THE GLACIER LAKE OUTBURST FLOOD PHENOMENON

Descriptive Overview of Icelandic *Jokulhlaup*

The first systematic research on *jokulhlaup* was undertaken by Ahlmann (1938, 1948, 1953) and Thorarinsson (1940, 1943) in Iceland during the 1930s. As part of a pioneering study of glaciological phenomena around the North Atlantic, Ahlmann made major contributions to glaciology science, and especially to studies of the relations between glaciers and climate (Ahlmann 1953).

Of particular interest to the current study is work conducted in Iceland, especially that on the Vatnajokull and its outlet glaciers. The glaciological studies in Iceland also established Sigurdur Thorarinsson as a leading international glaciologist and led to an Icelandic tradition of pure and applied glaciological research.

Among many other topics, Thorarinsson (1939) paid careful attention to the ice-dammed lakes that are especially numerous along the margins of the southern and southeastern outlet glaciers of Vatnajokull. His own studies, together with his ready access to the extensive knowledge accumulated by local farming communities, brought together an impressive body of data on the catastrophic and periodic drainage of many of these ice-dammed lakes.

A focus of attention, however, was the giant *jokulhlaup* emanating from the subglacial volcanic centre of Grimsvotn and draining under Skeidararjokull onto the extensive outwash plain Skeidararsandur, beneath the hillside farms of Skaftafell. This *jokulhlaup* event, known as the *Skeidararhlaup*, had a periodicity of approximately ten years from the middle of the nineteenth century, at least, until 1934 (Ragnar Stefansson 1953, pers. comm.). Usually the flood gradually accelerated over a 7 to 10 day period, then peaked, with the river reverting to a normal flow within 48 hours of the peak. At its maximum, over $700 km^2$ was inundated by fast-flowing, heavily silt-laden water that was estimated to equal in volume the Amazon River in full flood.

The last "great" *Skeidararhlaup* occurred in 1934 ; a moderately-sized *jokulhlaup* occurred in 1954, preceded by small *jokulhlaup* with shorter intervals ; since 1954, *jokulhlaup* have been irregular, more frequent, and relatively small. This change in character of the *Skeidararhlaup* is related to the progressive thinning of Skeidararjokull due to twentieth century climatic warming. Atmospheric and volcanic heat produced accumulation of melt-water in the Grimsvotn basin. The ice dam of the lower glacier responsible for ponding this melt-water had progressively less capacity to contain a specific volume of water so that *jokulhlaup* became more frequent and much smaller.

After 1954 the danger of heavy flooding was so reduced that a road with a bridge across the Skeidara River became feasible and now the hitherto isolated farms of Skaftafell are connected to Reykjavik by a daily bus service and have become the nucleus of the Skaftafell National Park.

While the *Skeidararhlaup* is the best-known of the Vatnajokull glacier outbursts, many ice-dammed lakes occur in the immediate vicinity of Skeidararjokull. On its northwestern margin is the 4 km Lake Graenalon which, during the first half of this century, drained approximately once every four years. Much smaller lakes along Skeidararjokull's eastern margin drain annually. If drainage of these occurs during the summer ablation period, which is usual, their contribution to the flow of the River Skeidara is not conspicuous.

At the other extreme are the rare volcano-induced *jokulhlaup* of Oraefajokull which accompanied the volcanic eruptions of 1362, 1598, and 1727. On these occasions entire valley and outlet glaciers partially melted and slid onto farmland of the surrounding plain and contributed to the devastation of the entire area. The fourteenth century event appears to have rendered the area uninhabitable for a generation, after which it became known as *Oraefi* (the desert).

However, it is the thickening and advance of the glaciers, especially of Skeidararjokull, with the onset of the Little Ice Age in the fifteenth and sixteenth centuries, that led to a succession of giant *skeidararhlaup*. These devastated the hitherto fertile plains and destroyed the rich settlements of Eyrarhorn and Raudilaekur (Ives 1956, 1966).

This descriptive introduction to the Icelandic *jokulhlaup* has been provided to establish the following points :

- o Thorarinsson was able to classify Icelandic *jokulhlaup* into vulcanogene and glaciogene types.
- o The magnitude and frequency of occurrence of the glaciogene (and in part the vulcanogene) type is directly related to the thickness and extent of the glaciers that form ice dams, and subsequent climatic changes.
- o Sufficient change in glacier thickness has occurred within living memory to affect fundamentally the *jokulhlaup* regimes.
- o Significant engineering works have been undertaken in Iceland in the path of *jokulhlaup*, but these have been based upon a thorough knowledge of the relevant glaciology and glaciohydrology.

Characteristics of Ice-dammed and Moraine - dammed Lakes

The Icelandic term *jokulhlaup* usually refers to the sudden drainage of water bodies ponded upon, within, under, or adjacent to glaciers. Glacial lakes also frequently form between a retreating glacier front and its recent end, or terminal moraines. Their formation is intimately related to glacier behaviour and their sudden drainage produces floods similar to the classical *jokulhlaup*. The term is expanded here, therefore, to include all glacial lakes.

Extension of the term *jokulhlaup* is particularly appropriate for steep, glaciated mountain terrain that has experienced significant glacier thinning and retreat during the present century, such as the Himalaya. In high mountain areas, moraine-dammed lakes are numerous and their catastrophic drainage is comparatively frequent. Thus the term **glacier lake** will be used in this paper to include all lakes dammed in association with glaciers ; **ice-dammed lake** and **moraine-dammed lake** are terms that will be used to differentiate the two predominant types.

