by vertical snow walls.

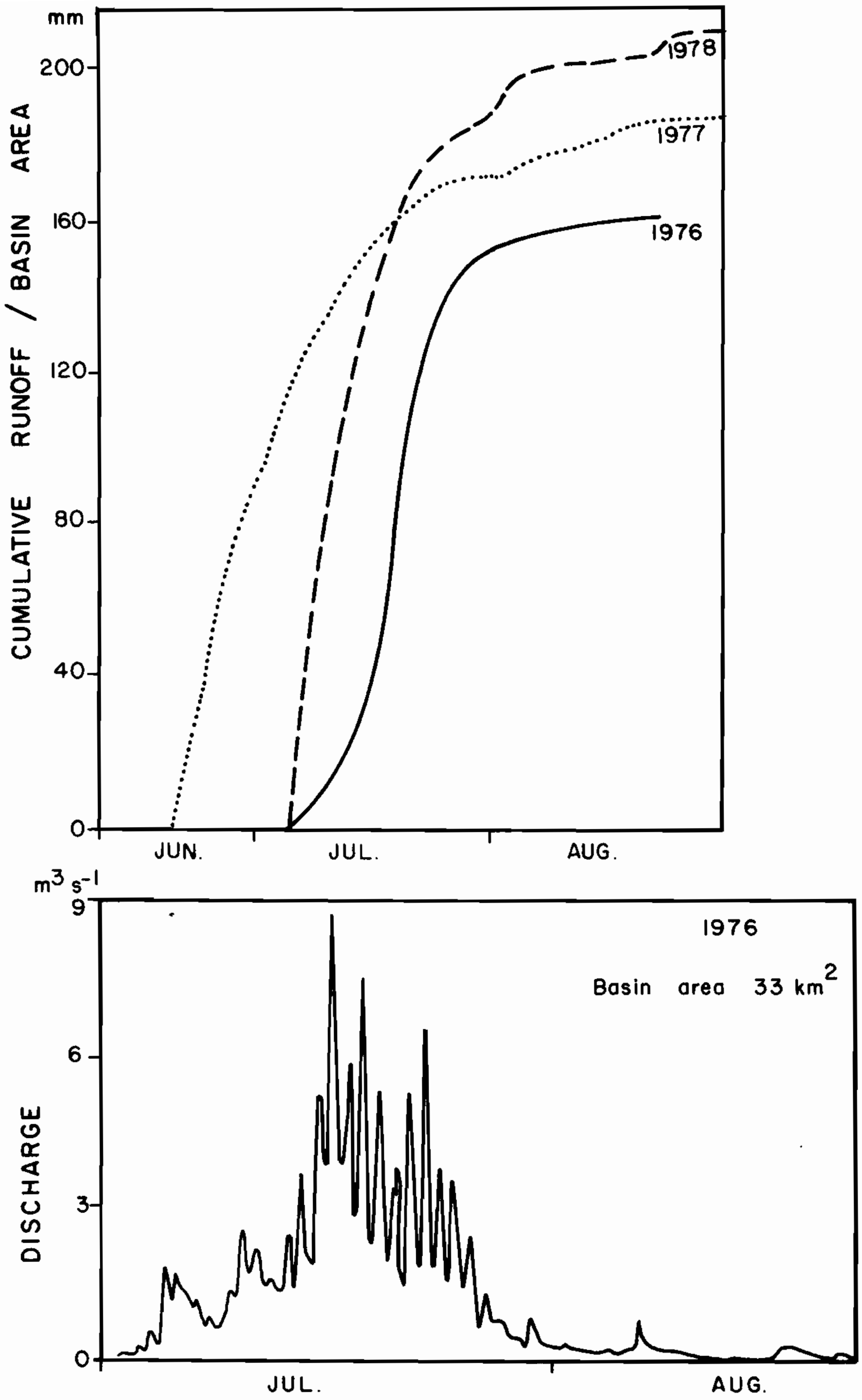

Fig. 7. (Top) Cumulative runoff for a small basin north of Resolute showing that the bulk of annual flow takes place during the breakup period. (Bottom) A typical hydrograph for the same basin showing prominent diurnal cycles due to snowmelt.

