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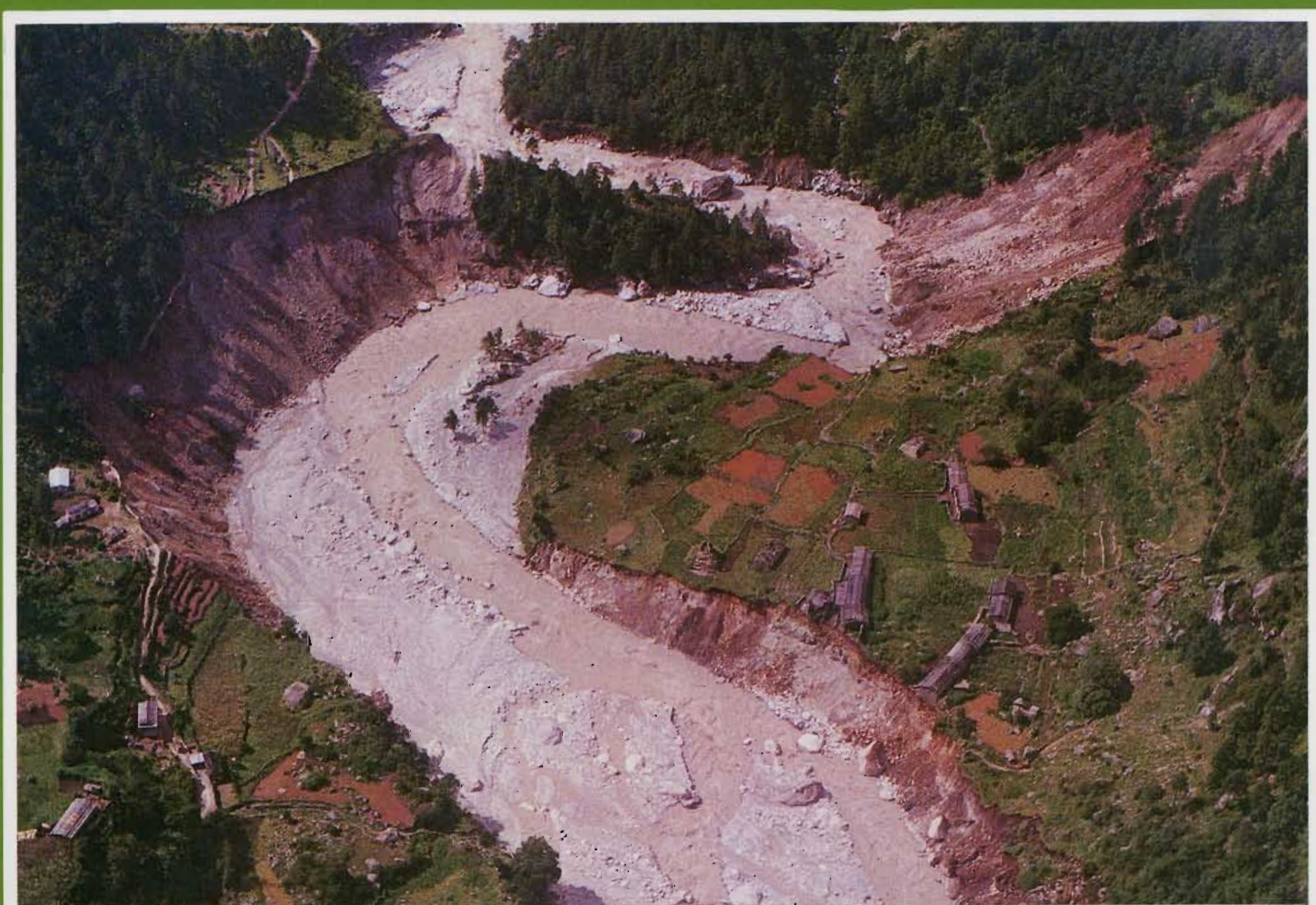
GLACIAL LAKE OUTBURST FLOODS AND RISK ENGINEERING IN THE HIMALAYA



Jack D. Ives

ICIMOD OCCASIONAL PAPER NO. 5

Kathmandu, Nepal
November, 1986

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GLACIAL LAKE OUTBURST FLOODS AND RISK ENGINEERING IN THE HIMALAYA

A Review of the Langmoche Disaster, Khumbu Himal, 4 August 1985

Jack D. Ives

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Cover photograph: Low level aerial oblique photograph showing loss of cultivable land, trail destruction and endangered houses. Dudh Koshi at Chat. Photograph by Dr. Victor Galay.

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Foreword

The physical geographer's technical term, "*jokulhlaup*", used for the often catastrophic surge of water and debris caused by the sudden outburst of glacier lakes in the high mountains, would certainly be unfamiliar to the vast majority of the peoples of the Hindu Kush-Himalaya but, sadly, the phenomenon itself is not. These glacier lake outburst floods have caused disasters to life and property in a number of places along the whole of the mountain range, resulting in serious death tolls and the destruction of fields, farms and costly mountain infrastructure. In Nepal alone in this decade, glacier outbursts with heavy debris flows destroyed (in 1981) a large stretch of the road linking Kathmandu and Lhasa, including the Friendship Bridge on the frontier, and (in 1985) similarly destroyed a Small Hydel Project in the Everest region with lives lost and much damage to land and forest and farmhouses.

Clearly these sudden and spectacular debris torrents are major hazards to human habitation and assoiated infrastructure development in the high mountains. It is increasingly obvious that catastrophic glacier lake outbursts have to be fully recognised as a significant factor in the design and construction of major infrastructure - in roads andbridges and large scale hydroelectric projects - in fragile mountain environments. In locating new infrastructure projects the degree of risk has to be assessed much more specifically, and indeed more skilfully, than appears to have been the case in the past. The Arun River Basin in Nepal, for example, with a number of sites currently being studied for major hydroelectric projects costing many hundred million dollars, may be at a considerable risk from glacier lakes to the north in the high mountains of the Upper Arun across the border in Tibet.

If essential but highly costly investments in mountain infrastructure are to be made with confidence, much more research is needed into the active physical processes at work in the high mountains. This 'risk engineering research' in mountain areas is increasingly urgent as, with increasing population pressure, the resources of the mountains are being exploited for hydroelectric power, mining, forestry, agriculture and tourism. A skilled examination of the physical processes - with the academic geomorphologist in close, practical alliance with the design engineer - may well lead to the development of the protective measures, in design and location criteria, that will reduce the risks of major disaster - given the inevitable and accelerating processes of mountain resource utilisation and infrastructure investment.

In the summer of 1986, with generous financial help from the International Development Research Centre (IDRC) of Canada, ICIMOD invited Professor Jack Ives of the University of Colorado, President of the International Mountain Society, and one of the world's leading scientists in the field of mountain geo-ecology, to prepare a special 'risk engineering' analysis of the glacier lake outburst flood that occurred in the Namche area of Nepal on 4 August 1985, wiping out the Hydel Project and causing heavy damage for some 40 kms downstream.

We are pleased to publish this particularly useful study, drawing on a wide range of international knowledge of the 'jokulhlaup' phenomenon, in the ICIMOD Occasional Paper Series. We must express our thanks to Professor Ives for this contribution to the international exchange of knowledge and experience with regard to one of the major hazards to habitation and infrastructure in the high mountains. As Professor Ives fully indicates, much practical field research is now required if these spectacular natural events - and the associated degree of risk in specific locations - are to be adequately understood in the Hindu Kush-Himalaya.

Colin Rosser
Director
ICIMOD

ACKNOWLEDGEMENTS

Work on the first draft of this report was completed at ICIMOD, Kathmandu, during July and early August, 1986, at the invitation of the Director, Dr. Colin Rosser. The International Development Research Centre, Canada, bore a significant proportion of the expense incurred.

On a personal level I wish to express my thanks for the kindness and encouragement showed by the entire ICIMOD staff. I am also indebted to Dr. C.K. Sharma, Executive Director, Water and Energy Commission, HMG/N, and to Mr. K.B. Malla, Chief, Remote Sensing Centre, HMG/N, for their encouragement and willingness to provide all manner of assistance. Drs. Victor Galay and Ramiro Mayor-Mora were unstinting in their provision of internal reports and first-hand Khumbu field experience. Drs. Suresh Chalise, Victor Galay, Ramiro Mayor-Mora, Gordon J. Young and Alton C. Byers all read and made helpful comments on an early draft of this report. Especially valuable has been the outstanding photography by Dr. Galay and his willingness to make it freely available.

This paper is an outcome of the United Nations University/Nepal MAB Programme, Mountain Hazards Mapping Project (Ives and Messerli 1981). The second phase of this project involved systematic hazard mapping of a section of Khumbu Himal and the production of a prototype hazard map, scale 1:50,000 (Zimmermann *et al* 1986).

It should be apparent that I have relied for much of the content on the field observations and office reports of individuals other than myself. In addition to those mentioned above, special thanks are due to Messrs. Daniel Vuichard and Markus Zimmermann, University of Berne, and members of the UNU/Nepal MAB Mountain Hazards Mapping Project.

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SUMMARY

On 4 August 1985, a glacial lake drained suddenly and sent a 10 to 15 metre high surge of water and debris down the Bhote Koshi and Dudh Koshi rivers, for more than 90 km. An estimated 1 mill. m^3 of water was released, creating an initial peak discharge of 2,000 m^3/sec; two to four times the magnitude of maximum floods due to heavy monsoon rains.

This spectacular natural event destroyed the nearly completed Namche Small Hydel Project, at a cost of about NRs 40 million. It eliminated all the bridges, including new high suspension bridges, for 42 km downstream between Thamo and Jubing; four or five people lost their lives.

In addition, more than 30 houses were destroyed, as well as considerable cultivable land, livestock, and forest, together with long stretches of the Lukla- Namche Bazar main trail. If the flood had occurred two months later, during the trekking season, the death toll could have been as high as 100 to 200 persons.

This type of catastrophic natural phenomenon is called a *jokulhlaup* (glacier leap or burst in Icelandic) since such terrifying events were first recognised and studied in Iceland. They are not unusual in the Himalaya. In 1981 a much larger *jokulhlaup* devastated the China- Nepal road. Much loss of life and property resulted over 30 km of the highway on the China side of the frontier; the Friendship Bridge was destroyed, and downstream impact extended for 30 km into Nepal. In 1977, a potentially lethal *jokulhlaup* originated from a glacier on the slopes of Ama Dablam, also in the Khumbu, and destroyed bridges for 35 km downstream.

With the accelerating development of small hydel projects, engineering works, and trekking tourism in the Himalaya, the potential for a major disaster during the next decade is very high. Of equally serious concern is that *jokulhlaup* cause massive changes to the river channels along which they flow. They prompt landslides and slumps, and undercut sections of the river terraces, thus dumping vast amounts of debris into river beds, forming high river sediment for years, if not decades, following a *jokulhlaup* event. This is of critical concern because it leads to excessive silting of reservoirs and the possibility of damage to large-scale hydroelectric and irrigation facilities in the outer regions and the Terai.

This ICIMOD Occasional Paper provides a general description of the *jokulhlaup* phenomenon, introducing examples from other parts of the mountain world. It also gives a detailed account of the 4 August 1985 Langmoche *jokulhlaup* and the siting and destruction of the Namche Small Hydel Project. A proposal for a glaciological survey and monitoring programme is introduced.

