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 6-10x10^6 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.

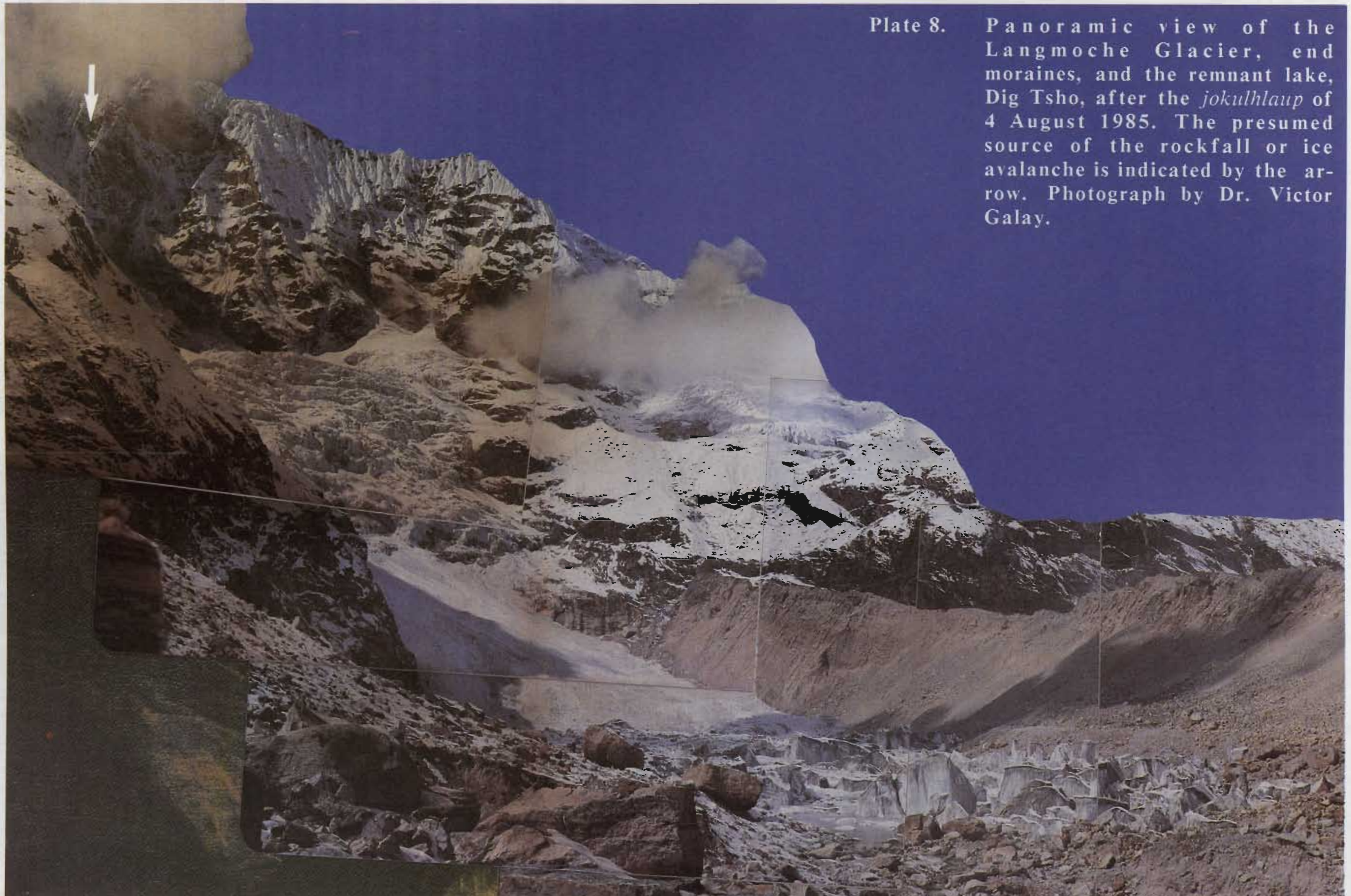


Plate 8. Panoramic view of the Langmoche Glacier, end moraines, and the remnant lake, Dig Tsho, after the *jokulhlaup* of 4 August 1985. The presumed source of the rockfall or ice avalanche is indicated by the arrow. Photograph by Dr. Victor Galay.