The largest ice-dammed lakes, which present the greatest hazards, are located in ice-free tributary valleys that are ponded by active glaciers occupying the main valley. In Alaska and Yukon Territory, such lakes may be 10 to 20km or more in length and more than 100 metres in depth, and are thus capable of producing gigantic floods. More common, however, are small lakes and ponds dammed against the valley walls along the margins of valley glaciers or outlet glaciers, or in depressions formed at the upper confluence of tributary glaciers. Although a few lakes occur slightly above the regional snow line, the majority lie below, along the lower reaches of glaciers. Depending upon actual side characteristics, small lakes have the capacity to produce extremely damaging *jokulhlaup*.

Following Post and Mayo (1971) no attempt was made to classify ice-dammed lakes according to the manner in which they are formed, such as by active or stagnant ice, or by advancing or retreating glaciers. Ice-dammed lakes can form, change size, or be destroyed in so many ways and in so many geomorphic settings that such classification would be both cumbersome and of little practical value.

Nevertheless, once a closed depression is formed, either by a glacier advancing to block a tributary valley, or by a tributary glacier retreating to leave an unglacierised section of the valley between its new frontal position and the glacier in the main valley, water will usually accumulate to form a lake. This will be a combination of accumulating rainwater, melting ice, and melting snow. Thus the rate of increase in the lake level will be highly seasonal, with a maximum in summer and a minimum in winter. When the depth of the lake reaches a level approximately nine-tenths of the thickness of the ice dam, drainage is likely to occur (Post and Mayo 1971).

Once sub-glacial flow is established, the opening will rapidly enlarge by melting due to the slightly warmer water and by friction and, with increasing rates of flow, by mechanical abrasion. The rate of increase in tunnel cross-section will accelerate rapidly following an exponential law (Meier 1960). Many such drainages are virtually instantaneous and lakes often drain entirely within a few hours. Once the lake level has been extensively lowered, however, the discharge may cease abruptly, the tunnel will close and the lake basin will begin to fill once again.

Mathews (1965) has referred to such lakes as " self-dumping ". Their importance as a hazard is related to this tendency for nearly instantaneous drainage, such that a small lake, a fraction of a square kilometre in area, can produce a flood crest with a discharge exceeding several thousand cubic metres per second. It is very significant that such high rates of discharge may greatly exceed the effects of snowmelt and normal peak rainy season discharges from mountain streams.

This self-dumping characteristic is often so closely regulated that many ice-dammed lakes drain once each summer. Others may drain several times a year; a small ice-dammed lake on the Gulkana Glacier, Alaska, drained at three-day intervals throughout the 1970 summer, according to Post and Mayo (1971); larger lake basins, such as Graenalon in Iceland, take several years to refill after a *jokulhlaup* has occurred.

Figure 1 is a sketch showing several typical locations of ice-dammed lakes. Figure 2 is a diagram of the lower part of the Langmoche Glacier illustrating the setting of a typical moraine-dammed lake. The latter are widespread in glaciated high mountain regions because of the recent history of glacier fluctuation.

Throughout much of the world mountain glaciers reached, or were close to, their Little Ice Age (Neoglacial) maximum between 1850 and 1905 and built up, or added to, prominent end-moraines at that time. This situation was also characteristic of the Himalaya (Mayewski and Jeschke 1979). With the pronounced climatic amelioration of the first half of the twentieth century, the majority of mountain glaciers thinned and retreated. Thus, in many glacier frontal situations a basin formed between the thinning and receding ice front and the end-moraines. Where the morainic dam was relatively impervious, a lake would form and enlarge as the glacier continued to retreat.

While an increasingly large number of mountain glaciers have begun to advance in recent years, such ice expansion has not yet significantly reduced the size of the moraine-dammed lakes. Furthermore, glacier advance into such water bodies could accentuate the precariousness of an already unstable situation. Moraines, by the nature of their formation and coarse-grained composition, are often unstable and permeable so that moraine-dammed lakes may slowly and harmlessly drain by seepage through the dam. However, moraines may be ice-cored. This increases their lake-ponding potential, but the ice core is also subject to progressive melting. Thus, a succession of unusually warm summers, periods of heavy rain, collapse of morainic frontal material exposing the ice core to melting by rain and incoming solar radiation, or a combination of all or several of these, may create a situation of rapid and imminent dam failure. When moraine-dammed lakes produce *jokulhlaup*, so much end-moraine may be washed away that lakes do not reform, or occasionally a smaller and shallower body of water accumulates.

The release of ice-dammed lakes may be initiated in several ways. They may drain by channel formation under the glacier, englacially, across its surface, or laterally between the lower glacier margin and the valley side. As described, once drainage begins, discharge will probably accelerate rapidly. Actual causes of lake release include the following, some of which may operate in combination :

- Increase of lake depth until it causes the ice dam to float (Thorarinsson 1939);
- Slow plastic yielding of the ice dam due to hydrostatic pressure differences between the lake water and the adjacent less dense ice of the dam (Glen 1954);
- Outward progression of cracks or crevasses under shear stress due to the combination of glacier flow and high hydrostatic pressure (Nichols and Miller 1952);

Figure 1. Schematic representation demonstrating typical locations of ice-dammed and moraine-dammed lakes

