Nordic Hydrology, 11, 1980, 285-300

Monitoring Glacier Outburst Floods

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A review is given of the phenomenon of glacier outburst floods. Geographical distribution, modes of occurrence of glacier-dammed lakes and modes of lake-emptying are discussed. Techniques of monitoring the filling and emptying of glacier-dammed lakes are evaluated and procedures for forecasting the magnitude and frequency of floods are analyzed. The histories of floods on the Salmon River (British Columbia/Alaska) and the Donjek River (Yukon) are given as examples.

Introduction

The presence of glaciers within a watershed can considerably affect streamflow. Usually peak flows are delayed until middle or late summer and during this period range in diurnal flow can be greatly increased. Most glacier fed streams have these distinctive seasonal and diurnal characteristics. Of far greater significance within a relatively small number of glacier-covered watersheds are "jökulhlaups", (the Icelandic term for glacier outburst floods), caused by the sudden and often catastrophic release of bodies of water impounded by the ice. The magnitude of these events varies, but it is not uncommon for peak discharge during a jökulhlaup to exceed by an order of magnitude a snowmelt or rain induced flood in the same watershed.

Glaciers are dynamic. They are constantly changing their size and shape in response to climatic changes. Some glaciers change very slowly while others, particularly surging glaciers, can change their shapes very quickly indeed. Lakes impounded behind an ice dam, within or on top of the ice, may be formed when the glacier reaches a certain size and shape and may disappear completely when a new set of conditions prevails. During its period of existence, which may vary from a few years to hundreds of years, the lake itself may go through several cycles of filling and discharging. Typically, the lake will fill to a critical level wherupon the dam will fail, the waters will be released and the dam will reform.

Jökulhlaups present particular problems for monitoring and forecasting because of their essentially ever-changing and ephemeral nature. While some characteristics are common to many jökulhlaups there is a certain uniqueness to each individual case. Thus, individual monitoring programs have to be established and normal regional methods of flood forecasting usually cannot be applied.

The literature on jökulhlaups is extensive. The most up-to-date theoretical treatment is given by Nye (1976) while a good review of the subject is given by Embleton and King (1968). Blachut and Ballantyne (1976) give a useful literature review and the article by Post and Mayo (1971) gives an excellent summary of the many types of jökulhlaups which occur in Alaska.

Geographical Distribution

Jökulhlaups are known to occur in most major glacier covered areas. Recent examples are known in such diverse places as the Karakoram, Mason (1935), Hewitt (1964), the Alps, Odell (1966), Keller (1950), and Norway, Aitkenhead (1960), Liestøl (1955). There are large concentrations of glacier-dammed lakes in Iceland, Thorarinsson (1939, 1953, 1957), Rist (1954), Björnsson (1975), Alaska, Post and Mayo (1971) and in some of the Canadian Arctic Islands, Maag (1969), Blachut (1976). The phenomena occur in many different climatic environments.

It is known that at the height of the last glaciation when ice sheets and glaciers were much more extensive than at present, glacier-dammed lakes and their associated outburst floods were much more extensive and presumably more catastrophic than at present. Floods in the distant past are often difficult to document and are thus largely conjectural, but some past outburst floods such as the emptying of Pleistocene Lake Missoula, Bretz, Smith and Neff (1956) and of glacier Lake Tahoe, Birkeland (1964) are well documented. There is also evidence for such floods in the area of the glacier lakes of Glen Roy, Scotland, Jamieson (1892).

Modes of Occurrence of Ice Dammed Lakes and Water Bodies

A lake may be impounded in an ice-free tributary valley at the side of a major valley glacier. This is probably the most common mode of occurrence of ice dammed lakes. Perhaps the most famous example of this type of lake is the Marjelensee in Switzerland, blocked off by the Aletsch Glacier, Embleton and

King (1968, p. 421). Other examples of this type of lake are Summit Lake (treated in detail later) and Tulsequah Lake both in British Columbia, Marcus (1960) and Phantom Lake on Axel Heiberg Island, Northwest Teritories, Canada, Maag (1969). Such lakes can vary greatly in size, most of them being very small and occurring adjacent to the lower reaches of the glacier, below the firn line.