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.

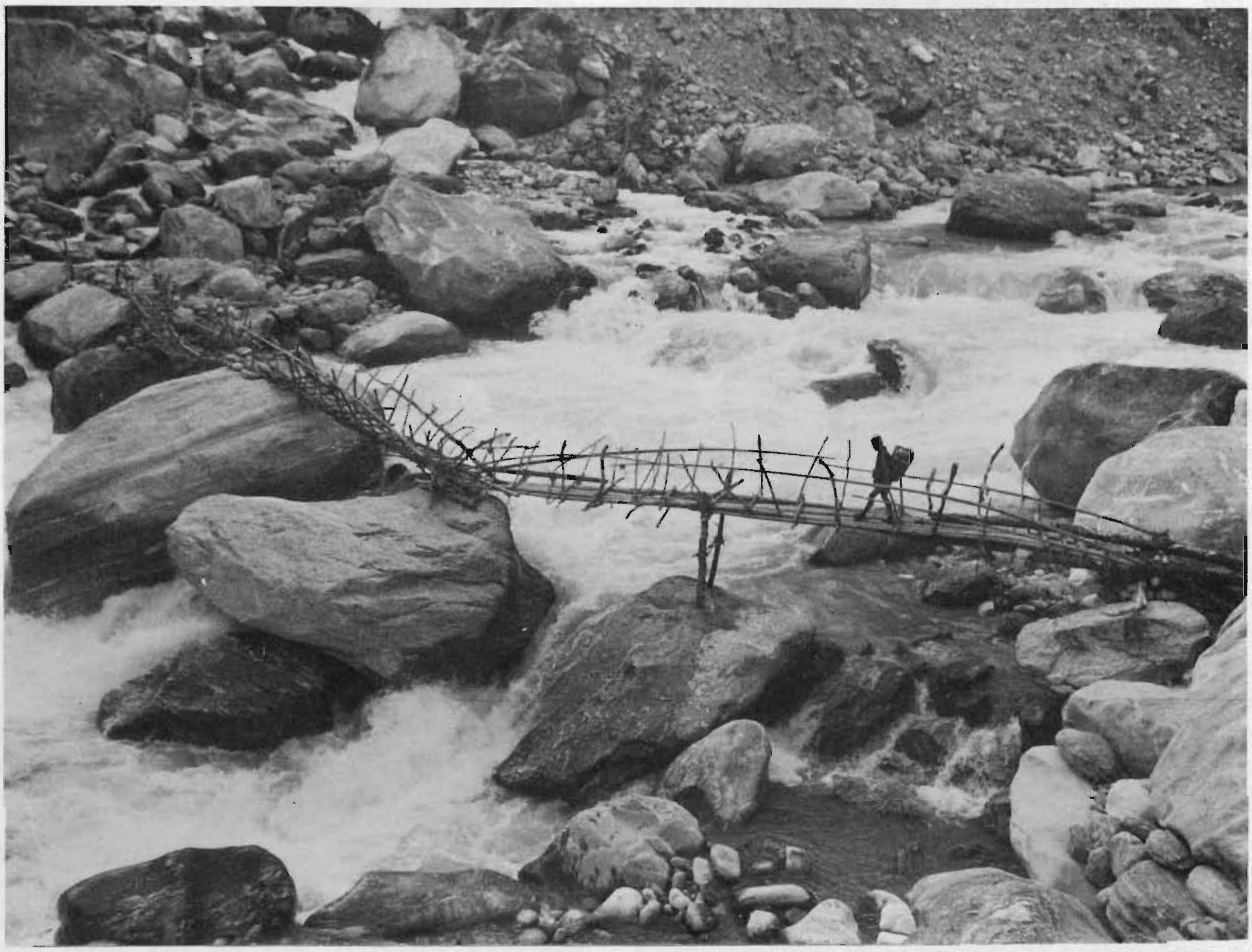
Overall economic losses are difficult to ascertain, although the Langmoche *jokulhlaup* must be regarded as a disaster on any human scale. It is even more difficult to estimate the psychological impact of the indefinite postponement of hydro-electric power supply to the main Sherpa villages after such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