It is concluded that many of the potential *jokulhlaup* danger areas can be identified and monitored at modest cost, insignificant when the potential for heavy loss of life and destruction of engineering works is considered.

New regulations are recommended so that future engineering projects include a prior assessment of *jokulhlaup* and related hazards. As in industrialized countries, blind development in the face of high natural risk should not be tolerated in Nepal and neighbouring Himalayan countries.

It is hoped that important lessons can be learned from the 4 August 1985, Khumbu disaster; prevention is always better than cure, especially when **prevention** is inexpensive and when **cure** is very costly and sometimes impossible to achieve.

INTRODUCTION

The commissioning of this report was prompted by the outbreak of a moraine-dammed lake below the Langmoche Glacier in Khumbu Himal, Nepal on 4 August 1985. The flood resulted in 4 or 5 deaths and destroyed the Namche Small Hydel Project, all the bridges, sections of trails, more than 30 houses and much arable land, for 40 km downstream on the Bhote Koshi/Dudh Koshi, (Galay 1985 ; Vuichard and Zimmermann 1986).

The catastrophic discharge of large volumes of water is characteristic of many mountain regions, and especially glaciated areas. Such discharges usually result from the collapse of unstable natural dams formed when stream channels are blocked by rockfall, landslide, debris flow, or ice and snow avalanches.

Another cause is the outburst of lakes dammed by glacier ice or by glacier moraines. These sudden discharges are referred to as *jokulhlaup*, (Icelandic for glacier leap), from their frequent occurrence and their early investigation in Iceland.

Geomorphologically such events cause major downstream aggradation and degradation, of an order of magnitude greater than the effects of normal hydrologic peak flows. *Jokulhlaup* are superimposed on the existing stream flow which may be high, medium, or low, depending upon timing; in each case the consequences may vary.

Depending upon the availability of loose material, the outbursts may be flood surges with a high sediment load, or actual debris flows, both of which may propagate tens of kilometres downstream.

In addition to the immediate and direct impact of a lake outburst, secondary and tertiary responses of the stream channel and valley sides can also be considerable. These include destabilization of talus cones and alluvial fans, undercutting and reactivation of old landslide and debris flow deposits, river bank undercutting, and the irregular deposition of enormous quantities of eroded and transported material in the stream channel and on the flood plain.

This report concentrates on *jokulhlaup*; the outburst of lakes formed in association with glaciers. This Icelandic term, which refers to glacier-dammed lakes *sensu stricto*, will be extended to embrace lakes dammed by glacial moraines. However, it should be noted that the effects of *jokulhlaup* show many characteristics common to other types of lake and man-made reservoir outburst.

In Iceland (Thorarinsson 1939), Norway (Liestol 1956), Alaska, British Columbia and Yukon Territory (Mathews 1965, 1971; Post and Mayo 1971; Clague and Mathews 1973; Young 1977), the Alps (Rothlisberger 1972), Pamirs (Krenke and Kotlyakov 1985), and Andes (Lliboutry *et al* 1977 a, b, c; Patzelt 1983); *jokulhlaup* have caused extensive property damage and loss of life. Investigation of this phenomenon has accumulated considerable information, much of which is relevant to the Himalayan situation.

The glaciated sections of the Himalaya and neighbouring ranges have remained isolated and sparsely populated until recent decades. Nevertheless, the occurrence of *jokulhlaup* and related phenomena has been known for more than a century (Mason 1935; Hewitt 1964, 1982). In recent years the age-old isolation has been broken by increasing population pressures, development of tourism, and accelerating efforts to develop natural resources, especially water resources.

Two aspects of the development of water resources are relevant to the current enquiry :

- o The establishment of small-scale hydroelectric installations and associated infrastructure at high elevations to service local communities;

- o Large-scale, even macro-scale, hydroelectric projects at various distances downstream from the glaciated high mountains, even in the subadjacent foothills and plains.

In the first case, the facilities are situated in close proximity to the potential *jokulhlaup* source areas and hence risk total destruction, heavy damage, or disruption as a direct or indirect consequence of a catastrophic flood. In the second case, especially where large and expensive intakes or artificial lakes have been constructed with no consideration of the *jokulhlaup* phenomenon, there is danger of damage, clogging and far more rapid siltation of reservoirs than design specifications indicate.

Several *jokulhlaup* have occurred in the Nepal Himalaya and neighbouring mountains in recent years. Hagen (1963) cited examples in the Manaslu region of Central Nepal. Similar events in Bhutan have been described by Gansser (1966). Fushimi *et al* (1985) provided a detailed account of the outburst of a moraine-dammed lake in the Dudh Koshi catchment that occurred in 1977. Xu (1985) made a thorough assessment of the 1981 *jokulhlaup* that originated in a tributary of the Boqu River (Sun Koshi). This last example, with an estimated peak discharge of 16,000 m^3/sec at the source, totally disrupted the China - Nepal highway, destroyed the Friendship Bridge, and modified the river channel for 30 km downstream into Nepal.

Sufficiently serious damage and loss of life has been incurred in Nepal and neighbouring countries to prompt the assumption that if the current rate of water resource development and tourist-related road and facility construction continues, there will be an acceleration in the loss of property and human lives. **There also is the potential for very large-scale losses.**

Thus, if these risks are to be reduced, the *jokulhlaup* hazard must be recognized, studied, and systematic steps taken to mitigate the effects. Identification of most *jokulhlaup* source areas can be undertaken at very low costs, so the potential for *jokulhlaup* occurrences can easily be taken into account when sites and facility design of engineering projects are being considered.

The Mountain Hazards Mapping Project recognized that the most serious hazard in the Khumbu region was associated with *jokulhlaup*. At least two, probably five, events have occurred within the previous 40 years. Similar floods were predicted for the Lobuche Khola, Gokyo Valley, Imja Khola, and Bhote Koshi.

News of the 1985 *jokulhlaup* in the Bhote Koshi reached Berne, Switzerland, when the colour proofs of the Khumbu hazard map were being checked. It was decided to make a reconnaissance of the effects of this event after the 1985 monsoon. A preliminary account is in print (Vuichard and Zimmermann 1986) with a more detailed presentation in press. [Vuichard and Zimmermann].

Organizations in Nepal have been aware of the hazards associated with *jokulhlaup*. The objectives of this paper are:

- o To provide a general overview of the *jokulhlaup* phenomenon;

- o To describe the Namche Small Hydel Project;

- o To present a detailed account of the 4 August 1985 Langmoche *jokulhlaup*;

- o To examine the feasibility for remote sensing mapping of potential *jokulhlaup* source areas in the Khumbu Himal;

- o To develop a strategy for rapid sensing mapping of the Central Himalaya;

- o To make general recommendations on the need to continue and expand the current *jokulhlaup* research programme being developed by the Water and Energy Commission, HMG/N.

Plate 1. Small outlet glacier with end and lateral moraines, northeast Baffin Island. The lake (X) is a typical moraine-dammed lake, held up by an ice-cored system of end moraines that are 100 metres high.

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 700km^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 :

- Thorarinsson was able to classify Icelandic *jokulhlaup* into vulcanogene and glaciogene types.
- 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.
- Sufficient change in glacier thickness has occurred within living memory to affect fundamentally the *jokulhlaup* regimes.
- 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 :

- o Increase of lake depth until it causes the ice dam to float (Thorarinsson 1939);
- o 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);
- o 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

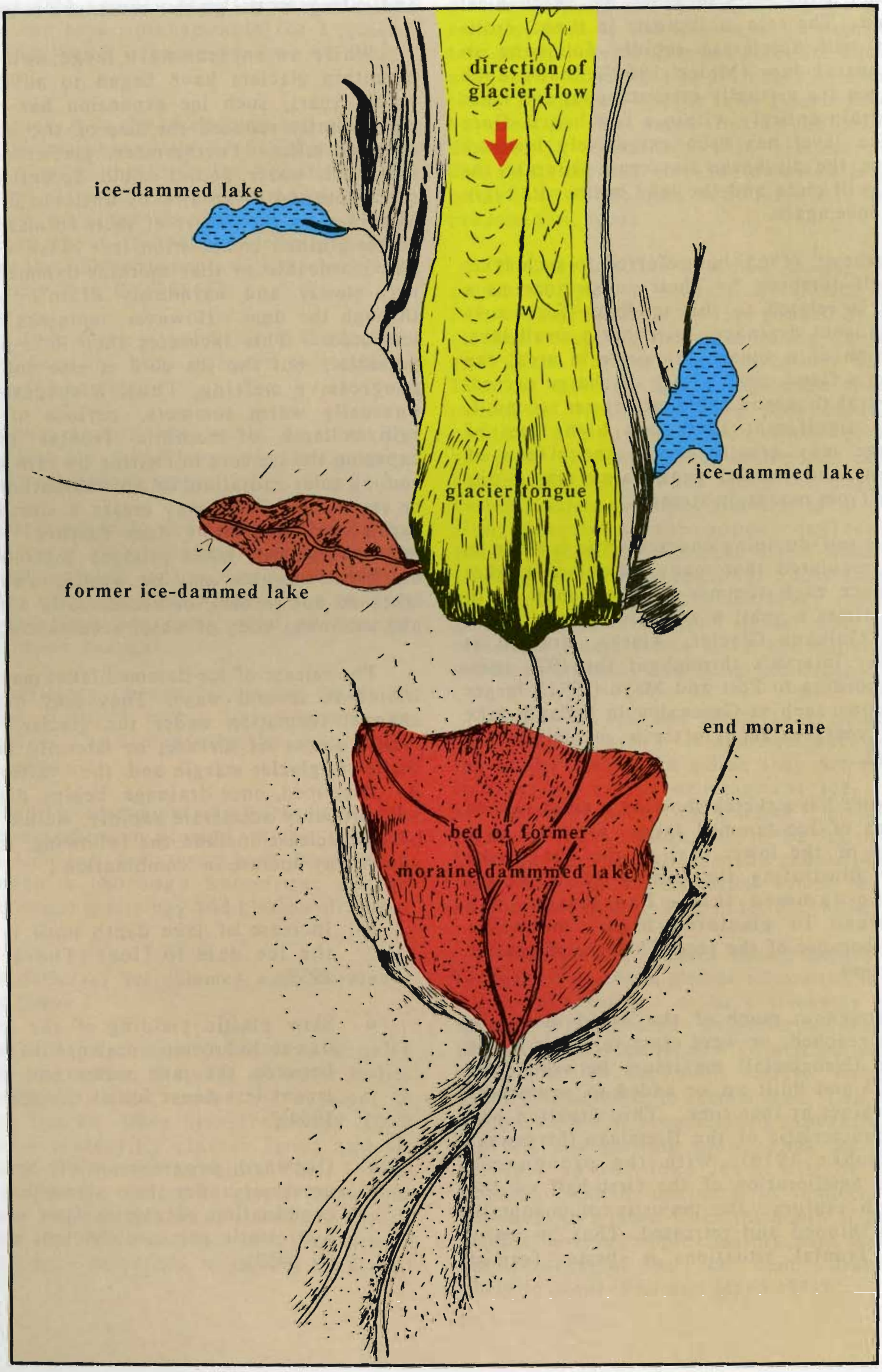
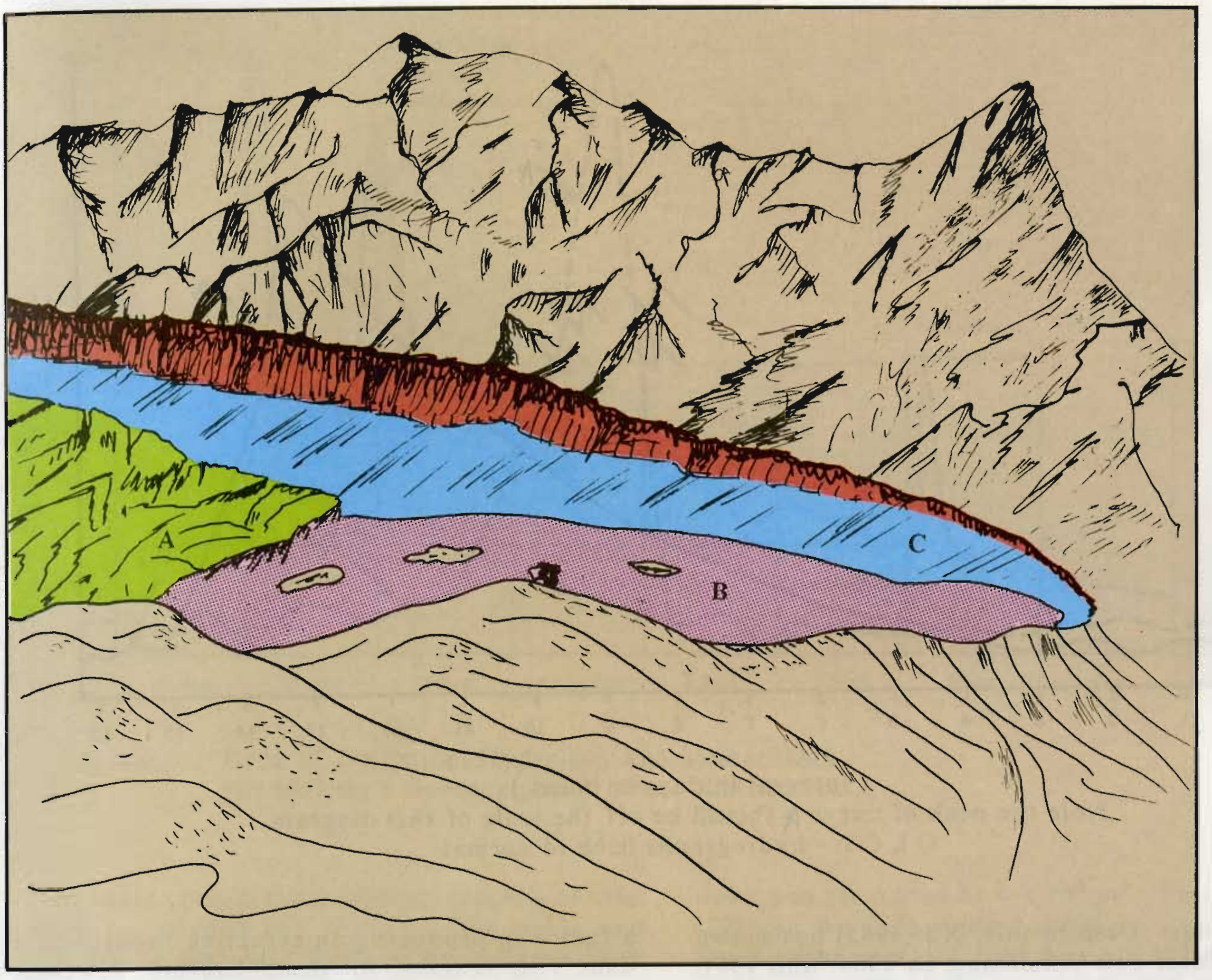