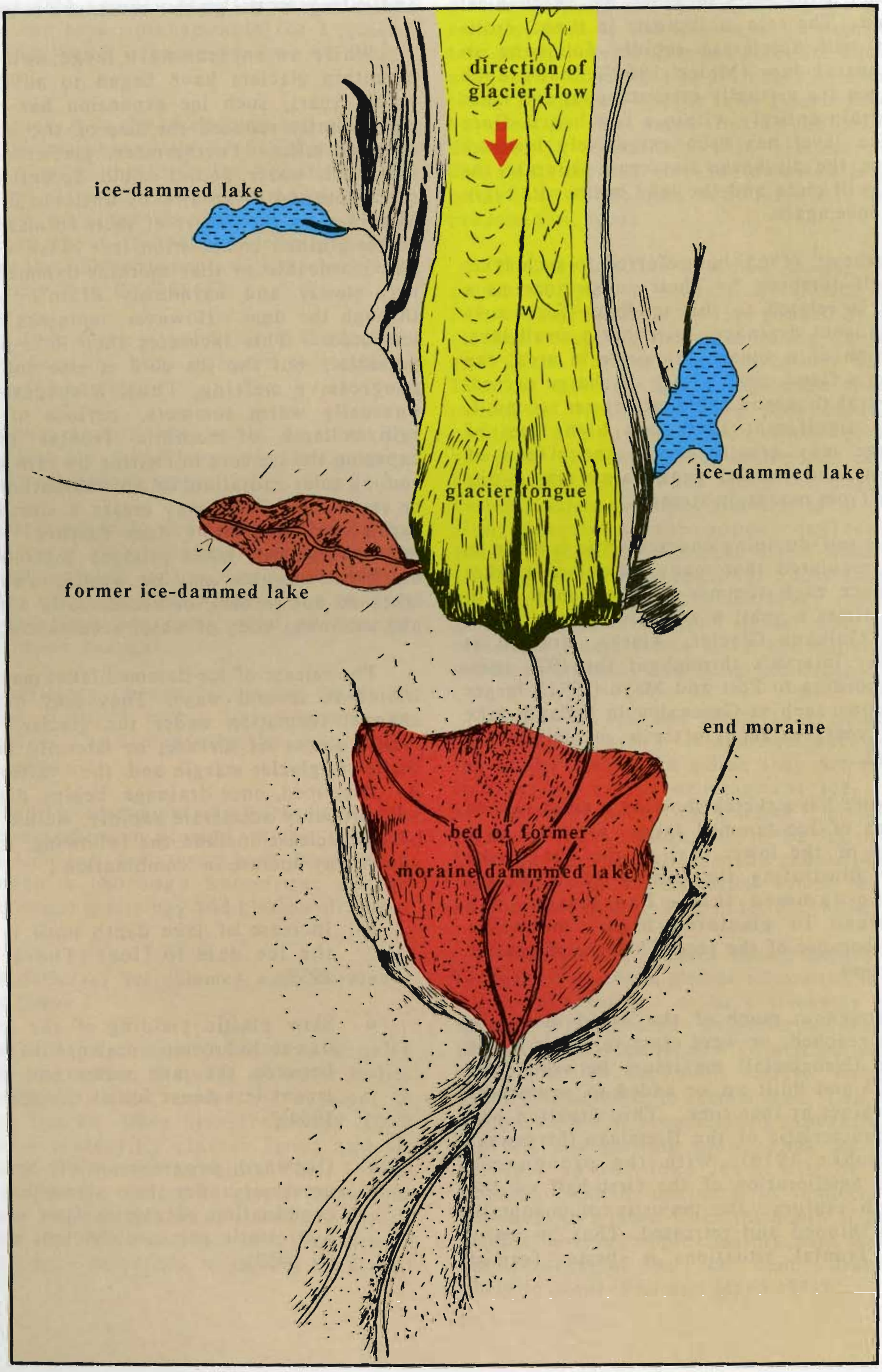
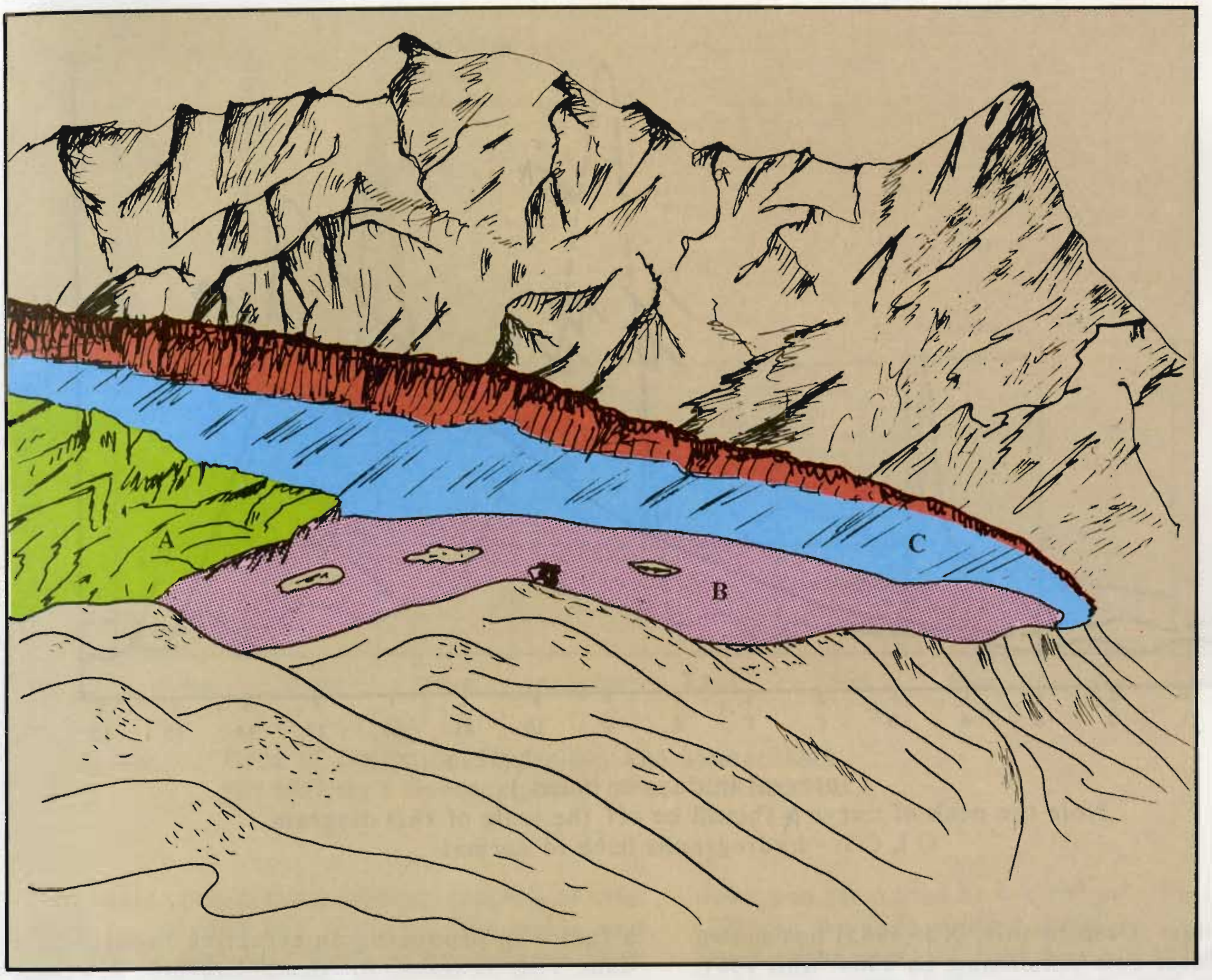