A less common, although often potentially much more catastrophic occurrence is when a major ice-free valley is blocked by the advance of a glacier from a tributary valley. In this situation it is possible that very large lakes may form, perhaps taking many years to fill. The advance of the Biafo Glacier in the Karakoram to block the main valley of the Braldu River is an example of such an occurrence Hewitt (1964). The Tweedsmuir and Lowell glaciers, British Columbia, are known to surge periodically into the main valley of the Alsek River, causing large lakes to form which sometimes discharge suddenly into the valley of the lower Alsek, Kindle (1953).

Occasionally, lakes are formed in the embayment between two converging glaciers. Between Lake formed at the junction of the White and Thompson glaciers on Axel Heiberg Island is an example of a lake of this type Maag (1969).

Bodies of liquid water are often held within or under glaciers. Most such englacial and subglacial bodies of water are small and although they are possibly numerous within many glaciers they are probably ephemeral and their sudden release will usually not be noticeable on the stream hydrograph. Occasionally, however, such water bodies attain very great proportions and the flood resulting from their release can be truly catastrophic. Grimsvötn under the Vatnajökull in Iceland is the classic example of a sub-glacial lake which catastrophically drains every few years, Nye (1976), Björnsson (1975). During a Grimsvötn jökulhlaup as much as 7 km^3 of water can drain through a 50 km long subglacial tunnel within a period of a few days to produce catastrophic flooding of the outwash plain below. The 1934 outburst of Grimsvötn climaxed in a drainage of about 4 or 5 $\times$ $10^4 m^3 s^{-1}$, Thorarinsson (1953, 1957).

Lakes can form on the surface of glaciers. The most common type of supraglacial lake is a shallow lake formed where there is a reversal in the surface slopes of the glacier filled by meltwaters from the glacier surface. Such features are usually small and ephemeral. Larger water bodies can be formed in sinkholes or by collapse of the ice-roof of a subglacial lake. Sinkholes 300 m wide and 90 m deep filled with water have been reported on the Martin River Glacier, Alaska, by Reid and Clayton (1963).

Modes of Emtying

There is a great deal still to be learned about the modes and timing of jokulhlaups. By their very nature they are difficult to observe. It is often costly and time-consuming to mount a monitoring program capable of adequately observing an event which may occur at an indeterminate time and last only a few days once every several years. It is usually almost impossible to measure the precise quantities of water involved in the huge stream discharges. The work can be very hazardous. As a result of these difficulties, relatively few complete and well-documented observations of outburst-floods have been made. Often only approximate timings are known, total amounts of water are roughly calculated from inferences about the size of the lake. These inferences are difficult enough if the lake is visible (shorelines and old photographs are commonly used) but doubly difficult if the lake is sub or englacial.

Reconstruction of the flood hydrograph is thus usually only very approximate. Blachut and Ballantyne (1976) give a detailed listing and description of most well documented jökulhlaups.

General theories to explain jökulhlaups are difficult to make for there are such a variety of local situations with a large number of possible combinations of mechanism. The greatest advances in our understanding of the possible mechanisms of flood release have been made in those situations where floods are repeated at approximately regular intervals and where for a variety of reasons a detailed monitoring program has been undertaken. The Grimsvötn jökulhlaups have been extensively studied by many people including Thorarinsson (1953, 1965), Björnsson (1975), Tomasson (1975) and Nye (1976). Summit Lake, British Columbia, and its associated jökulhlaups have also been extensively studied.

There are two main ways in which glacier dammed water bodies drain; they drain either a) through or underneath the ice or b) over the ice. It is difficult to directly observe instances of englacial or subglacial drainage. The water can often be observed entering a tunnel in the ice and can be seen issuing from the ice downvalley, but the way that it travels in between (in one or a number of tunnels or as sheet-flow under the glacier) and the mechanisms by which the passage is initiated and maintained are still largely conjectural.

Glen (1954) has shown that it is possible for liquid water bodies to move through glacier ice by slow plastic deformation of the ice. This process may be speeded up by water finding its way into preexisting cracks and veins in the ice or between the ice and rock caused by ice movement. A steady flow of water may eventually be possible. The flow will remain approximately constant and stable if melting of the tunnel walls by the water equals the closing of the tunnel by plastic deformation of the ice due to gravity. It is debatable for how long such a stable condition can exist.