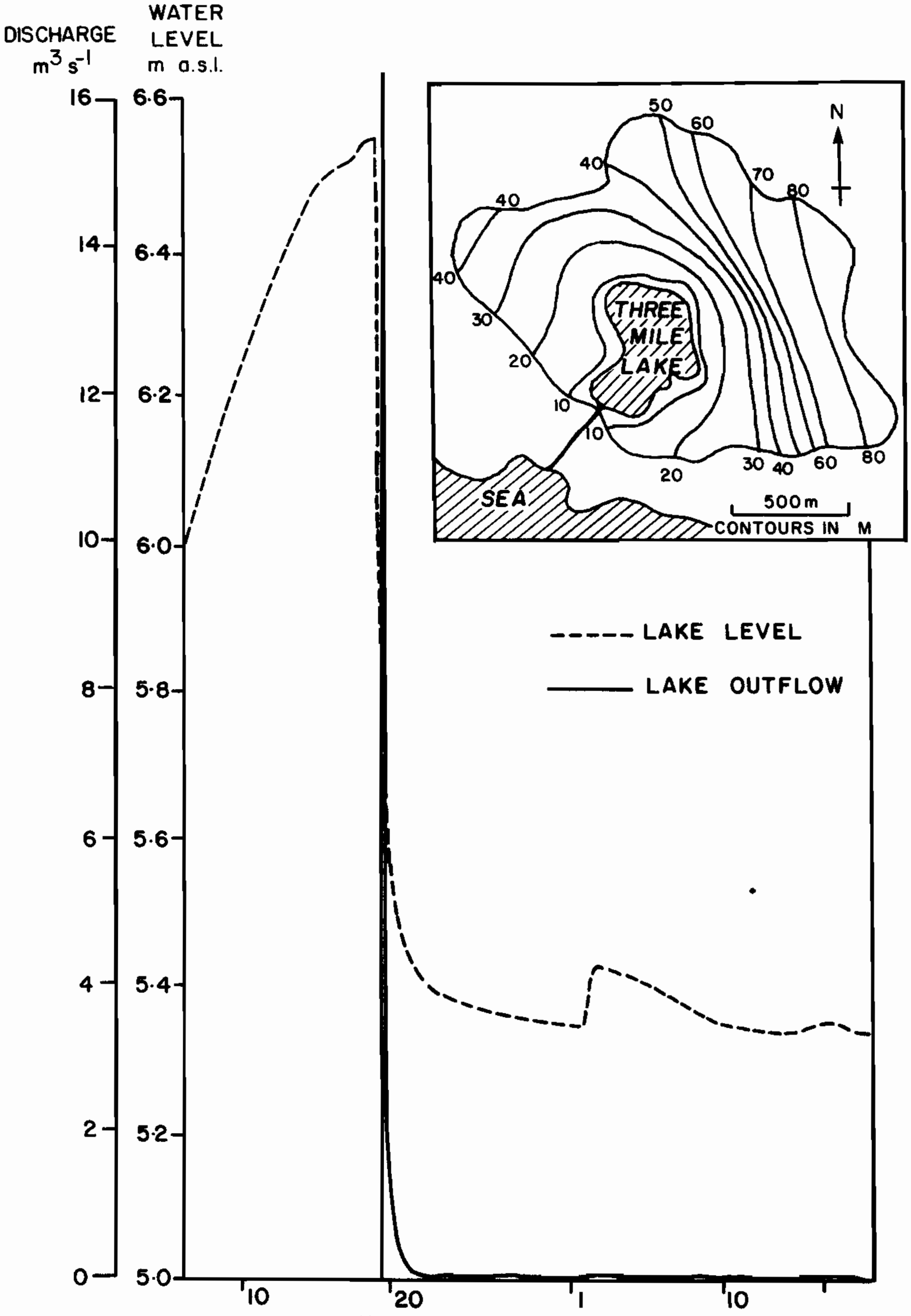

Fig. 8. Lake level and lake outflow hydrographs of Three Mile Lake showing a catastropic release of lake water as snow jam at the lake outlet was breached.