Figure 2. Sketch of the moraine-dammed lake, Dig Tsho and the lower part of the Langmoche Glacier, Khumbu Himal, Nepal. This reconstruction is to show the approximate appearance of the lake prior to the 4 August 1985, *jokulhaup.*



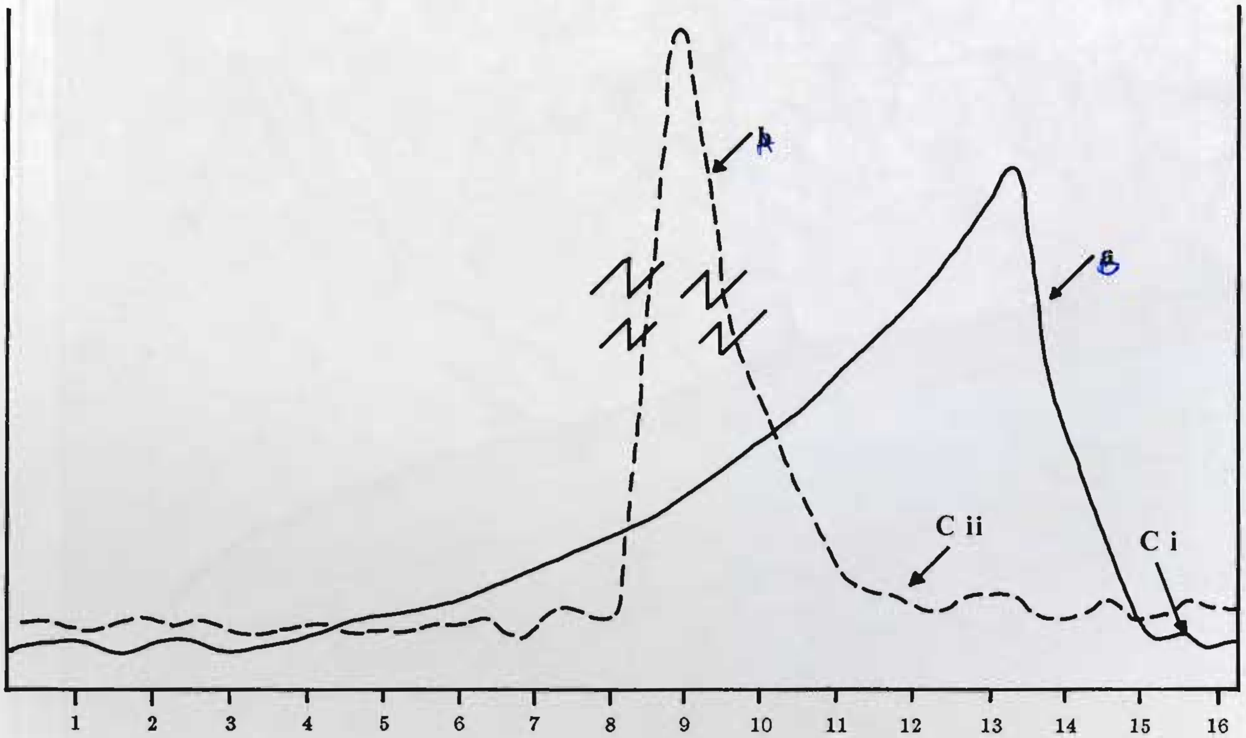
A. Glacier Snout
B. Moraine Dammed Lake
C. End Moraine

- o Water overflowing the ice dam, generally along the lower margin (Liestol 1956; Maag 1963);
- o Sub-glacial melting by volcanic heat (Thorarinsson 1939, 1953);
- o Weakening of ice-dam by seismic activity (Tryggvason 1960).

Jokulhlaup that occur through the drainage of englacial and sub-glacial water bodies are considerably more problematic simply because there is no available method to ascertain their presence until after the event. Unlike sub-aerial lakes, moraine-dammed or ice-dammed, which are clearly visible and can be monitored, englacially and sub-glacially-induced *jokulhlaup* can only be incorporated into resource development decision making as activity records are compiled over a period of time.