Röthlisberger (1972) and Shreve (1972) discuss possible mechanisms in detail. During a jökulhlaup the condition becomes unstable for a number of possible reasons, and flow rapidly increases to a peak discharge and then even more suddenly ceases, see Fig. 1. As the water body becomes larger there will be a greater tendency for the glacier to float on the water for hydrostatic head will increase. Water temperature may rise (most especially when water is flowing from

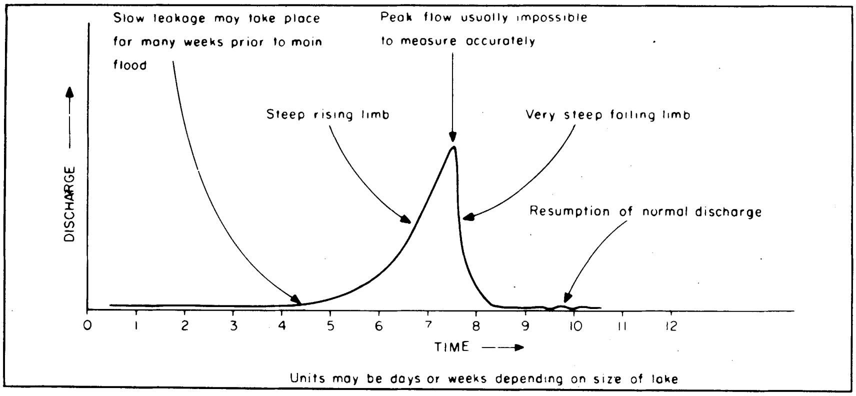

Fig. 1. Generalized Jökuhlaup Hydrograph.

surrounding rock into the lake) and thus more heat will be available for melting the ice. It is possible too that as the subglacial tunnel changes its dimensions and configuration there will be more frictional heat available per unit area of tunnel wall and thus the rate of melting and tunnel enlargement will become even faster. Nye (1976) has given this subject a detailed theoretical treatment.

While most jökulhlaups seem to be subglacial, there are many instances of lakes overflowing the ice, cutting channels in the ice and thus draining. This seems to be the most common mechanism for the many glacier dammed lakes on Axel Heiberg Island, Maag (1969). Maag has documented in detail how the overflow stream from Between Lake can cut a channel many meters deep through White Glacier within a few days, and how many marginal lakes overflow between the ice and rock at the edge of the glacier, cutting deep gorges which may be bridged by collapse of the ice so that the channel becomes subglacial for parts of its course.

The subglacial and supraglacial modes of drainage are not mutually exclusive. A single drainage channel from a lake may be partially below the ice surface and partially above. In addition, as in the case of the Marjelensee in Switzerland, some floods may be over the ice, others under the ice.

During the period of its existence, a glacier dammed lake may empty and refill many times and jökulhlaups may occur with consistent periodicity. The two main factors which govern such periodicity are the rate at which the glacier is changing its shape, thus affecting the size of the lake before discharge, and the consistency of the supply of water for lake formation. Glaciers usually change their shapes only slowly through time and thus the lakes will usually fill to approximately the same level on subsequent refills although there may be a trend towards increasing or decreasing size over larger time periods. However, there can be considerable climatic fluctuation from year to year which may affect the periodicity of outbursts especially if the cycle is a relatively short one. For example, Between Lake (Axel Heiberg Island) usually drains annually in July or August, but during the exceptionally cold summer of 1964, insufficient meltwater was produced to fill the lake and no outburst occurred.

The mechanisms for jökulhlaup releases can be more complex in volcanic or earthquake prone areas such as Iceland or some of the Alaskan mountain ranges. A sudden increase in geothermal heat-flow, especially if associated with a volcanic outpouring, or an earthquake which weakens the ice dam may be sufficient to initiate a flood which will then be self-sustaining by the previously mentioned mechanisms. Tryggvason (1960) shows that in Iceland volcanic activity is often associated with jökulhlaups but it is not always clear if the volcanic activity causes the flood or whether the flood, by suddenly releasing weight from the earth's surface, initiates earth tremors and volcanic activity.