Figure 2. Sketch of the moraine-dammed lake, Dig Tsho and the lower part of the Langmoche Glacier, Khumbu Himal, Nepal. This reconstruction is to show the approximate appearance of the lake prior to the 4 August 1985, *jokulhaup.*



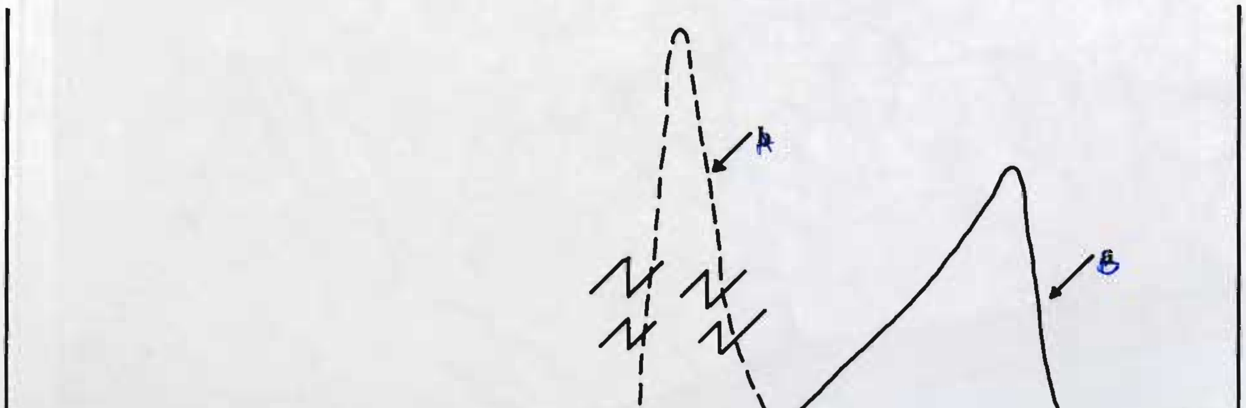
A. Glacier Snout
B. Moraine Dammed Lake
C. End Moraine

- 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

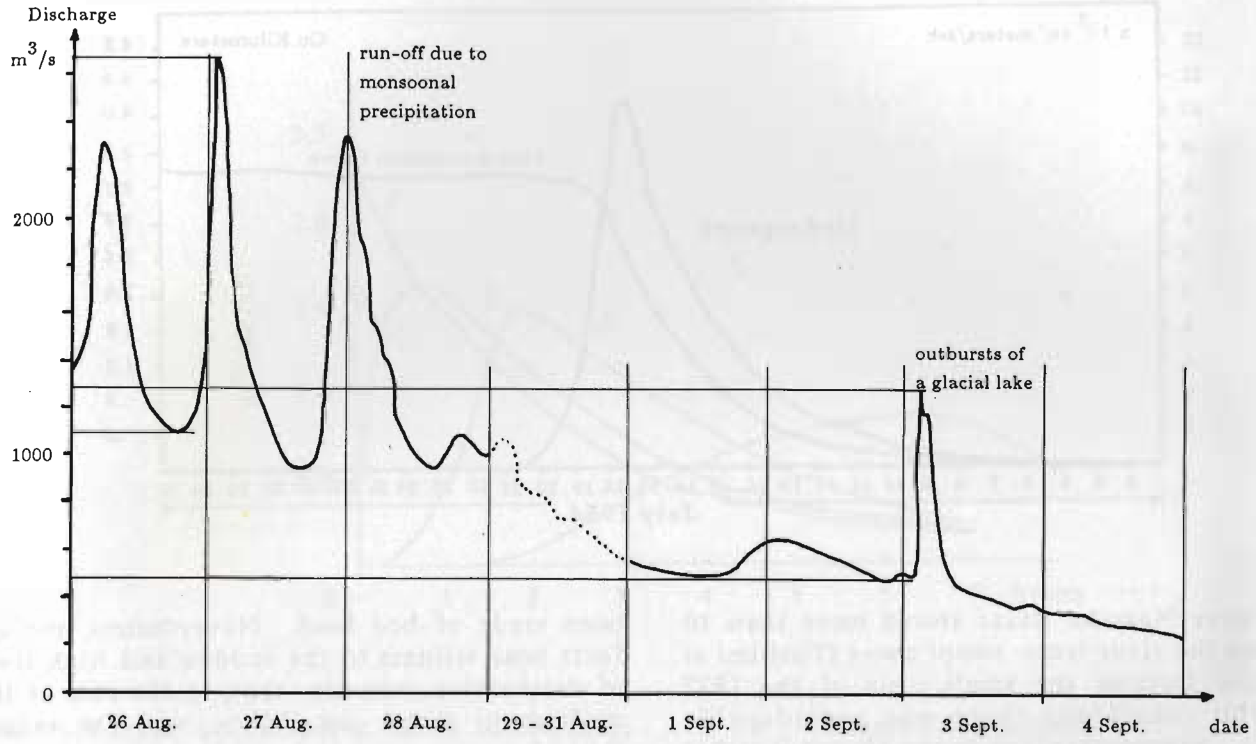
the process. Despite this, Xu (1985) has shown that at least two *jokulhlaup*, in 1964 and 1981, originated from the same moraine-dammed lake. The possibility of multiple events, therefore, cannot be ruled out.

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*

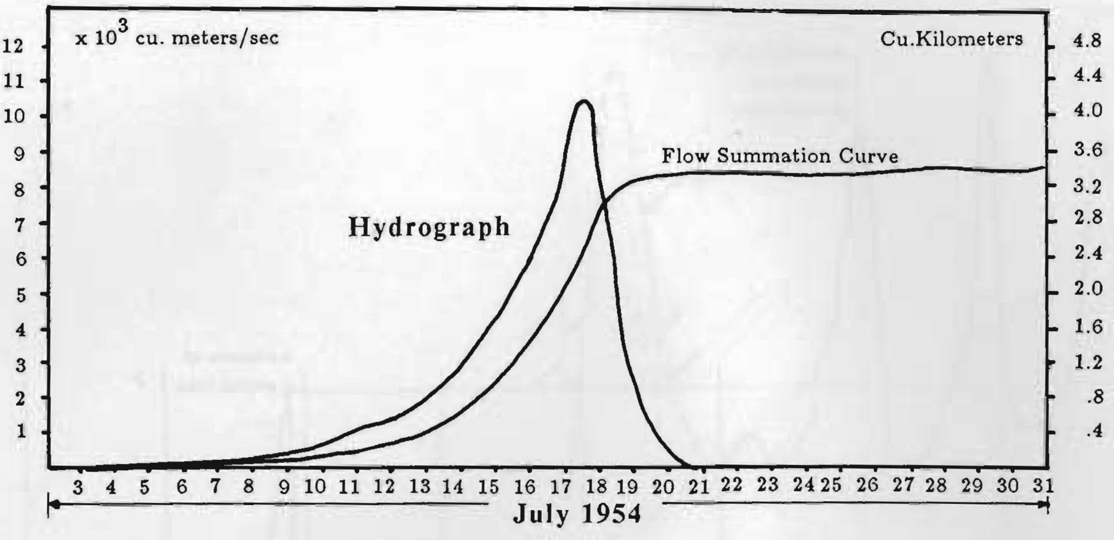
As implied in the foregoing sections, the catastrophic nature of the downstream effects of *jokulhlaup* is the result of extremely sudden and high peak flows. Obviously, therefore, *jokulhlaup* impact will be proportional to the volume of ponded water subject to near instantaneous release in association 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 x 15^5 m^3 (Fushimi *et al* 1985). An independent estimate was made by Buchroithner *et al* (1982) at 5 x 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.