The major difference between ice-dammed and moraine-dammed lakes is that the former frequently have a history of repeated, catastrophic discharge at regular intervals, whereas the latter will usually drain only once because the moraine dam will be destroyed in

Figure 3. *Jokulhlaup* **hydrographs from a moraine-dammed source (a) and from an ice - dammed lake source (b)**
(Note the much steeper forelimb of curve (a) indicating a much more abrupt outbreak of flood waters)



(interval in days or hours)
Note the peak of curve a should be off the scale of this diagram
C i, C ii - hydrographs back to normal

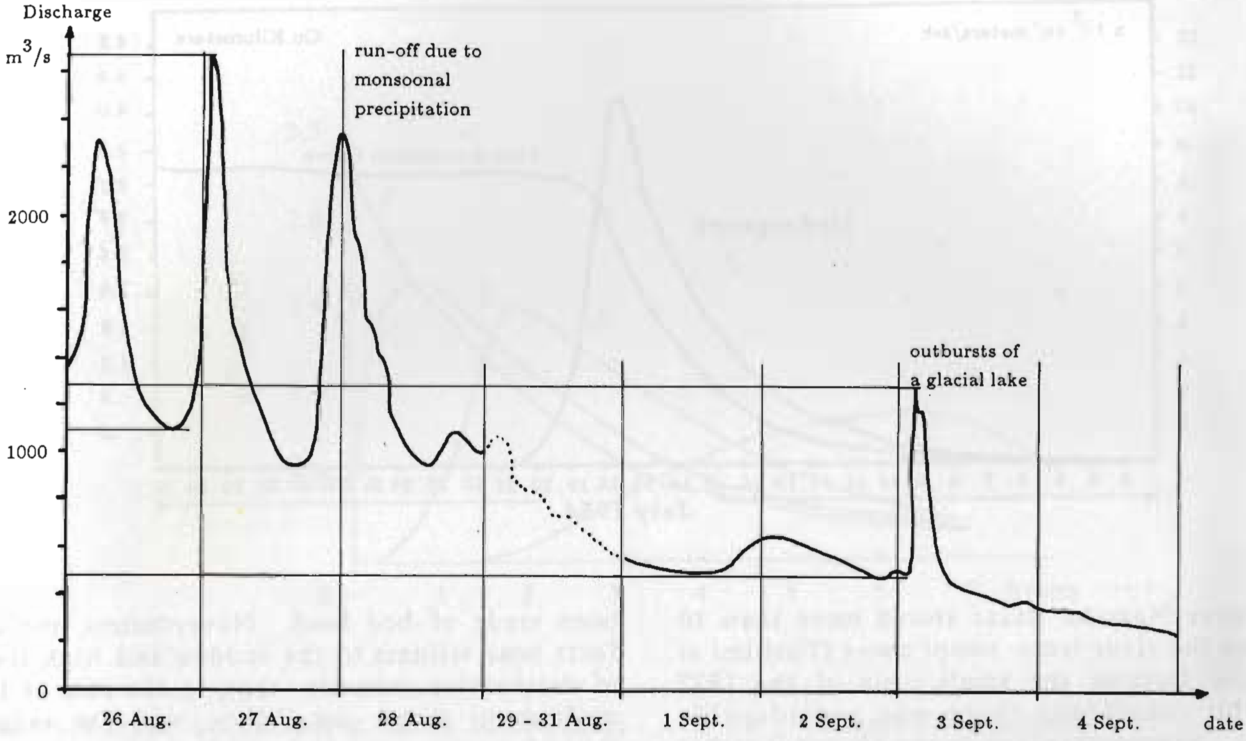
the process. Despite this, Xu (1985) has shown that at least two *jokulhlaup*, in 1964 and 1981, originated from the same moraine-dammed lake. The possibility of multiple events, therefore, cannot be ruled out.

Drainage mechanisms of moraine-dammed lakes are somewhat different to those of ice-dammed lakes. As indicated above, an ice core within the morainic dam may melt over time giving rise to a single catastrophic failure, or a moraine dam without an ice core may be progressively weakened by seepage and eventually collapse with the same result. In other instances, a moraine-dammed lake may experience a rockfall, ice fall, or avalanche from steep mountain walls rising above it. The ensuing impact on the lake surface may send a surge wave which overflows the moraine dam precipitating catastrophic failure.

The occurrence of permafrost in glacier end moraines must also be taken into account as a factor in producing an effective impermeable dam. This is liable to destablization, however, during a period of climatic amelioration, or change in surface cover. Figure 3 hypothetically compares the two forms of *jokulhlaup* hydrograph. The main difference is the abruptly steep forelimb of the curve for the moraine-dammed lake outburst compared to the more gradual build-up of the ice-dammed lake outburst. Thus, in the case of the former, a comparable volume of water could provide a much higher peak discharge.

Somewhat similar to moraine-dammed lakes and their eventual outbreak are the temporary lakes dammed behind debris that block a mountain stream channel due to various types of mass movement, such as rockfall, ice and snow avalanche, debris flow, and landslide. These forms of short-lived lakes are extremely widespread in the Himalaya, especially those dammed by debris flows during periods of heavy summer monsoon rainfall. Each year

Figure 4. Hydrograph of the 1977 Dudh Koshi *jokulhlaup* (source Ama Dablam) compared with " normal " peak summer monsoon flows (modified from Zimmerman *et al* 1986)



Source : Dept. of Irrigation, Hydrology and Meteorology, His Majesty's Government of Nepal, Kathmandu

they cause considerable damage and loss of life. They are beyond the scope of this paper and will not be discussed further. They do warrant, however, a separate, systematic investigation.