Compound Catastrophies

Jökulhlaups can be catastrophic by themselves, but if their timing is such that they coincide with another flood or that particular conditions prevail within the watershed, the catastrophe can be compounded. The timing of jökulhlaups, even when successive floods have a consistent periodicity, need not be at the same time each year. Thus, there is always the possibility of the coincidence of a jökulhlaup with a snowmelt flood or a major rainfall event; the combination can have great significance for the watershed.

When there are many glacier dammed lakes within the same watershed, there is the possibility of two or more lakes releasing simultaneously or in the case that one lake drains into another of a flood from the upper lake triggering the release of the lower lake with a possibly increased maximum instantaneous discharge.

In some places a winter jökulhlaup can be much more disastrous than a flood of the same magnitude in summer. Post and Mayo (1971) describe how the Kenai River flooded unusually in winter; a relatively small outburst flood on the tributary flowing from Skilak Glacier was sufficient to break the ice on the Kenai River causing ice jams which in turn impounded the water and caused severe flooding.

As suggested earlier, jökulhlaups can occur in association with earthquakes and volcanic activity. Under certain conditions, landslides and mud flows may increase the intensity of the floods.

Networks for Monitoring and Forecasting Jökulhlaups

It is necessary to monitor jökulhlaup events so that better understanding of the phenomena are gained and so that better statistical forecasts may be made. However, as a result of their diverse modes of occurrence and the variety of emptying mechanisms, it is not possible to lay down rules in a conventional manner either for the monitoring of jökulhlaups or for the way in which forecasts of the magnitude and timing of such floods should be made. Rather, individual case histories must be built up in attempts to make better individual forecasts and situations of potential hazard must be identified.

The identification of Glacier Dammed Lakes

Present day lakes. It is a relatively easy matter to identify glacier dammed lakes from air photographs or, nowadays, from satellite imagery. Once lakes have been identified differentiation must be made between lakes which are stable in size and those which vary in size and shape. This is becoming an easier task as more and more frequent satellite imagery is becoming available for many parts of the earth's surface. Once unstable lakes have been identified, they must be studied individually as to their regimes of filling and emptying. Use will be made of former shorelines and features produced by floods such as scour marks and the destruction of vegetation in attempts to ascertain the magnitude and frequency of flood events.

Lakes which are at present stable must not be dismissed as harmless – rather the ways and rates at which the glacier is changing its shape must be estimated and estimates made of the timing of the critical glacier thicknesses which would allow overflow or subglacial drainage of the lake.

The identification and delineation of subglacial water bodies is much harder. However, there is usually some manifestation of such water bodies on the glacier surfaces – they usually occur where there are local reversals of glacier surface slope and crevasse patterns often indicate local subsidence of the roofs of ice caverns.

Any water body, especially a large one dammed by a small amount of ice, must be regarded as a potential source of a jökulhlaup flood even if the lake is stable at the present time. Estimates of magnitude and frequency of floods must be made for each individual case – evidence of clear cyclic flood events in the past should not automatically suggest a continuance of cyclic flood activity.

Particular attention should be given to situations in which floods compounded by other factors such as river ice break-up in winter are possible.

Past lakes. While it is obviously most important to identify and monitor existing lakes, evidence of past lakes and their associated floods must be compiled. The position of past lakes may be far removed from present day glaciers and evidence of their extent and mode of drainage must be sought in the geomorphological and vegetational record. In the case of recent Lake Alsek, dammed by the surging Lowell Glacier, evidence of lake extent can be seen in the abandoned shorelines and evidence of sudden flooding is seen in the giant ripple and scour marks on the lake floor formed when the water suddenly rushed out and in the trees removed from the valley slopes below the lake.

Identification of Potentially Hazardous Situations

It is sometimes important to envisage situations in the future which could result in the creation of glacier dammed lakes. Lakes are most likely to be formed when glaciers advance to block tributary or main valleys. The probability that glaciers will advance must be anticipated. Surging glaciers present a particular problem in this regard for they can advance so quickly. As illustrated in the case of recent Lake Alsek, blocked by a surge of the Lowell Glacier, Kindle (1953), there is other good evidence in the record of past lake shorelines to suggest the probable extent of future lakes should similar conditions once again prevail.