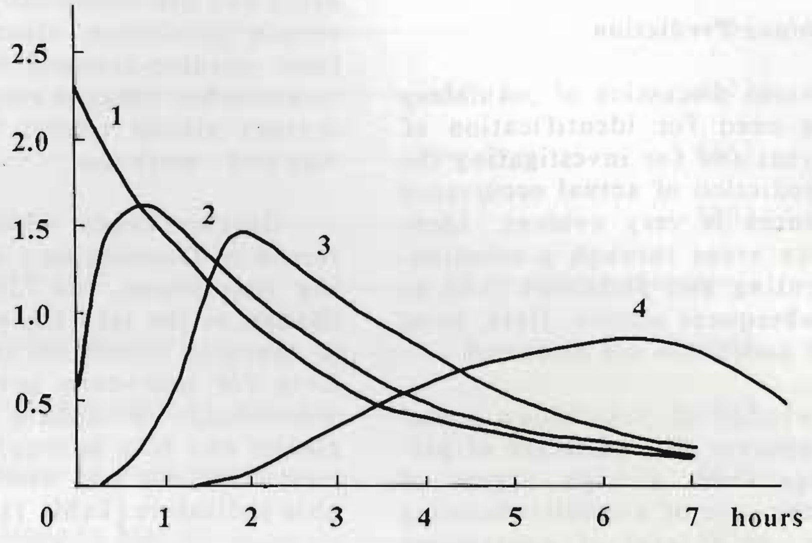
The second point is that the limited hydrographic data recorded from such events will be subject to considerable inaccuracies ; this will relate especially to estimates of transported material, and it is reasonable to conclude that no accurate determinations have been made of bed load. Nevertheless, 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.

THE NAMCHE SMALL HYDEL PROJECT, KHUMBU HIMAL

Decision Making, Project Design, and Site Characteristics

In April 1976 His Majesty's Government of Nepal requested the technical and financial assistance of the Austrian Federal Government for the construction of a small hydroelectric power station to service Namche Bazar and a number of neighbouring villages. The basis of this request was the rapid growth in trekking tourism and mountaineering in Khumbu Himal and the progressive transformation of the Sherpa economy as it adjusted to the disruption of its traditional pattern which was based in large part on open trade links with Tibet (Furer- Haimendorf 1964, 1984).

The number of tourists and mountaineers passing through Namche Bazar each year had exceeded the total Sherpa population by the early 1970s and had nearly doubled again by 1981. Guest houses and tea houses were constructed, especially along the trekking route from Lukla to Mount Everest base camp, and in Namche Bazar itself.

Rapid growth in demand for construction timber, together with the great increase in the use of fuelwood for cooking, hot water, and camp fires for trekking parties was perceived as a threat to the local mountain forests. Despite the establishment of Sagarmatha (Mount Everest) National Park, and increasing efforts to enforce the regulations against tree-felling within the park, this threat was perceived to be continuing unabated. Thus, the desire to harness local water energy was a rational government response.

The Austrian Federal Government granted the request in principle, and planning and site studies were undertaken by the Hydrology Department of the Universitat fur Bodenkultur, Wien, and the Verbund-Plan Ges. m.b.H., a group of Austrian consulting engineers. Various negotiations, site visits, and planning sessions led to the selection of a site near Dramo on the Bhote Koshi River. This is situated about six kilometres upstream from the confluence of the Bhote Koshi River and the Imja Khola to become the Dudh Koshi, " as clearly the most favourable possibility ".

Various design modifications, primarily to adjust to significant increases in estimated costs, and to reduce the amount of cement needed in the construction, were effected. Excavation began in October 1978, with initial scheduled completion by September 1982.

The plant design included a weir, intake, and headrace canal to a surge basin and penstocks, giving a vertical displacement to a power house and tailrace 35 metres below. From the intake the headrace canal extended for 285 metres across the lower slopes of a debris fan. Thus excavation was primarily in colluvium, alluvium and probably some till. The facility was designed for a minimum water flow capacity of $2m^3/sec$ -- this figure apparently derived from a hydrologic study of the Imja Khola (1971-1975) despite the fact that its course was in a somewhat different micro-climatic environment to the Bhote Koshi.

The site itself, the lower slopes of a debris fan, was sparsely vegetated in contrast to valley slopes both upstream and downstream which carried a fairly complete cover of forest (including *Abies spectabilis, Betula utilis, Rhododendron spp.*), and shrub forest, except where debris flow tracks and torrents cut down to the river from the steeper slopes above.

The hydro-plant debris fan is marked by several conspicuous debris flow deposits and small torrent channels. The possibility of mudslide and soil creep occurrence was taken into account in the project design. Ground photographs, however, show that sections of the debris fan toe were being undercut by the Bhote Koshi prior to excavation and quite extensive undercutting is apparent in a November 1984 photograph when the excavation work was nearly complete (Plate 5, A & B).

The lowest point of the project, the power intake, is at 3,300m.a.s.l.; the altitude of Namche Bazar is 3,440 metres. Thus the project site lies well within the High Himalaya belt and has a severe, mountain-attenuated monsoon climatic regime. The total catchment of the Bhote Koshi is 444 km^2 and the power intake controls 88 percent of this. Several mountain peaks along the rim of the catchment exceed 7,000m with a maximum altitude of 7,532m.

The engineering report estimated that 34 percent of the catchment was covered by permanent ice and glaciers. The largest glacier, Nangpa Glacier, which descends from the Nangpa La (5,716 metres) on the border with Tibet (People's Republic of China), is about 18km in length. It has several tributary glaciers, the largest being the Sumna Glacier, which is almost 8km in length. The source of the Bhote Koshi originates from the indefinite and debris-covered terminal zone of this complex of glaciers. The Bhote Koshi also receives several west-bank tributaries draining from a series of valley glaciers and cirque glaciers that originate high on the western rim of the catchment. One of the more important of these drains from a series of glaciers into the Langmoche Valley which is confluent with the mainstream about 6km above the project site. Another tributary enters the Bhote Koshi about 2.5km above the site which drains the glaciers and ice-fields of the Trashi Labtsa Pass. Many of these glaciers are partially nourished by massive snow and ice avalanches which fall from the spectacular mountain wall above. Large rockfalls are also an obvious component of the suite of geomorphic processes.

Most of the glaciers in Khumbu Himal have been thinning and retreating for several decades. This process has led to an increase in the area of debris-covered and apparently stagnant ice, characteristic of the lower reaches of many of the larger Himalayan glaciers. Another feature of the recent glacier thinning and retreat has been the development of many small lakes dammed between the innermost end-moraines and the glacier margins. Lakes are also apparent in supra-glacial positions on many of the larger glaciers, and there are also ice-dammed lakes lateral to the main trunk glaciers. In 1977 one of these lakes, a moraine-dammed lake in the Imja Khola catchment (Fushimi *et al* 1985, see above), drained catastrophically causing much damage and destroying all the bridges for 35km downstream. Vuichard and Zimmermann (1986) reported that oral tradition among the Sherpa communities indicates the probable occurrence of four or five similar *jokulhlaup* over the previous forty years.

No evidence was obtained from the available Namche Small Hydel Project documents to the effect that any special attention was paid to the possible occurrence of catastrophic geomorphic events, despite the fact that the project was being sited in one of the highest and most precipitous mountain regions in the world. Even the Engineering Report (DRG. No. 1.01, n.d.) provides only an abbreviated overview of the terrain and a very unbalanced view of the climate, making the surprising claim, for instance, that the mean annual air temperature for Namche Bazar is 11°C (actual m. a. a. temp. is 6.4°C).

Construction Phase and Restraints

"The planned Namche Bazar Hydropower Station can be regarded as an extraordinary engineering project in every respect " (DRG. No. 1.01, n.d., p. 9). This is because of the high altitude and severe climate at the site and its extreme difficulty of access. Access in the late 1970s involved a 12 to 15 day walk from the nearest point on the China Road, a three day walk from the STOL airstrip at Lukla on the Dudh Koshi, or a three hour walk from the Pilatus STOL landing strip at Syangboche. Thus, from an economic as well as an environmental impact point of view, maximum use was to be made of local materials and the overall design was established to consume an absolute minimum amount of cement. The original design called for the transport of 900 tons of cement to the site within a three-year period. This was deemed impractical and to reduce the amount required still further (to 300 tons) "certain operational safeties, which under normal circumstances would be required as a matter of course, were dispensed with..." (DRG. No. 1.01, n.d., p. 9). It was planned that the necessary structural steel and mechanical equipment, such as turbines, generators, and transformers, would be flown in by helicopter.

In addition to the power plant itself, several construction auxiliaries were required. These included an all-weather foot-bridge across the Bhote Koshi, a cable crane installation at the weir, a power distribution system so that the villages of Namche Bazar, Khumjung, Khunde, and Thamo could be supplied with electricity and sundry support buildings.

The project met with a number of construction delays and a change in engineering consultants. A site inspection report dated 29 May 1985, revealed that most of the civil engineering construction had been completed, excavation for the foundations of the power house prepared, and some on-site modifications had been made. Plans were in hand for the design, fabrication, and delivery of the generators, turbines, and transformers, and the power house was scheduled for construction during October/November, 1985. Installation of the penstocks and hydroelectric structures was planned for completion prior to the 1985/86 winter. It should be noted that during a heavy flood in 1984 -- presumably normal summer monsoonal peak -- the river bank above the power house was eroded, necessitating the construction of a stone protection wall.

The original planning called for a facility with an annual power output of 6,350,000 kWh at an estimated cost of NRs 24.13 million. Some years of delay ensued and final cost estimates increased to NRs 45 million. Nevertheless, the prospect was for the provision of reliable and very cheap power to the neighbouring communities. A diesel power plant, for instance, would entail fuel costs alone exceeding by six times the total energy costs of hydropower (DRG. No. 1.01, n.d., p.35).

On 4 August 1985, the Dig Tsho moraine-dammed lake in front of the Langmoche Glacier overtopped and burst its dam.

The Namche Small Hydro Project was virtually destroyed.

Destruction of the Namche Hydel Project

Comparison of two sets of ground photographs, one set from the north side of the Bhote Koshi looking directly across the river onto the debris fan, and the other set taken from the Namche Bazar trail looking upstream, clearly demonstrate the extent of the damage. The first set was photographed by Dr. Victor Galay in November 1984, and after 4 August 1985 ; the second set was photographed by Daniel Vuichard on 4 April 1985, and 19 October 1985 (Vuichard and Zimmermann 1986, p. 93, Figures 5 and 6). These are reproduced as Plates 2, 3, 4, and 5.

The debris fan underwent extensive undercutting, erosion, and transport, with most of the erosion occurring in three distinct areas :

- o The vicinity of the weir and intake to the headrace canal;
- o The central tract of the toe;
- o The downstream tract in the vicinity of the power house site and tailrace.

Much erosion also took place on the north side of the stream. This erosion resulted in the total destruction of the weir and headrace intake, the upstream half of the headrace canal, the lower half of the penstock channel, the foundations for the power house, the tailrace, and the helicopter landing pad. In addition, the river channel, or flood plain, was extensively widened and heavily aggraded with three to seven metres of large-diameter debris. The character of the Bhote Koshi channel in this section, as well as that of the debris fan, has been totally changed. This has probably made the site unsuitable for any salvage or reconstruction action, even if it is assumed that the draining of Dig Tsho was a unique event and that there is no likelihood of future *jokulhlaup* occurring from any alternate source within the Bhote Koshi catchment. The latest report from the Small Hydel Development Board is that the feasibility of constructing several micro-power stations away from the main stream is being explored.

Thus ended nine years of negotiations, planning, construction, and comparatively heavy expenditure, and nine years of anticipation on the part of four or more Sherpa villages that eventually they would receive a hydroelectric power supply.