Downstream Effects of *Jokulhlaup*

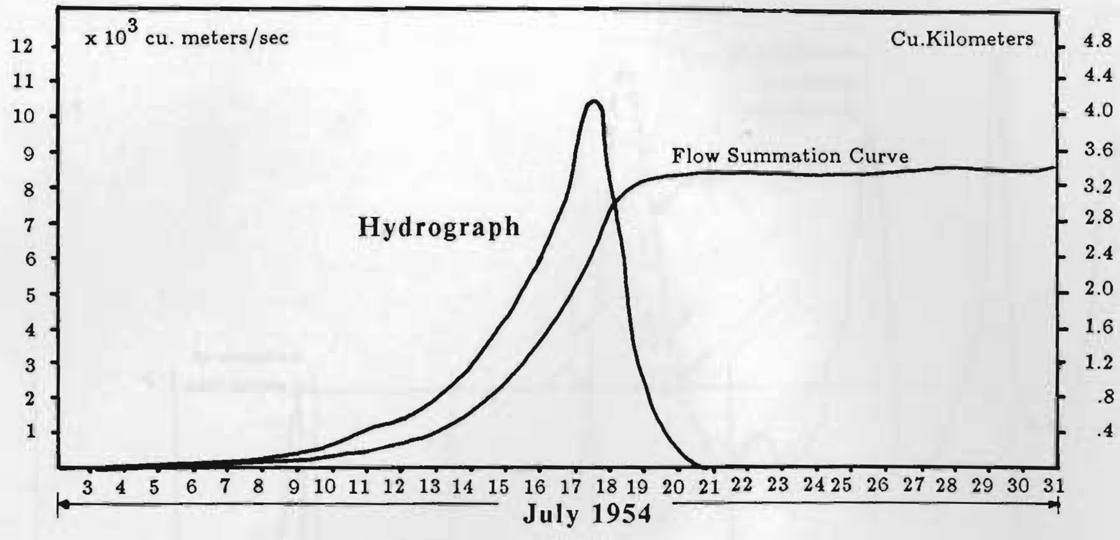
As implied in the foregoing sections, the catastrophic nature of the downstream effects of *jokulhlaup* is the result of extremely sudden and high peak flows. Obviously, therefore, *jokulhlaup* impact will be proportional to the volume of ponded water subject to near instantaneous release in association with downstream channel characteristics, especially the availability of easily erodible material.

Figure 4 shows the hydrograph of the 1977 Dudh Kosi *jokulhlaup* as recorded at the government gauging station at Rabuwa Bazar, 90 km downstream from the source; in this case the *jokulhlaup* peak is attenuated to an unknown degree. The volume of water in the lake was estimated at 4×15^5 m^3 (Fushimi *et al* 1985). An independent estimate was made by Buchroithner *et al* (1982) at 5×10^5 m^3 with a peak discharge at the source of 800 m^3/sec. By comparison run-off peaks due to heavy monsoon rains were considerably larger than the *jokulhlaup* peak (Figure 4).

The rainfall and *jokulhlaup* hydrographs are not strictly comparable, however, because the gauging station is located far downstream from the *jokulhlaup* source; depending upon the precipitation pattern, the rainfall peaks can be accentuated as the river collects progressively more water from tributaries, while the *jokulhlaup* peak may have been significantly attenuated with increasing distance downstream.

Nevertheless, the *jokulhlaup* resulted in 2 or 3 deaths, destruction of all the bridges on the Dudh Koshi for 35 km below the point of origin, and the triggering of many debris flows. Construction materials for a small hydro-power station for the Everest View

Figure 5. 1954 *Skeidararhlaup* hydrograph ; an example of a major *jokulhlhaup* event.



Hotel near Namche Bazar stored more than 10 m above the river were swept away (Fushimi *et al* 1985). Despite the small scale of the 1977 Khumbu *jokulhlaup* there was considerable damage, presumably due to the abrupt increase in flood level.

At the other end of the scale, Figure 5 shows the form of the 1954 *Skeidararhlaup* hydrograph with an estimated peak discharge of 3.5 km^3 (Rist 1955). Figure 6 provides a series of smoothed theoretical hydrograph curves for stations at successive distances downstream from the source (Krenke and Kotlyakov, 1985, p. 123, Figure 6).

Two points need to be stressed from the foregoing discussion of *jokulhlaup* hydrographs. The first is the very abrupt nature of the initial discharge, as shown graphically in Figures 3-6. This supports the various eye-witness accounts which often indicate a wall of water, boulders, and even trees, of 10 to 20 metres in height, travelling at great speed and accompanied by a roaring noise like thunder and a putrid, earthy odour. The potential for extreme destructiveness is self-evident.

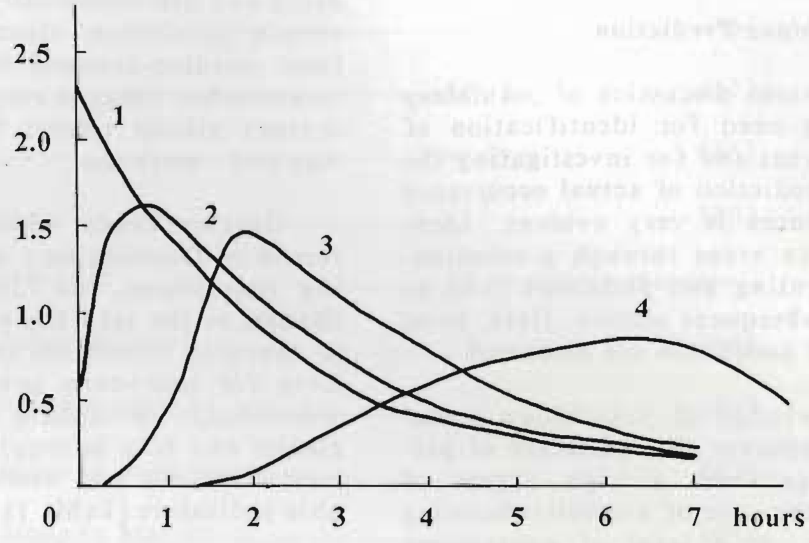
The second point is that the limited hydrographic data recorded from such events will be subject to considerable inaccuracies ; this will relate especially to estimates of transported material, and it is reasonable to conclude that no accurate determinations have been made of bed load. Nevertheless, the effects bear witness to the sudden and high level of destructive capacity that, in the case of the medium or larger *jokulhlaup*, will far exceed that of most normal hydrologic peak discharges.