Glacier retreat can also produce lakes which are prone to emptying. This is especially likely if glaciers in small tributary valleys are retreating and being replaced by lakes impounded by a main valley glacier. Such situations are difficult to predict but such attempts should be made if the economic losses from outburst floods are potentially high.

Monitoring and Forecasting Techniques

The practical need to monitor jökulhlaup situations and to make flood forecasts will depend on the importance of the flood in human terms. If the river flows through areas of no human activity the need for monitoring will probably be low. On the other hand, when towns, roads, mining operations, etc. are threatened by the flood then careful monitoring may be justified. It is quite possible to make forecasts of floods without understanding the processes involved before and during the flood, although the more the processes of flood release are understood the better will be future forecasts. Thus the monitoring program will be appropriate to the particular situation being considered.

A valuable empirical relationship linking maximum instantaneous discharge to maximum water volume of the lake has been developed, Clague and Mathews (1973), based on data from 10 different jökulhlaup sites, including the example of Summit Lake, treated in detail below. The equation has the form

$$Q_{max} \equiv 75\, V_{max}^{\;0.67} \qquad (r^2 = 0.96)$$

Where Q_{max} is the maximum instantaneous discharge ($m^3\ s^{-1}$), V_{max} is available water storage ($m^3 \times 10^6$). If lake volume can be measured or calculated, this equation may be used as a good first approximation of flood magnitude immediately below the ice dam. A more physically based predictive method of forecasting the shape of the flood hydrograph is being developed (G.K.C. Clarke, personal communication).

In the case of a possible future formation of a lake it may be necessary to reassess the probable timing of lake formation every few years whereas in the case of an existing lake the monitoring program will probably have to be much more intensive.

The simplest situation in which to make forecasts of jökulhlaups is when there has been a history of cyclical lake releases and when there is little change through time in the size and shape of the glacier. Under these conditions the lake will usually fill to a known critical level before release and probabilities that the lake will reach the critical level at a given time can be estimated. A lake water level recorder can be installed, with telemetry capability if needed, to give warning that the critical level is imminent. The contributing drainage area to the lake can be delineated and estimates of flows into the lake can be made to give more precise estimate of rates of inflow. Past records can be used to relate rates of inflow, lake levels and timings and magnitude of jokulhlaups.

While several case histories of jökulhlaups have shown a marked periodicity of flood events, making jökulhlaups predictable, it should not be assumed that cycles will continue forever. Several case histories have shown interruptions to cycles or abrupt cessation of flood activity – changes which have not been predictable.

Until the processes of jökulhlaup activity are much better understood the best motto to follow seems to be »Expect the unexpected«.

Case Histories

As stated previously, there are considerable differences between individual case histories of jökulhlaups. The examples cited here illustrate this variety. For more details on case histories, the reader is referred to Post and Mayo (1971) where several examples are given.

Summit Lake

Summit Lake, British Columbia, is an example of what is probably the most common type of jökulhlaup situation and one which has been well documented. Articles have been written on the formation of the lake and its drainings by Doell (1963), Mathews (1965, 1973), Gilbert (1969, 1971, 1972) and Fisher (1973); it is also cited as an example by Post and Mayo (1971).

Summit Lake (latitude 56°13'N, longitude 130°05'W) is dammed by the Salmon Glacier, see Fig. 2. Even when full, the lake is relatively small – 5.25 km long and varying in width from 0.45 to 1.25 km. Its maximum depth near the ice front is more than 200 m. When full with the surface level at 826 m a.s.l., overflow takes place over bedrock northwards into the Bowser River.

The Salmon Glacier has been thinning and retreating during the twentieth century. Fig. 3 shows that the extent of the thinning has been very considerable over the entire lower part of the glacier. The seismic survey of Doell (1963) showed that within 2 km of Summit Lake, the ice dam was up to 600 m thick. Although this survey was not complete over the whole glacier, it established that the bottom topography was irregular. The part of the Salmon Glacier which flows towards the lake has been retreating also, thus enlarging the size of the lake basin.