A number of compelling questions demand attention :

- o What was the viability of the decision to respond to a perceived need for hydroelectric power in the Khumbu in the first place ?
- o Why was there no investigation of the hydro-glaciology of the Bhote Koshi catchment prior to site selection, espe-

Plate 2. Site of the Namche Small Hydel Project looking upstream from the Namche Bazar trail. Photographed on 4 April 1985, by D. Vuichard.

Plate 3. Nearly identical view to Plate 4, photographed after the *jokulhlaup*, 19 October 1985, by D. Vuichard. Note the extensive erosion to the debris fan and the massive accumulation of coarse alluvium in the now much widened riverbed.

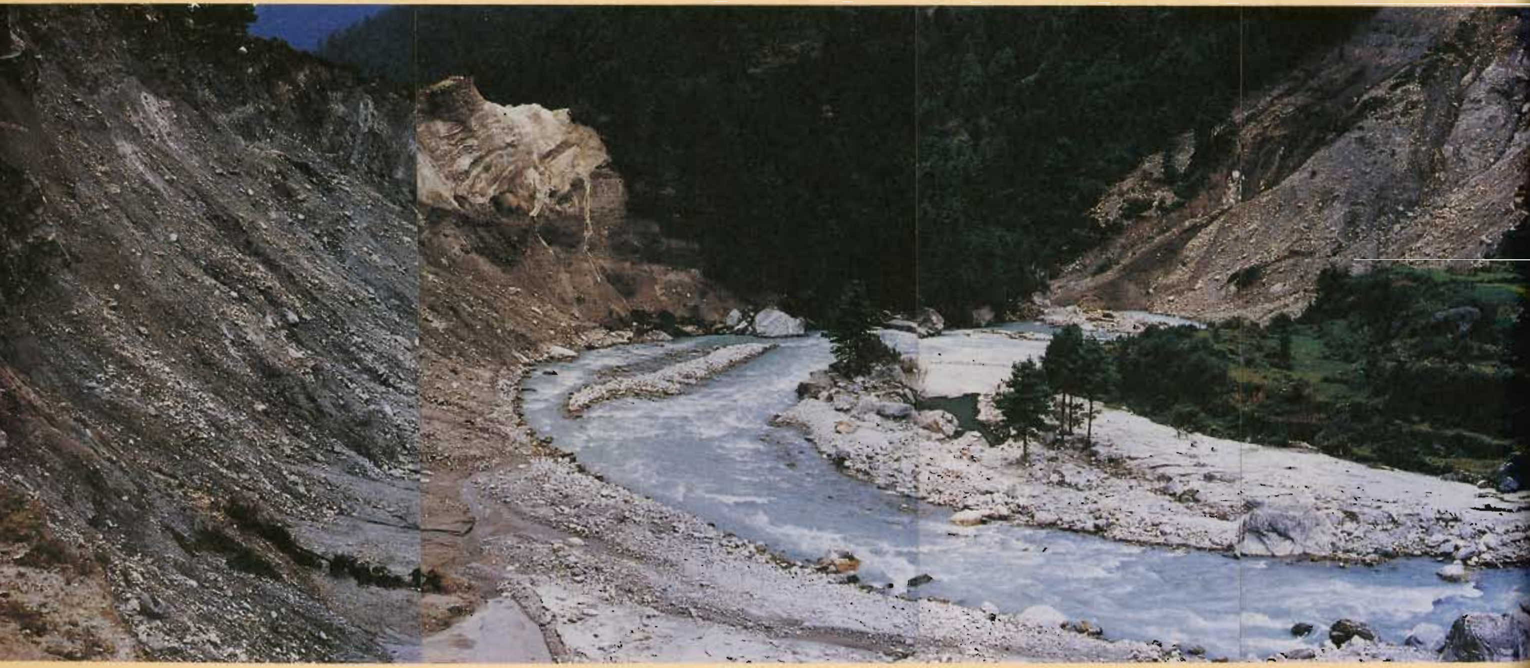
cially to locate possible ice-dammed and moraine-dammed lakes ?

- Once seepage from Dig Tsho and a degree of overtopping was noticed in August, 1984, why were no steps taken to partially drain the lake, or at least to set up a monitoring and early warning system, or to review the design and site selection parameters ?

These questions may well be dismissed as excellent hindsight and of purely academic importance. They are certainly not intended as criticism for its own sake ; rather they are posed to set the stage for demonstrating the need for integration of glaciological reconnaissance and research with future planning, design, and construction of waterpower (and other) projects in glaciated areas of the Himalayan region.

Plate 4. Panoramic view of the Namche Small Hydel Project site by Dr. Victor Galay in November 1984. The photographs are taken from the north side of the Bhote Koshi looking onto the debris cone. The headrace canal cuts conspicuously sub - horizontally across the fan. Undercutting of the fan has occurred during the preceding summer monsoon at (a) and (b).

Plate 5. **The Bhote Koshi after the 4 August 1985, *jokulhlaup* showing aggradation and extensive bank undercutting and a large landslide.**
Photograph by Dr. Victor Galay.



Characteristics of Langmoche and Triggering Mechanism

The Langmoche Valley (latitude 27° 52'N; longitude 86° 35'E) is aligned approximately west-northwest to east-southeast for a distance of 10 km in Khumbu Himal. It is a compound glacial cirque with individual cirques combining to form a U-shaped valley, tributary to the Bhote Koshi. It ranges in altitude from about 3,970 m, at the confluence with the Bhote Koshi, to 6,940 m at the summit of Tangi Ragi Tau, on the southwestern valley rim. Many secondary summits exceed 6,000 m, although the crest of the northeastern valley wall is generally below 5,800 m. The gigantic crescent-shaped headwall along a distance of more than 10 km, nourishes a series of hanging cirque glaciers and one small valley glacier, the Langmoche Glacier, which is 3 km long. The cirque glaciers, and especially the Langmoche Glacier, are partially fed by avalanching ice and snow from the precipitous headwall.

Much of the ridge crest rising above about 5,900 m is ice-mantled and the higher parts of the rock headwall carry festoons of fluted, high-angle ice. Extensive and well - preserved neo-glacial moraines bear witness to the greater extent and thickness of the glaciers in the recent past. The neo-glacial end moraines of the Langmoche Glacier extend down to about 4,400 m. An earlier and much more extensive glacial phase is marked by pronounced end moraines at 4,120 to 4,160 m, immediately above the Bhote Koshi confluence. Their age is not known but they are presumably of Late Glacial origin.

The lower Langmoche Valley exhibits a broad open form and supports relatively luxurious alpine meadow vegetation with fell-field communities on the lower slopes. This provides the basis for the three small summer settlements of Dig, Langmoche, and Mingbo, which are used by the Thame Sherpas for grazing their yak and cross-breeds.

The recent thinning and retreat of the Langmoche Glacier from its neo-glacial end moraines has resulted in the formation of a small moraine-dammed lake, Dig Tsho. Prior to 4 August 1985, it was approximately 1,000 x 400 m in extent with a relatively level floor, maximum depth about 20 to 25 m. A crude estimate of its maximum volume is 6-10×10^6 m^3. The lower part of the glacier, virtually a secondary avalanche accumulation ramp, extended and calved into the lake. It is almost separated from the main part of the glacier by a small bedrock step of variable height over which avalanche debris frequently cascades.

Little information could be obtained about the recent history of the lake, Dig Tsho. The so-called Schneider map, Khumbu-Himal, scale 1:50,000, based upon fieldwork and photogrammetry between 1955 and 1963 (Second Edition 1978), shows the Langmoche Glacier and the pronounced neo-glacial end moraines, but does not indicate the presence of Dig Tsho. Since a small moraine-dammed lake 3 km north of the Langmoche Glacier is shown on this map, it could be that Dig Tsho is of very recent formation and that it post-dates the terrestrial photogrammetric work of Schneider (1955-1963). Without checking the original photographs, however, the possibility that the photo-angles simply did not expose an existing lake cannot be ruled out. Moreover, Dig Tsho is shown on the Survey of India 1:63,360 map No. 72 1/9, First Edition, 1974, surveyed in 1973, so it appears that the latter explanation is the most likely.

A photograph taken on 3 Sept. 1982 (Plate 6) by M. Zimmermann clearly shows Dig Tsho. Furthermore, it can be seen that on that date the lake level was coincident with the lowest point of its end moraine dam across which a small stream discharged. Drainage also may have occurred by seepage through the lower part of the moraine. The intact end moraine and small outflow stream are also apparent.

From the foregoing discussion it is apparent that Dig Tsho Lake had existed for some years prior to 1982 (and possibly for some decades) and that between September 1982 and August 1985, it was overtopping (or close to overtopping) the moraine dam. This is also confirmed by the reported observation by the Namche Hydel Project engineer in August 1984.

Dig Tsho lies about 11 km upstream of the Namche Hydel Project weir and headrace canal intake. From the limited available information referred to, it is apparent that the lake had been potentially unstable for several years and the possibility for a gradual, or catastrophic, increase in the rate of discharge was considerable. That a catastrophic discharge occurred on 4 August 1985 was dependent on the activation of a specific triggering mechanism. Evidence for the immediate cause of this is ambiguous. Vuichard and Zimmermann (1986, 1987 in press) report that, according to local witnesses, the Khumbu experienced a long period of warm and clear weather throughout much of July 1985 which continued into early August. This is assumed to have resulted in some melting of the large mass of ice high on the rock wall above the Langmoche Glacier, which consequently avalanched in the early afternoon of 4 August. The avalanching mass appears to have hit the mid-section of the glacier, cascaded over the lower rock step, overridden the glacier avalanche ramp, and splashed into the lake. The impact of the avalanche initiated a surge wave that overtopped the moraine lip, causing rapid erosion of the sill and lowering of the outlet. Once this process had begun a large volume of water was available for overflow which, in turn, would accelerate erosion of the sill and initiate a major rupture in the end moraine. This allowed rapid drainage of the lake, releasing one or more catastrophic flood crests down the Langmoche Valley, into the Bhote Koshi, through the Namche Small Hydel Project site, and down the Dudh Koshi.

A Water and Energy Resources Development Project report (Pradhan and Gysi 18 December, 1985, unpubl.) gives a somewhat different explanation. This account proposes that a period of heavy monsoon rain and snow and subsequent melting, "initiated a massive rockfall from the steep rockface above the Langmoche glacier". The proposed source of such a rockfall is seen on Plate 7). The rockfall debris is presumed to have hit the glacier surface triggering the "detachment of huge ice blocks at the toe of the glacier" which entered the lake. From this point the two explanations are identical.

Whichever reconstruction is correct, both agree that the immediate cause of the Langmoche *jokulhlaup* was the sudden fall into the lake of a large mass of avalanche ice (and possibly rockfall debris) which sent a surge wave across the moraine dam. A precondition for the *jokulhlaup*, however, was that the level of Dig Tsho was at, or close to, the low point on the end moraine dam. As has been shown, this condition had prevailed for much, if not all, of the preceding several years (minimum, 1982-1985). Pradhan and Gysi concluded that within a few minutes 1 mill.m^3 of water were released and, in places, the flood wall in the Bhote Koshi and Dudh Koshi exceeded 15 metres in height.