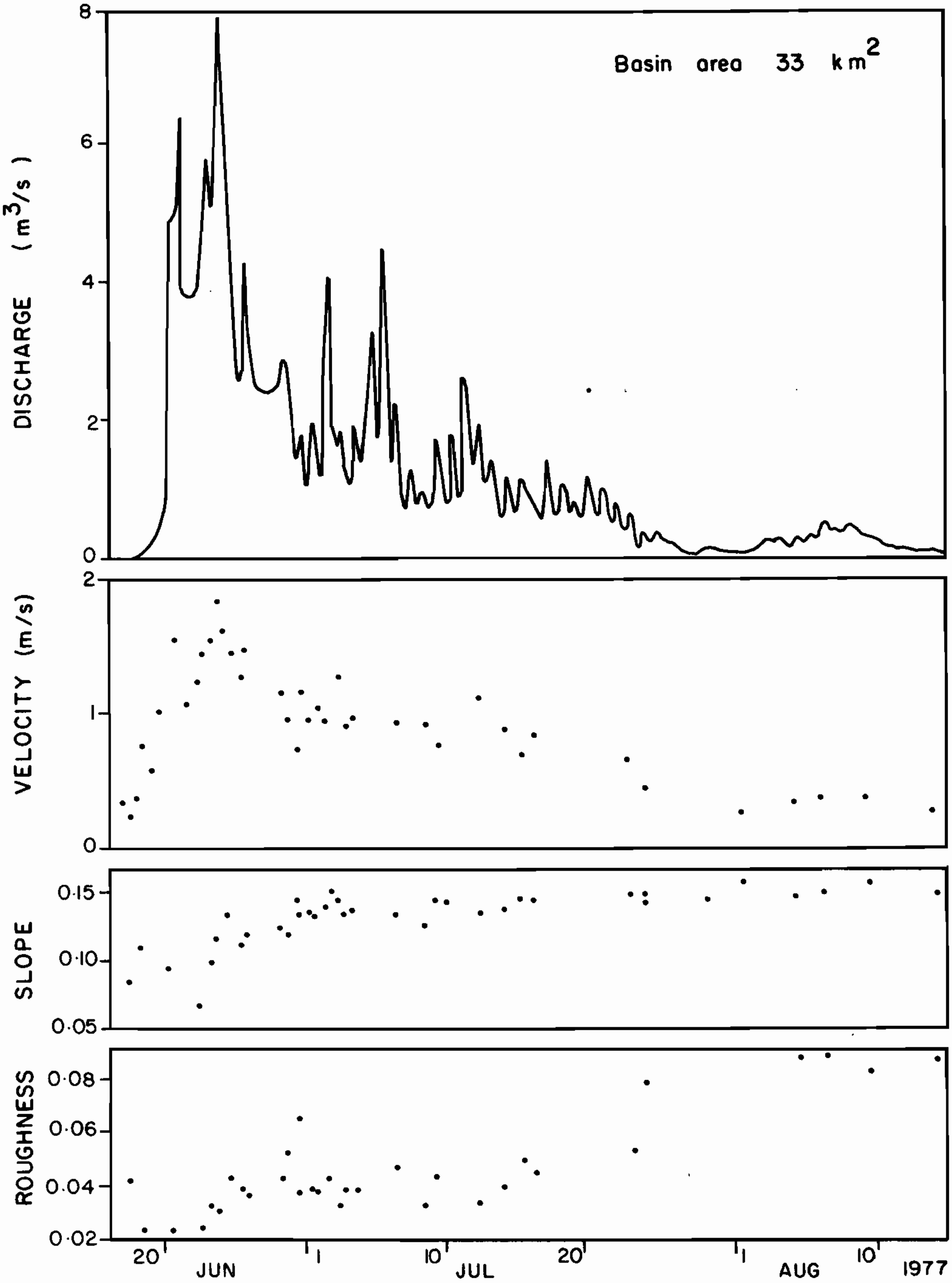

Fig. 9. Hydrograph, spot measurements of velocity, hydraulic gradient and computed Manning's n for a guaging station located north of Resolute.

With high flow accompanies large tractive force which permits the transport of bedload that otherwise cannot be removed by ordinary flow. In addition, during this high flow period, the channel is cut in snow and the roughness coefficient is much reduced. At a typical station, a measure of roughness (n) was obtained using the Manning equation

$$n = R^{0.67} S^{0.5} V^{-1} \qquad (2)$$

where R is hydraulic radius, approximated by mean depth of flow, S is slope and V is velocity. Computed values for the 1977 field season are shown in Figure 9. The stream flowed on snow and ice between June 16th and June 24th, but after which, flow was on gravel. This led to a gradual increase in roughness after the breakup period.

DISCUSSION

Based on the findings of 1976 to 1978, the general disposition of valley snowpacks did not vary greatly from one year to another, a fact attributed to the consistency of local wind directions during the several winters concerned. The same pattern appeared in a set of aerial photographs taken in 1969 which shows the position of late-lying valley snowpack. It is therefore hypothesized that the position of snow jams are relatively consistent, and this provides a basis for qualitative prediction of breakup events.