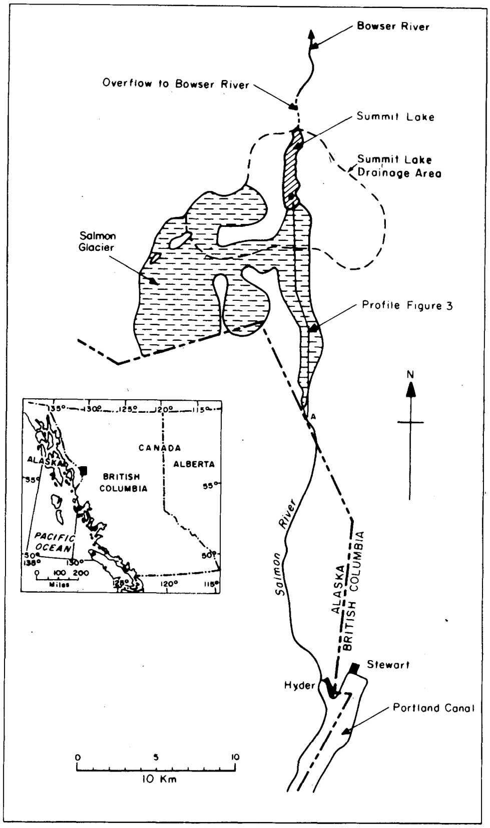

Fig. 2. Location of Salmon Glacier.

From 1900 until 1961 there is no record that Summit Lake emptied. There is vegetational evidence that there was a long period before 1900 when there was also no emptying, large trees on the banks of the Salmon River were killed during the 1961 and 1965 floods. Before jökulhlaups occurred, Summit Lake always drained over the col into the Bowser River system. There is no evidence that the lake has ever drained supraglacially or marginally around the ice.

Fig. 4 shows the timing of the five jökulhlaups between 1961 and 1970; there have been subsequent drainage not documented here. Although similar to each other, these events have not been identical. The floods have occurred at different times of the year, varying between August and December. The lake has not always filled completely before discharge – in 1961, 1965 and 1967 it did fill completely, but in 1968 it filled to about 72% capacity and in 1970 to 93% capacity. As inflow to the lake from surrounding rock and ice varies considerably with meteorological conditions from day to day, it has been difficult to establish the timing of the start of draining. However, there is considerable evidence that draining starts weeks or months before the final catastrophic escalation in flow,

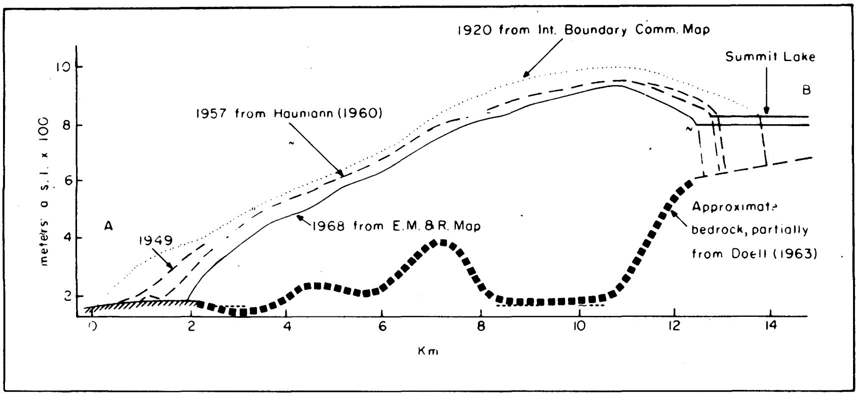

Fig. 3. Longitudinal Profiles of Salmon Glacier showing surface lowering from 1920 to 1968.

indeed dye tests conducted by Fisher suggest that there may be a continuous subglacial leakage from the lake. The variation in flow through time has been similar in each instance, see Fig. 5, although peak discharges have been slightly different (estimations of peak discharges have been subject to considerable measurement error).