Vuichard and Zimmermann (1986) estimate that 6 - 10 x $10^6 m^3$ of water drained from Dig Tsho within about four hours, giving an average discharge of 500 m^3/sec. However, when they considered the character of the triggering mechanism, they assumed that the initial peak discharge may have exceeded 2,000 m^3/sec. There appears to have been several surges, since the bridge at Jubing, 40km downstream, was washed out 90 minutes after the initial surge had passed. So far it has not been possible to obtain access to the hydrograph chart from Rabuwa Bazar, near the confluence of the Dudh Koshi with the Sun Koshi, so that the details of the attenuated *jokulhlaup* form can only be estimated. The apparent occurrence of multiple surges may have resulted from a succession of resistant layers in the moraine dam that were successively overcome by the discharging flood waters. Other possible causes include temporary damming downstream by landslides and temporary impoundment of tributary valleys.

Local eyewitnesses reported that the surge front appeared to move down - valley rather slowly as a huge black mass of water full of debris. The movement was of a rolling type, splashing from one river bank to the other, depending upon the curvature and cross - section of the channel. Waves overtopped the river banks in places. Trees and large boulders were dragged along, or bounced around ; some of the trees were in upright positions. The surge emitted a loud noise, " like many helicopters ", and a foul mud smell. The valley bottom was wreathed in misty clouds of water vapour, the river banks trembled, houses shook, and the sky was cloudless.

Plate 6. A wide angle view of Dig Tsho, and the intact curve of the end moraines with the small stream draining from it.
Photograph by M. Zimmermann, 3 September 1982.

Plate 7. Similar view to 6., but taken after the 4 August 1985 *jokulhlaup* showing the breach in the end moraine of the Langmoche Glacier.
Photograph by D. Vuichard.

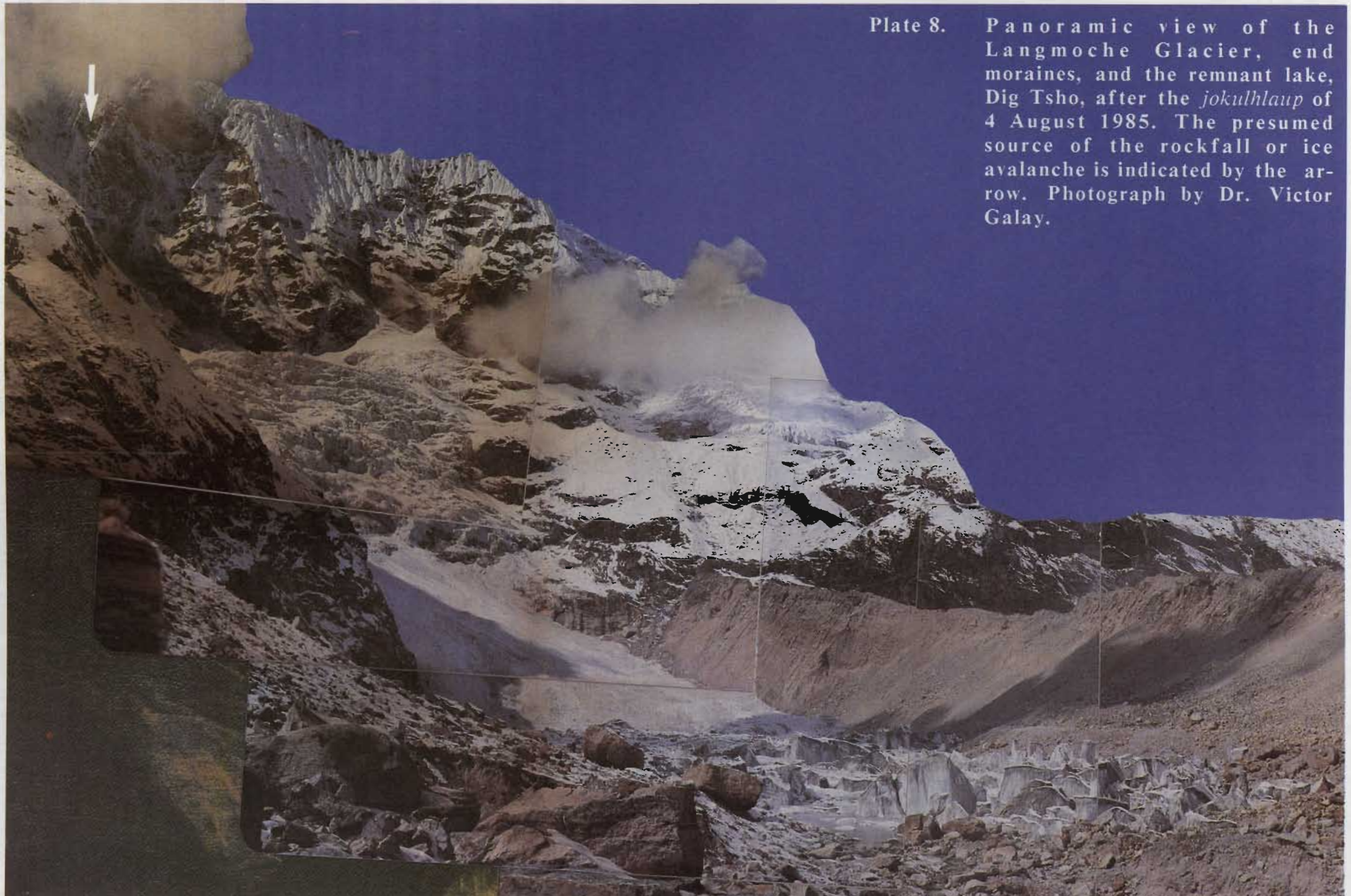


Plate 8. Panoramic view of the Langmoche Glacier, end moraines, and the remnant lake, Dig Tsho, after the *jokulhlaup* of 4 August 1985. The presumed source of the rockfall or ice avalanche is indicated by the arrow. Photograph by Dr. Victor Galay.

Vuichard and Zimmermann (1986) estimated that the magnitude of the peak discharge was two to four times that of any previous *jokulhlaup* that has occurred in the Khumbu within living memory. Certainly, the extent of the changes in the river channel and lower valley slopes between Dig Tsho, the point of origin, and the Sun Koshi confluence 90km downstream indicate that the upper limit of this estimate is reasonable.

Downstream Impact

The single most spectacular impact of the Langmoche *Jokulhlaup*, of course, was the effective destruction of the nearly completed Namche Small Hydel Project already described (pp.27-28). Nevertheless, extensive damage resulted along the entire length of the Langmoche Khola - Bhote Koshi - Dudh Koshi down to the confluence with the Sun Koshi, an overall distance of about 90km. The total damage, together with the long-term instability of many sections of the river channel and lower valley slopes, may far exceed the loss of the hydropower project.

Vuichard and Zimmermann (1986, 1987 in press) described the destruction of, or extensive damage to, the following infrastructure: All 14 bridges over the 42 km distance between Langmoche and Jubing, including the new high suspension bridges at Jorsale, Phakding, Gyuphede, and Jubing, were destroyed. An unspecified number of houses were destroyed above Thamo in the Langmoche Valley, and about 30 in the Namche and Chaurikharka Panchayats. This destruction probably deprived many families of their entire property.

Some of the houses were destroyed by the direct action of lateral erosion of the river banks ; in other places lateral erosion destabilised the river terraces and lower valley slopes, and houses slipped into the riverbed, there to be broken up and engulfed by the flood waters. This process continued for several days after the *jokulhlaup* occurrence. Some houses collapsed as a result of vibrations caused by the surge.

Another form of destruction was the erosion, undercutting, and destabilisation of long stretches of the main trail by the triggering of debris flows. This trail is not only the primary access to the weekly market at Namche Bazar, but is an integral part of the main trekking route from the STOL airstrip at Lukla to the Mount Everest base camp via Namche Bazar and Tyangboche. The bridge and trail destruction effectively isolated the entire Khumbu region for several days and caused closure of the market on three successive Saturdays. Price increases were reported to average 50 percent for staple supplies when it reopened.

Additionally, one of the most severe effects was the destruction of much cultivable level land which may have deprived communities of a large part of their subsistence base. Also to be counted among the losses was the stripping of forest cover, for example between Thamo and the Bhote Koshi - Imja Khola confluence.

Massive changes occurred in the riverbed over most of the distance between Dig Tsho and the Sun Koshi confluence. This was due to a combination of erosion and deposition, both within the same stretch of river (Plate 5) and in successive sections depending on channel and valley characteristics. Large and medium sized debris flows were touched off by lateral erosion in numerous localities (Plate 9) and innumerable small slumps occurred (cover plate).

Below Jubing the extent of the damage seems to have diminished (in a downstream direction) but even in the vicinity of the Sun Koshi confluence, intermittent valley slope and river terrace slippage as well as extensive aggradation of the river bed occurred.

The net result has been the provision of a vast quantity of alluvium, some of very coarse grade, to the river channel and the destabilization of many sections of the valley sides. This instability is likely to persist for several years as the unvegetated loose slopes will remain highly susceptible to further movement during subsequent periods of heavy monsoon rain. Similarly, the large quantities of material accumulated in the riverbed will remain a source of sediment for a long period so that, even at considerable distances downstream, sediment loads can be expected to remain high during summer rains, probably for one or more decades.

The local communities, of necessity, replaced the eroded sections of trail. These emergency efforts were piecemeal and uncoordinated, and the end result was less than satisfactory (Plate 9). For instance, seven acci-

Plate 9. Channel of the Bhote Koshi in the vicinity of the hydel project after the 4 August 1985, *jokulhlaup*. Note the extensive aggradation as well as heavy erosion (of the debris fan) in the same stretch.
Photograph by Dr. Victor Galay.

dents, two reported as fatal, occurred on the improvised trail section between Ghat and Namche Bazar during the second half of October 1985.

Actual loss of life was remarkably low. There were only 4 or 5 deaths reported (Galay 1985), attributable to the fact the three day Sherpa Phangnhi festival was in progress in the home villages when the catastrophe occurred. Another factor is, many of the villages are situated well above the river. Some livestock losses were reported.

Figure 7 is a rough sketch of the river course between Dig Tsho and Chaurikharka, and gives an impression of the types of damage and its distribution along the Bhote Koshi and upper Dudh Koshi.