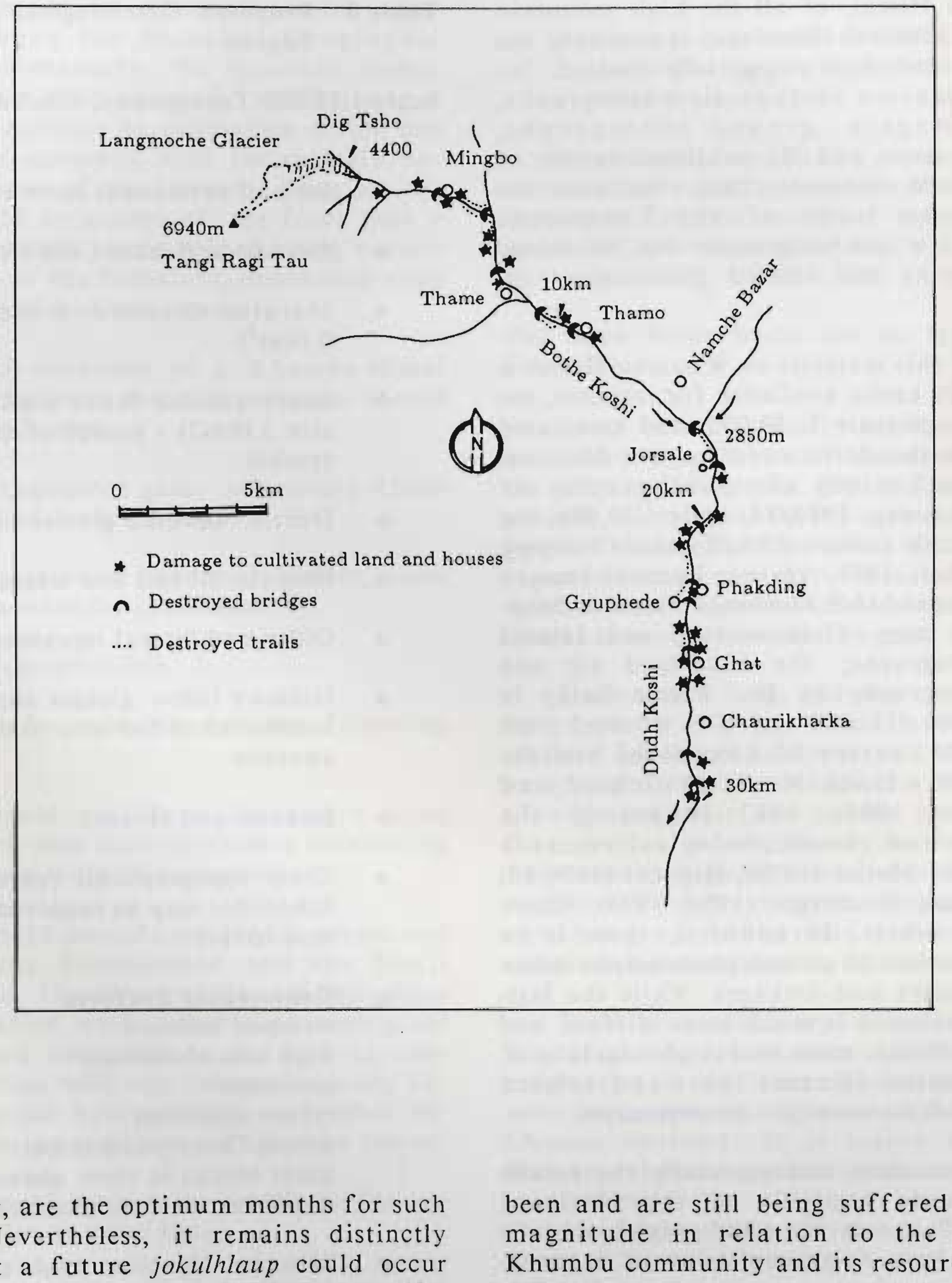
Disaster Scenario 2 : Mid-October 1985 :

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.