It is safe to link the jökulhlaups with the marked recent thinning of Salmon Glacier. It is safe too, to predict that more jökulhlaups of similar magnitude are likely to occur in years to come. The more exact timing and magnitude of these events is not certain, however, for the mechanisms may alter as the glacier thins

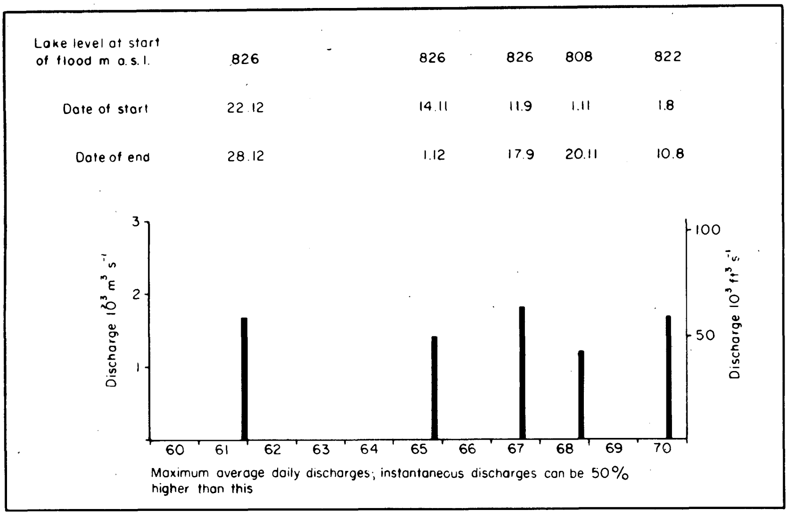

Fig. 4. Timing of Summit lake Jökuhlaups, 1960-70.

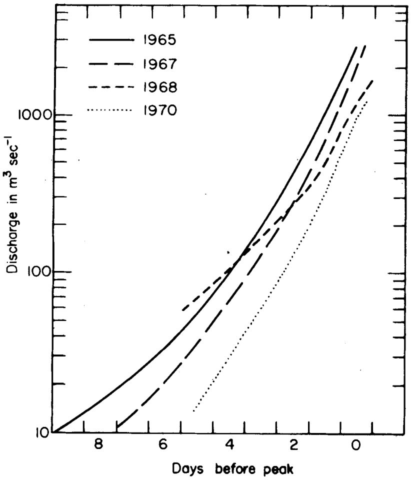

Fig. 5. Discharge during four recorded drainings of Summit Lake, based on change in lake volume in 1965, 1967, and 1970, and on volume change and discharge measurements in Salmon River, 1968.

and retreats further and the lake accordingly changes its dimensions.

The methods currently employed to monitor and forecast jökulhlaup events at Summit Lake are very simple. Approximate rates of lake infilling can be estimated from past records. Rates of infilling are slow in winter but increase rapidly in summer when snowmelt and ice-melt rates are high. A more precise estimation of time taken to fill to a particular level could be calculated from a forecast of likely temperature and precipitation events. Once the lake surface has reached approximately 800 m above sea level a careful monitoring of the surface level is undertaken. As soon as lake level begins to drop it is known that the peak flow will occur within 3 to 5 days. This gives the mining company sufficient time to stockpile supplies in case the road should be damaged by the flood.

Lakes in the Yukon

Floods from glacier-dammed lakes in the St. Elias Mountains have recently assumed significant practical importance with the proposal to construct a natural gas pipeline along the route of the Alaska Highway and with proposals to upgrade the Highway itself. Useful illustration of forecasting and monitoring techniques for flood prediction are thus provided in this area. A more detailed description of the problems and the methodologies used are given in Canada, (1977) and by Young (1978). A location map is provided in Fig. 6.

By examining aerial photographs it was estimated that in each of the White and Donjek river basins there are about 100 glacier dammed lake sites of which about one third are full at the present time. However, most lakes are associated with surge type glaciers which are characterized by sudden advance. Therefore, the lakes may be recreated with little warning.