From a geomorphic point of view, the downstream effects of a catastrophic release of large volumes of water will depend upon the amount and grade of materials removed at the source, and the nature of the lower river channel and valley sides, in particular the channel gradient and the amount of superficial material available both in the stream channel and on the lower valley slopes.

In the high Himalaya river channel gradients are frequently steep and also highly variable over short distances. Channel and valley side characteristics vary and may be bedrock, both in open valley form and deeply engorged, or extensive deposits of alluvium, colluvium, and glacial moraine, or large talus cones and debris fans with slopes of several hundred metres.

Therefore, the geomorphic effects of *jokulhlaup* include both vertical and lateral channel erosion, the undercutting of colluvial deposits with further downstream transport and aggradation. The vertical and lateral erosion of the stream channel has the potential to destabilise talus slopes, former debris flows and landslides, and to initiate new ones. These

Figure 6. **Hypothetical *jokulhlaup* hydrographs showing the change in form and attenuation with increasing distance downstream from the source (modified from Krenke and Kotlyakov 1982).**



processes leave an extensive series of unstable slope sections with broken vegetation cover, which is subject to intermittent movement over several years following the *jokulhlaup* occurrence. Further downstream, especially as the channel gradient decreases, aggradation may progressively exceed degradation. At greater distances downstream, and as the flood wave becomes attenuated, the grain size of the transported material may be reduced. However, at considerable distances from the outbreak source large quantities of silt are still in suspension. Furthermore, the periodic destabilization of long stretches of river valleys, and the dumping of enormous masses of debris ensure that valleys affected by *jokulhlaup* provide much larger sources of river sediment than valleys not so affected.

The following table provides a list of indicators of former *jokulhlaup* occurrence. They serve as an aid to identifying valleys possibly affected by *jokulhlaup*, both through remote sensing or photographic interpretation and field survey.

Table 1. Indicators of former *jokulhlaup* discharge

A. Glacier Environs

- o perched lake shorelines
- o collapsed end moraines
- o stranded icebergs in former lake basins
- o lake sediment
- o alternate high lake spillways
- o lateral and sub-lateral glacial drainage channels

B. Downstream

- o stripped bedrock
- o giant blocks
- o coarse stream deposits in excess of normal flood competence
- o undercut river terraces
- o undercut toes of talus slopes and alluvial cones
- o large numbers of undercut landslides and debris flows
- o extensive siltation
- o accounts of local inhabitants and folk lore

While several of the individual features also occur as the result of normal peak discharges due to heavy summer monsoon rains, their occurrence in combination should prompt a more detailed investigation.

Problems of *Jokulhlaup* Prediction

From the previous discussion of *jokulhlaup* characteristics the need for identification of potential source areas and for investigating the possibilities for prediction of actual occurrence and the consequences is very evident. Identification of source areas through a combination of remote sensing and fieldwork will be dealt with in a subsequent section. Here, some of the problems of prediction are discussed.

Overall knowledge of *jokulhlaup* occurrences makes it apparent that accuracy of prediction may range from a high degree of reliability, as in the case of annually-dumping ice-dammed lakes, to a level of uncertainty such that a special approach is needed for incorporation into the design of engineering facilities. Nevertheless, this problem can be broken down and a first approach can be made that would be a vast improvement on the current situation prevailing throughout the Himalaya.

Assume that a reliable reconnaissance map has been compiled showing all existing and former ice-dammed and moraine-dammed lakes (see below). It follows from the foregoing that sub-glacial and englacial bodies of water will not be identified. However, if the map also includes the phenomena listed in Table 1 at least it will serve as an indicator of the maximum possible area at risk under recent climatic-glaciologic conditions. In terms of the timing of *jokulhlaup* events, however, this will still leave a range of possibilities from regular and annual (or more frequent) to indefinite.

The magnitude and frequency of river floods from rainstorms and/or snowmelt can be predicted from long-term stream records and probability analysis. It is standard practice in many parts of the world, for instance, to estimate the largest flood that can be anticipated over a ten-year, or a hundred-year period (recurrence interval indicates that such a flood has a ten percent and a one percent chance, respectively, of occurring in any one year), and the concept of the hundred-year flood-plain is a standard component of land-use planning in the U.S.A. The methods associated with these predictions, however, cannot be applied to ice-dammed lakes, and especially not to moraine-dammed lakes. This is in part because the hydrological characteristics of glacierised drainage basins may change suddenly and discontinuously and, in part, because certain *jokulhlaup*, especially those emanating from moraine-dammed lakes, may be one-time catastrophes: delayed responses to the twentieth century glacier retreat from recent Little Ice Age end - moraines.

Glacier lakes which have no previous record of flooding may abruptly begin producing *jokulhlaup*, the flooding sequence may change, or the lake basin may cease filling due to changing conditions in the damming glacier. Even for short-term predictions of individual *jokulhlaup*, up-to-date information on both glacier and lake is required in addition to historical records and assessment of the geomorphic indicators (Table 1).

Some of the reasons for difficulty of prediction can be illustrated by describing the flood histories of five Alaskan rivers. The examples given below are taken from Post and Mayo (1971), with only minor abbreviations.

Salmon River : This river experienced no *jokulhlaup* for some time prior to 1890 until 1960, during which time Summit Lake, British Columbia, impounded behind the Salmon Glacier, drained over a bedrock col. A highway, a bridge, and the small town of Hyder were built in the Salmon River valley during this period. In 1961, Summit Lake unexpectedly drained under the Salmon Glacier and the ensuing *jokulhlaup* caused severe damage to the facilities along the Salmon Valley. Four more *jokulhlaup* occurred between 1961 and 1970. Salmon Lake is only 4.2km^2 at its maximum, yet a *jokulhlaup* that occurred on 30 November, 1965, produced a peak discharge of 3,100 m^3/sec. This case, therefore, is one where an ice-dammed lake with a long period of stability unexpectedly began a series of catastrophic *jokulhlaup*.