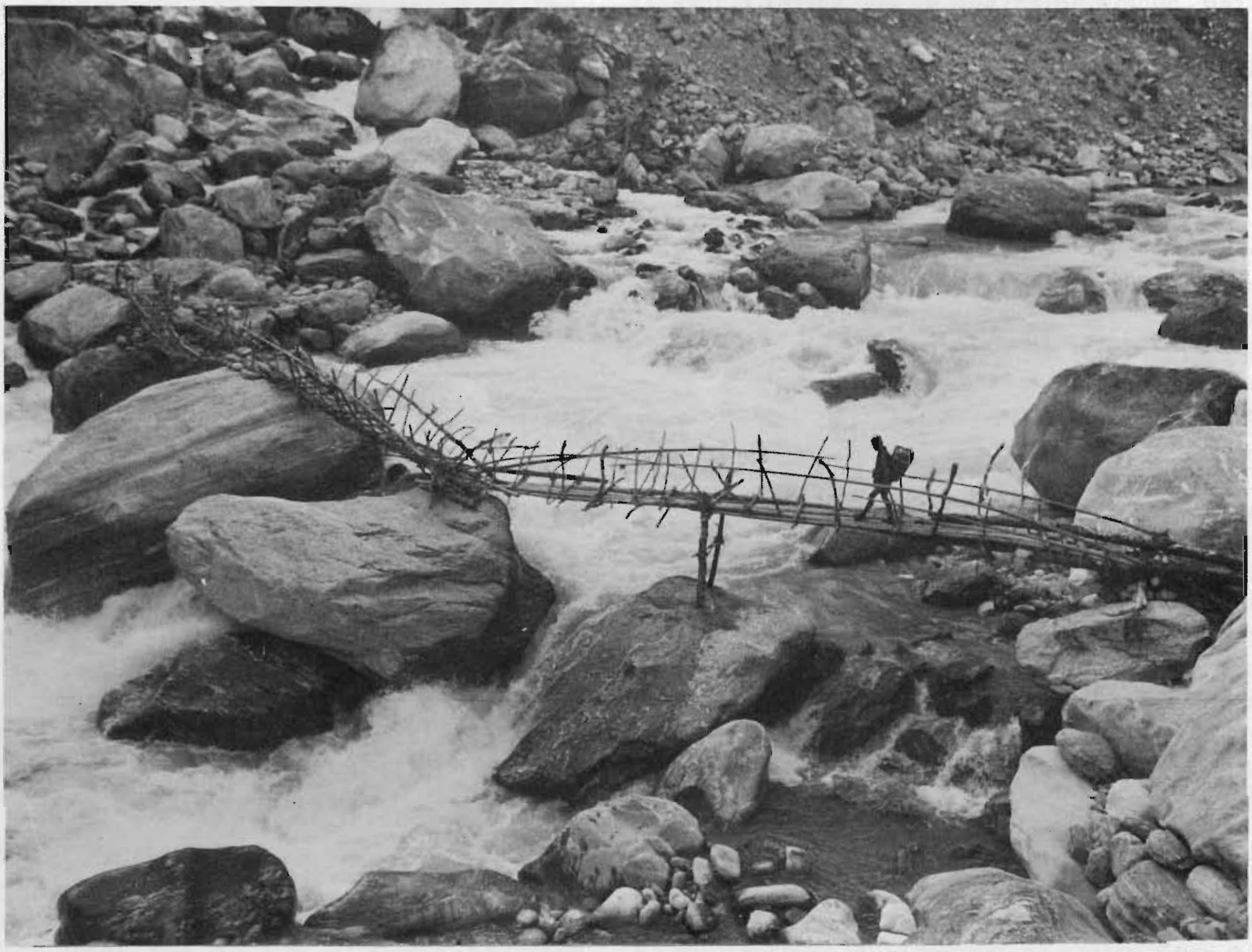
Overall economic losses are difficult to ascertain, although the Langmoche *jokulhlaup* must be regarded as a disaster on any human scale. It is even more difficult to estimate the psychological impact of the indefinite postponement of hydro-electric power supply to the main Sherpa villages after such a long wait and high anticipation.

Finally, it is instructive to consider what the potential maximum losses could have been if the *jokulhlaup* had occurred before or after the Phangnhi festival, during the summer monsoon period, or later in the year in mid-October for instance, when the trekking season is at its height.

Disaster Scenario 1 : 15 August 1985 :

To complete such a scenario in any detail would require a careful survey of community activities during the summer monsoon and the disposition of the local people. However, it is reasonable to conclude that the loss of life would have been significantly higher.

Plate 10. The precarious nature of the temporary bridges that were constructed by the local people is clearly demonstrated in this photograph by D. Vuichard, October 1985.



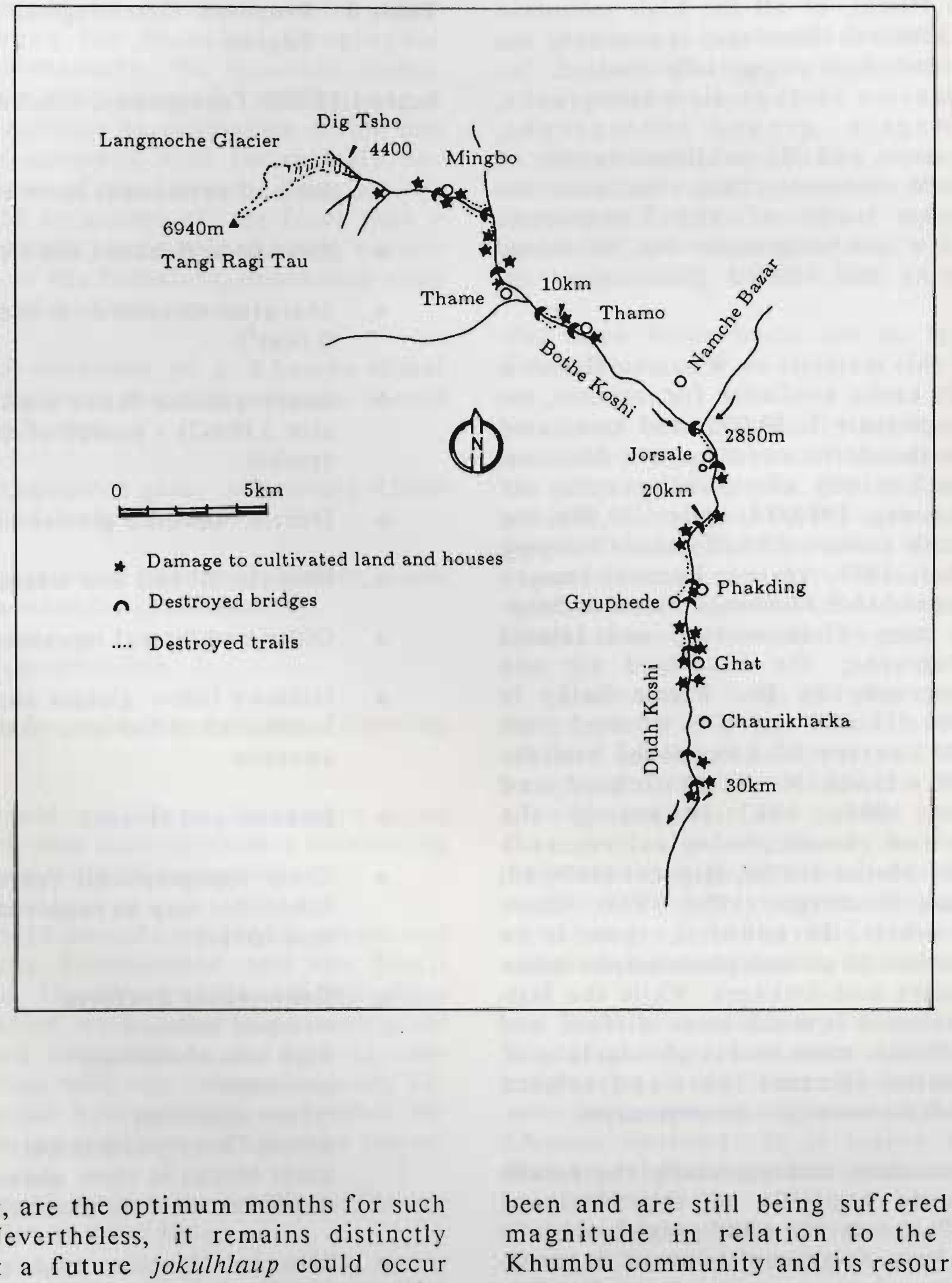
Disaster Scenario 2 : Mid-October 1985 :

At this time of year trekking and mountaineering activities would be at their height. It must be assumed that many trekking parties and their porters would be scattered along the trail between Lukla and Namche Bazar. If the event occurred during the night, many trekking parties would be camped in highly vulnerable positions in relation to the height of the *jokulhlaup* crest wave. The number of potential victims could be as high as 200 trekkers and porters. Assuming that the day of the catastrophe was a Friday or a Sunday, then additional large numbers of porters and traders would be carrying their produce up to, or down from, the Saturday market at Namche Bazar. Allowance must also be made for the presence of trail and bridge maintenance workers within the danger zone.

In either of the two scenarios, the damage to infrastructure, trail, fields, and forest cover would not change from that which actually occurred. However, the loss of life undoubtedly would have been higher in scenario (1) -- perhaps only moderately so -- but in scenario (2) it would have been very high indeed. Such a worst-case disaster would attract worldwide attention and, in view of the large losses among tourists, have had an adverse, if temporary, effect on Nepal's tourist industry.

Another question which must be added to this discussion of risk assessment is what the likelihood is of a *jokulhlaup* actually occurring in October. Considering the relatively long period when Dig Tsho was at or close to the level of the outlet sill, the question resolves itself into one concerning the likelihood of the triggering mechanism occurring in the pre- or post-monsoon trekking period. Since the triggering mechanism was an ice - avalanche, or a rockfall, apparently requiring a period of warm weather with or without significant precipitation, it must be admitted that August and July,

Figure 7. Sketch of the Bhote Koshi showing location and type of damage. Modified from Vuichard and Zimmermann (1986).



in that order, are the optimum months for such an event. Nevertheless, it remains distinctly possible that a future *jokulhlaup* could occur during the trekking season. Moreover, the moraine dam burst could be set off by other causes.

While this discussion must inevitably be very general because of lack of data, it is emphasised that 4 August 1985, was the absolute optimum moment for the Langmoche *jokulhlaup* to occur in terms of minimum risk to human life. In any event, the actual losses that have been and are still being suffered are of high magnitude in relation to the size of the Khumbu community and its resource base.

The possibility of another *jokulhlaup* in Khumbu, or in a similar area within the Himalayan system, is extremely high -- so high, in fact, that it must be considered a near certainty within the next ten years. It is imperative, therefore, that an effective and carefully thought-out response be developed. Some guidelines are provided in the next section.

MAPPING OF POTENTIAL JOKULHLAUP SOURCE AREAS IN KHUMBU HIMAL

Khumbu Himal, of all the high mountain areas of the Central Himalaya, is probably the best known and most extensively studied. Information sources include air photographs, satellite imagery, ground photographs, topographic maps, and the published results of natural science research. This reinforces the choice of the study of the Langmoche *jokulhlaup* as a test programme for *jokulhlaup* hazard mapping and related glaciological research.

Much of this material on Khumbu Himal is comparatively easily available: for instance, the Schneider maps scale 1: 50,000, and associated ground photo-theodolite coverage; the National Geographic Society air photography of December/January, 1983/84, scale 1:30,000; the SpaceLab metric camera ESA/Earthnet imagery of 2 December, 1983; various Landsat images; the UNU/Nepal MAB Mountain Hazards Mapping Project map, field survey, and related ground photographs; the hand-held air and ground photography by Dr. Victor Galay in 1985 and 1986 (35 mm and 60 x 60 mm) ; the October, 1985, survey of Langmoche and the Bhote Koshi - Dudh Koshi (Vuichard and Zimmermann 1986, 1987 in press); the glaciological and geomorphological research undertaken by Muller (1958), Higuchi (1976-80) and colleagues, Heuberger (1956, 1974), Khule (1986), and others. In addition, there is an enormous number of ground photographs taken by mountaineers and trekkers. While the last-mentioned material is much more diffuse and difficult to obtain, some useful photographs of ice and moraine-dammed lakes and related glaciological features might be obtainable.

These materials, and especially the results of stereoscopic analysis of the National Geographic Society's air photography, can be used as the basis for compilation of a reconnaissance map of glaciological hazards. The Schneider map, **Khumbu Himal**, scale 1:50,000, would provide a suitable cartographic base. A proposed legend is given in Table 3.

The two specific (Mingbo and Langmoche glaciers) and two or three additional glacier tongues should be selected for long-term monitoring during "ground-truthing" of the reconnaissance map in the field. Sketch maps on smaller scales (1:500/1:2,500) should be made of these small areas and permanent photograph stations should be installed.