Figure 10 depicts the various breakup sequences in snow-jammed valleys. The flowchart enables a prediction of breakup events given information on the nature of the snow cover and the position of flow developed on or in the snow. Breakup follows the various combinations of downcutting, lateral shifting, tunnelling and ponding in snow. Since a given set of events usually recur at a particular valley segment, the scheme provided will allow a qualitative assessment of flood hazards, channel stability and sediment transport capacities of High Arctic streams.

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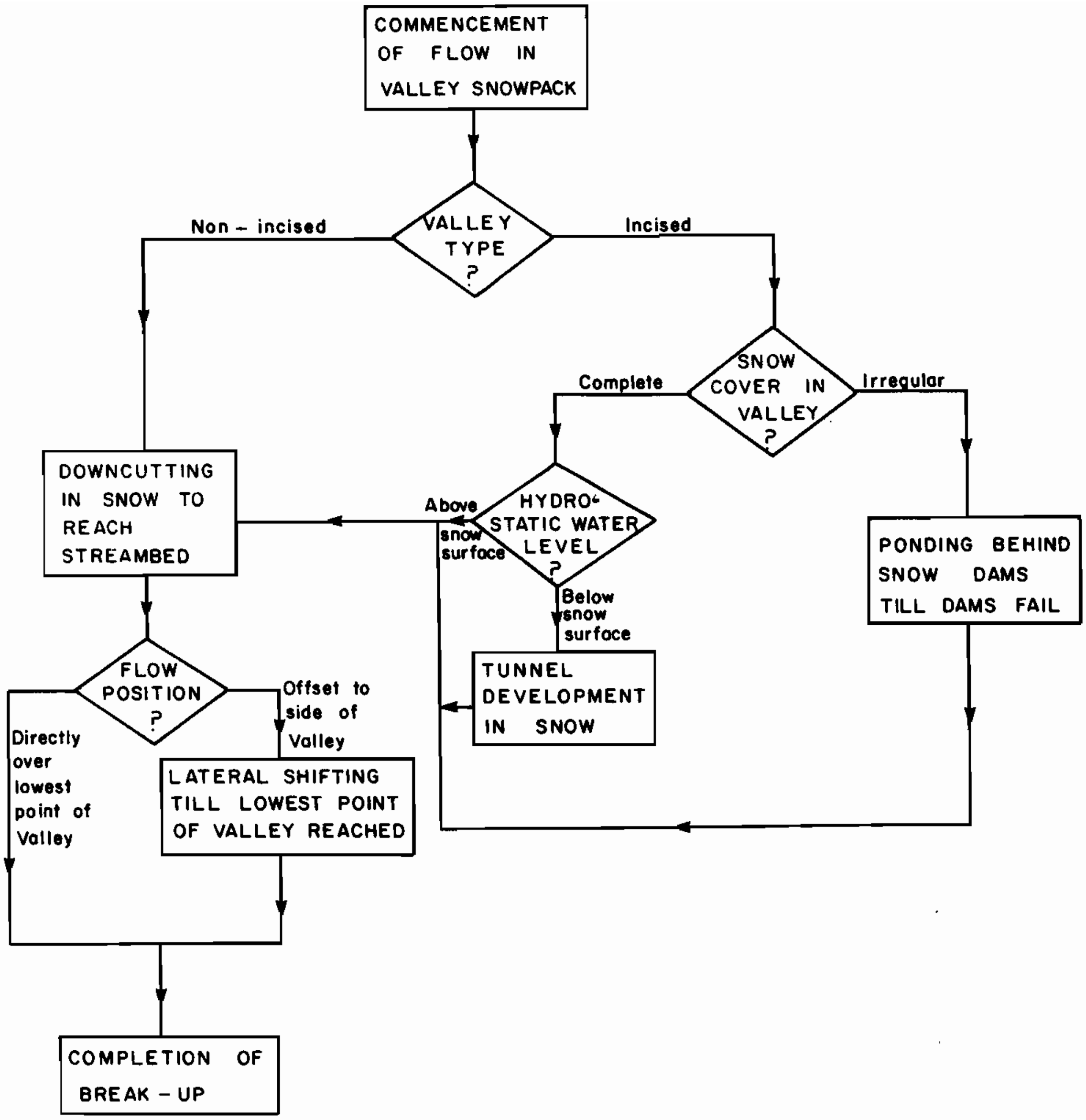

Fig. 10. Flow-chart summarizing the various breakup sequences in snow-jammed valleys of the High Arctic.