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 :

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

- Large-scale, even macro-scale, hydroelectric projects at various distances downstream from the glaciated high mountains, even in the sub-adjacent 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 Gansner (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:

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

- To describe the Namche Small Hydel Project;

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

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

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

- 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.