Table 3 Proposed Glaciological Hazards Map Legend

Scale 1:50,000-Topography, E.Schneider

- o Ice and permanent snow cover
- o Ice-dammed lakes (min.size $0.1km^2$)
- o Moraine-dammed lakes (min. size $0.1km^2$)
- o Supra-glacial lakes (individual min. size 0.1km2) - groups of small lakes by symbol
- o Debris - covered glacier tongue
- o Neo-glacial end and lateral moraines
- o Older and lateral moraines
- o Hollows below glacier snouts that may become sites for new lakes if glaciers advance
- o Streams and rivers
- o Other topographical features from the Schneider map as required (e.g., vegetation cover)
- o **Geomorphic Features**
  stripped bedrock
  high lake shorelines
  spillways
  recent alluvium
  debris flows (landslides)
  giant blocks in river channel
  condition of river channel
- o Mingbo Glacier and site of 1977 jokulhlaup
- o Langmoche Glacier and site of 1985 *jokulhlaup*

Some glacier details of the sections of the Schneider map are not accurate, or conditions have changed since the ground photogrammetry was completed (see discussion on the age and development of Dig Tsho). Where possible, detailed corrections should be effected by reference to the more recent photographs. The map should also include all settlements, bridges, trails, and other elements of human infrastructure.

The final step in this phase of the proposed programme should be a remote-sensing comparison between the National Geographic Society air photography, the SpaceLab metric camera imagery, and selected Landsat images. This would facilitate an estimation of the loss of detail and accuracy with increasingly unfavourable scales of the imagery. Thus an impression would be gained of the form that a reconnaissance map would take showing a much larger section of the Himalaya, dependent upon interpretation of Landsat imagery.

The final document of a Khumbu-Himal glaciological hazards mapping exercise should include the following:

- o reconnaissance map, selectively field-checked, scale 1:50,000;
- o comprehensive report of glacier, snow and avalanche conditions;
- o Photographic file.

It would be valuable for the following reasons:

- o it would provide a benchmark upon which data derived from a monitoring project could be evaluated;
- o it would provide the H.M.G. Water and Energy Commission and the Small Hydel Development Board and other agencies with a basic glaciological hazard document to be used in conjunction with any future site study for proposed hydro-electric and other engineering works in the Khumbu region;
- o it would serve as a prototype for expansion to other areas.

For each lake identified the following data should be obtained:

- o lake geometry and volume;
- o estimation of the likelihood of a similar drainage triggering mechanism to Dig Tsho;
- o assessment of the possibility of remedial measures, for example, artificial draining.

In addition, installation of stream gauging instrumentation at selected localities would be important for the eventual accumulation of long-term hydrologic records.

The Arun River Basin and its Hydro-Electric Potential

There is a potentially highly valuable intermediate step that can be inserted between the proposed Khumbu Himal scheme and the general Himalayan survey using Landsat imagery. This relates to on-going discussions for a co-operative survey of the nearby Arun catchment, which is also included on the outstanding SpaceLab metric camera images.

Since a very large and expensive cascade of hydro-electric power installations is being planned for the Arun River, and since there are on-going discussions between Nepalese and Chinese scientific and survey teams (much of the upper Arun catchment lies in the Xizang Autonomous Region), these activities should be supplemented by remote sensing and field checking of dangerous ice-dammed and moraine-dammed lakes in this area.

From a preliminary examination of the SpaceLab metric camera imagery, there is evidence of at least 50 ice-dammed and moraine-dammed lakes, most of them located in Chinese territory. It is highly recommended that an exhaustive investigation be undertaken to determine the potential hazard posed by these and other lakes before any final decisions are made concerning engineering works on the Arun River.

CONCLUSIONS

This report has provided a general description of the *jokulhlaup* phenomenon and its highly destructive potential, drawing on examples in various parts of the mountain world.

It has also discussed the *jokulhlaup* situation in the Nepal Himalaya. In particular, it has used the 4 August 1985 catastrophe (Langmoche *Jokulhlaup*) in Khumbu Himal as a case study. It has concluded that the lack of awareness of the possibility for such an event is unfortunate. Steps should be taken to reduce the prospects for future catastrophes by the introduction of appropriate legislation and development planning regulations. Finally, an outline has been sketched for initiation of a remote sensing survey and modest field programme as part of a measured response to reduce the likelihood of future disasters.

The main conclusions and recommendations are as follows:

1. *Jokulhlaup* will continue to occur in the Central Himalaya with sufficient frequency and magnitude to cause significant loss of life and property and severe disruption of community activities.

2. As the development of infrastructure, especially hydro-electric facilities and increases in trekking tourism continue to expand, the potential for a major disaster will progressively heighten. A major disaster is defined as loss of life in excess of 100 persons and/or the destruction of a medium or large-scale engineering structure, or comparable private property.

3. Many potential jokulhlaup source areas (especially sub-aerial lakes) can be easily and inexpensively located and mapped. Some source areas, such as englacial and sub-glacial water bodies, cannot be readily identified but mapping in indirect indicators, such as unusual accumulations of coarse grade alluvium and stripped bedrock, provides some indication of a potential hazard.

4. A much clearer understanding of the potential for jokulhlaup occurrence can be gained from a better assessment of the dynamics of Himalayan glaciers. In some cases a high degree of predictive capability could be generated.

5. All development projects and especially hydro-electric projects, should be required by law or regulation to examine the natural hazard potential, and especially the jokulhlaup hazards, of the immediate area (catchment). Siting, design, and final development decision making should be integrated with the hazard assessment findings.

6. The development response to the jokulhlaup (and debris flow) hazard within the Water and Energy Commission of HMG/N should be formalized. This should include a modest applied glaciological programme with emphasis on the jokulhlaup danger. Remote sensing techniques (through the HMG/N Remote Sensing Centre) should be developed and applied. The programme could be enlarged to take on an international mode through the participation of ICIMOD or the United Nations University. A training component, for field work and remote sensing, should be part of any programme development. Ethnographic studies to examine the behaviour and attitudes of local communities to the jokulhlaup and related hazards, are also recommended. The resources and training capabilities of the Department of Meteorology, Tribhuvan University, should be utilized.

7. An effort should be made to increase public, government, and development agency awareness of the jokulhlaup hazard.

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Jack D. Ives is professor of mountain geoecology, Department of Geography, at the University of Colorado. Since 1979 he has served the United Nations University as coordinator of its highland-lowland interactive systems project, responsible for initiation of the UNU/Nepal MAB Hazards Mapping study. In the formative years of the Unesco Man and the Biosphere (MAB) Programme he was chairman of the international working group for MAB Project 6.

In addition to his work in Nepal, he has collaborated with Chiang Mai University on a UNU study of deforestation and soil erosion in the mountains of northwestern Thailand. More recently, in collaboration with the Chinese Academy of Sciences, he has worked in Xizang, western Sichuan, and northwestern Yunnan.

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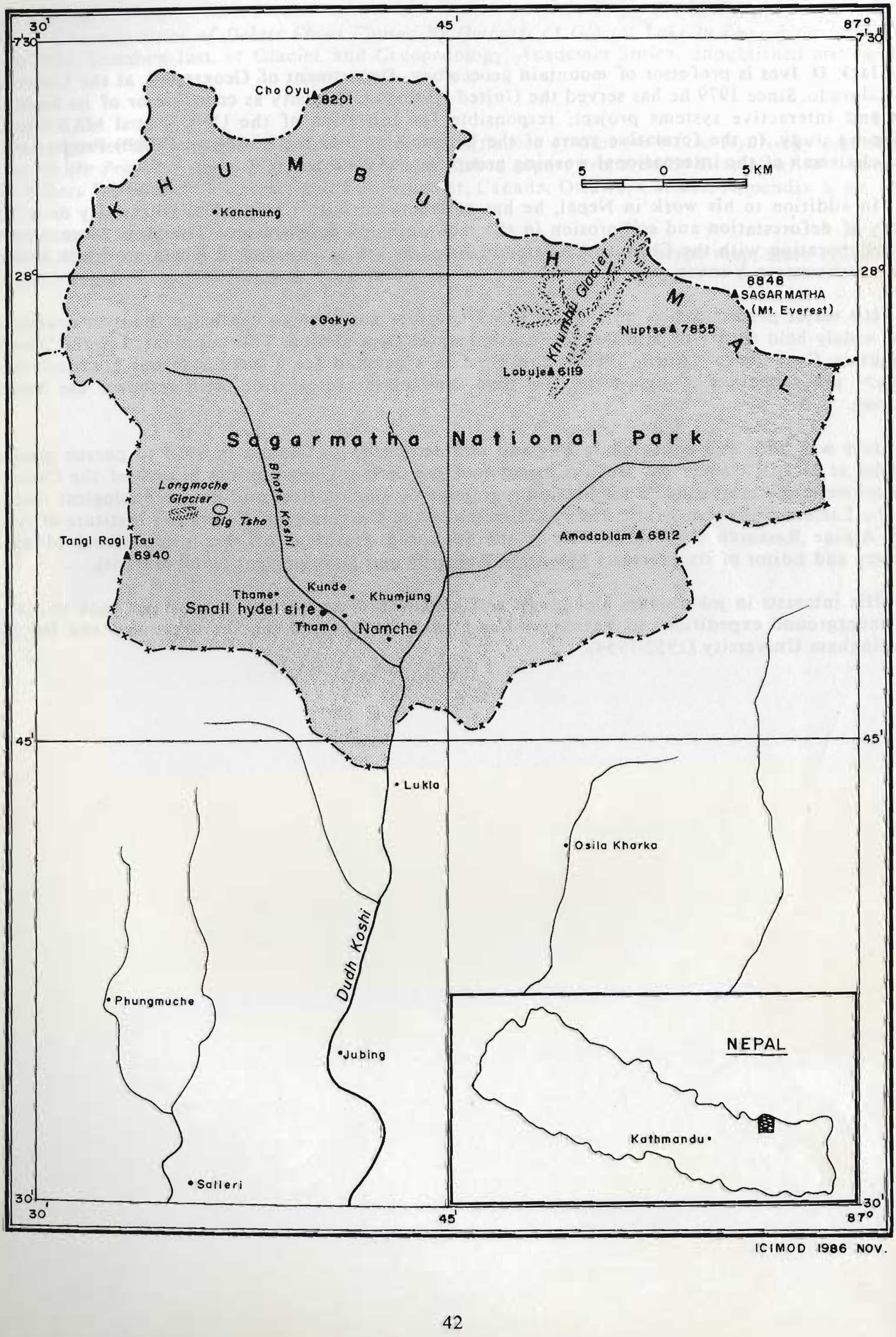
Ives was born and educated in England and emigrated to Canada in 1954 to pursue graduate studies at McGill University. He was director of the former Geographical Branch of the Canadian Government and established a long-term programme of glaciological and geomorphological research on the Eastern Canadian Arctic. He was Director of the University of Colorado's Institute of Arctic and Alpine Research (1967-1979). He is the founding President of the International Mountain Society and Editor of its quarterly Mountain Research and Development (1980-present).

His interests in jokulhlaup, glaciology, and catastrophic mountain floods dates back to a series of underground expeditions to Vatnajokull and southeast Iceland that he organized and led from Nottingham University (1952-1954).

Map of Khumbu Himal and Sagarmatha National Park.



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