Knik River : This river, near Palmer, is famous for its destructive *jokulhlaup* originating from the ice-dammed Lake George, which in recent years has been the largest of Alaska's ice-dammed lakes. Since 1918 the lake has emptied annually, a pattern that continued until 1963 when the ice dam did not reform. Annual *jokulhlaups* again occurred between 1964

Table 2 Dates of the more recent occurrences of *jokulhlaup* of Skeidadadsandur and eruptions of Grimsvotn

Jokulhlaup	**Eruption**
1850	1850
1861	1861
1873	1873
1883	1883
1892	1892
1897 (medium *hlaup*)	(no visible eruption)
1903 (major *hlaup* in June)	1903
1913 (major *hlaup* in March)	1913
1922 (major *hlaup* in September)	1922
1934 (major *hlaup* in March)	1934
1938 (major *hlaup* in May-June)	1938
1939 (minor *hlaup* in May-June)	(no eruption)
1945 (minor *hlaup* in September)	(no eruption)
1948 (minor *hlaup* in February)	(no eruption)
1954 (medium *hlaup* in July)	(no eruption)

and 1966; since 1966 the dam has not reformed and the lake has not refilled. In contrast, the annual *jokulhlaup* along the Knik River were so regular between 1918 and 1963 that bridge maintenance crews and tourists reserved a week each summer for sight-seeing. Because of this popular spectacle the area was designated as a Natural Landmark by the National Park Service. In this case a strictly annual *jokulhlaup* ceased briefly and later stopped altogether.

Snow and Kenai Rivers : *Jokulhlaup* on the Kenai River above Skilak Lake originate from an ice-dammed lake at the headwaters of the Snow River. The first recorded *jokulhlaup* was in December 1911. The events continued, usually biannually during the winters, causing ice jams and overflow icings that damaged railway and highway bridges. Until 1961 the discharge peaks of *jokulhlaup* were generally lower than the annual peaks due to snow and ice melt and summer rainstorms. After 1961 this situation was reversed. Since 1958, however, the interval between *jokulhlaup* has extended to three years and the peak discharges have been higher.

Tazlina River : This river basin contains four ice-dammed lakes, all of which produce *jokulhlaup*. Two of the lakes appear to have drained sometime between 14 April and 11 September, 1964, but no clear evidence of these was apparent on the Tazlina River hydrograph. In other years, two *jokulhlaup* are indicated on the hydrograph chart, implying that at least two of the lakes drained suddenly on different dates. A large flood occurred in 1962 when two of the lakes drained simultaneously. In 1932 a flood destroyed the Copper River railway bridge at Chitina during a period of clear weather in August; this could have resulted from the release of one or more of the Tazlina ice-dammed lakes. This is a case of extremely complex *jokulhlaup* history, in part because of the different dynamics of four ice-dammed lakes and two glaciers.

Bering River : Berg Lake, when first observed by Martin (1908), was a large basin occupied by five small lakes in an embayment marginal to the Bering Glacier. The water level stood at 247m.a.s.l., although lake shorelines 60 metres higher attested to the earlier existence of a much larger lake. Some time prior to 1940 it appears that thinning of the Bering Glacier lowered the ice dam and the lake level became fixed at 207m.a.s.l., discharging over a bedrock spillway. Despite the lowering of the lake level, its area increased from $12.2km^2$ in 1905 to $28km^2$ in 1970 because of the melting of a large mass of glacier ice in the embayment. No *jokulhlaup* had occurred for a period of at least 30 years prior to 1970. However, as the Bering Glacier continues to thin and the ice dam weakens, a future *jokulhlaup* of immense proportions is possible with an estimated peak discharge far exceeding $30,000m^3/sec$.

For comparison, the historical data of the Icelandic *skeidararhlaup* are provided in Table 2.

The distinctly different case histories of the five Alaskan examples, as well as Icelandic history, all relate to progressive glacier thinning and retreat that has characterized most of the twentieth century. Some of the changes in pattern and periodicity of *jokulhlaup* occurrence have been systematic and are rationally explicable in terms of present knowledge of the changes in condition of their damming glaciers.

The tendency for an increasing proportion of mountain glaciers to thicken and advance in recent years, however, indicates that any similar trend in the Himalaya will require careful monitoring. This will be particularly important where such positive glacier fluctuations may result in the closing of hitherto open depressions. In this respect, much can be learned from very ancient *jokulhlaup* related to late Wurm-Weischelian-Wisconsin glacier fluctuations when ice-dammed lakes were much more numerous and more extensive than those of today (Ives and Andrews 1963; Figure 10). Another possibility is the danger from surging glaciers that can be extremely difficult to predict. This topic is discussed in some detail in relation to the proposed Alcan Pipeline route through Yukon Territory, Canada, by Young (1977).

Englacial, supra-glacial, and sub-glacial lakes, and moraine-dammed lakes, however, provide little opportunity for real-time discharge prediction. Nevertheless, moraine-dammed and supra-glacial lakes can be plotted on air photographs. Furthermore, field examination of the condition of moraine-dammed lakes can lead to an approximate assessment of their stability. The very fact that the 4 August 1985, Khumbu catastrophe originated with the outburst of a moraine-dammed lake would serve to justify the mounting of a small research programme aimed at mapping and monitoring such lakes. "Moreover, word-of-mouth reports to the effect that Namche Small Hydel Project engineers were aware that Dig Tsho Lake was overtopping its moraine dam in 1984" (Dr. V. Galay 1986 pers. comm.) begs the question of why steps were not taken to meet the portending catastrophe. Wider public and official awareness of the *jokulhlaup* phenomenon might be able to minimize, or even prevent, future disasters.