A small number of potentially hazardous lakes were identified. The largest of

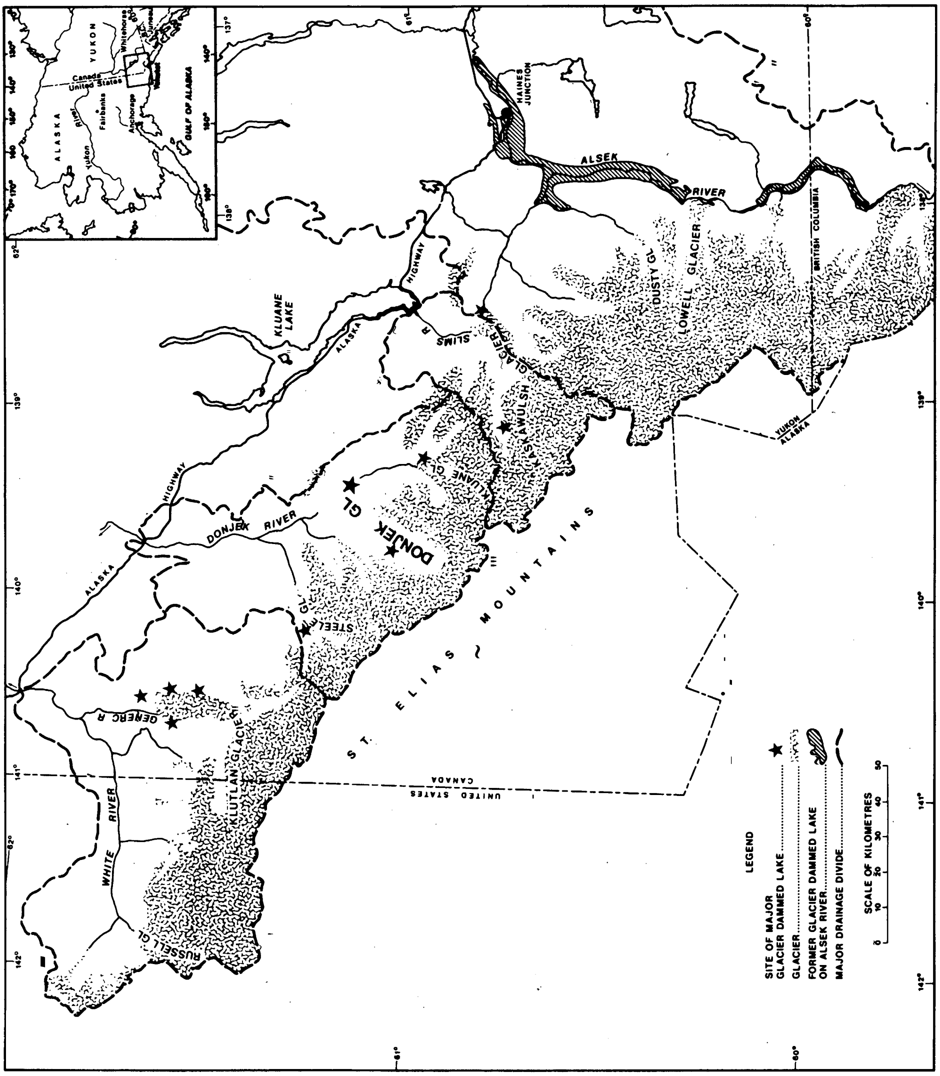

Fig. 6. Glacier dammed lake sites, Yokon territory, Canada.

these is a now empty lake site at the snout of the Donjek glacier. Using aerial photogrammetry and evidence of past shorelines the volume of the lake at maximum extent was calculated as $229 \times 10^6 m^3$ which would produce a maximum instantaneous discharge during flood of 2,860 m^3s^{-1} according to Clague and Mathews' empirical formula. This flood discharge would be superimposed on a normal hydrograph on which the high summer flows are usually about 700 m^3s^{-1}.

In the case of this lake and other similar lakes in the area the monitoring procedure will be to keep careful note of all surge activity within the area so that lake formation can be predicted. This need only be done once or twice a year. Once a potentially hazardous lake begins to form then a much more careful watch must be maintained on lake level so that, as in the case of Summit Lake, a short warning period may be given of a flood. Most lakes in this area are sufficiently remote that lake level recorders with telemetry devices may prove economical to operate.

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Received: 8 April, 1980

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