GLACIER LAKE OUTBURST FLOODS IN NEPAL

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1. GENERAL

Nepal, stretching about 800km from east to west, lies in the lap of the Himalayas. There are more than 6,000 streams and rivers in Nepal. Most of the river systems are snowfed, originating from the high Himalaya. About 18 per cent of the country is covered by snow and ice. There are numerous active glaciers in the high Himalaya that are retreating for the most part at present and contributing to discharge downstream. The catastrophic discharge of large volumes of water is characteristic of many mountain regions, especially glaciated areas.

Most mountain glaciers were formed during the Little Ice Age (Neoglacial) and built up prominent end moraines at that time. Due to the pronounced climatic amelioration in 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, 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.

Glacier lakes are predominantly created by the action of surging glaciers and can be broadly classified into three categories, based upon the material composition of the dam: (1) moraine dam lake, (2) glacier ice-dammed lake (sometimes referred to as a glacier dammed lake), and (3) ice-core moraine-dammed lake.

2. CAUSES OF GLOFS

The water level in the lake may rise due to climatic conditions and other natural processes in the glacier and lake areas, causing the lake to reach breaching point. The bursting of the morainic dam can be caused by progressive erosion of dam material or by the sudden removal of a portion of dam material. The erosion of dam material can be caused by over-topping of the dam due to a progressive rise in lake levels; by the creation of a surface wave, either due to landslides, rockfalls, or icefall; by glacier ice supplied by the upper end of the lake; or by wind waves. Breaching can also be caused by piping through the dam material. Floods caused by the sudden bursting of glacier lakes, which are either ice-dammed or moraine-dammed, are called **Glacial Lake Outburst Floods** (GLOFS). Moraine-dammed lakes generally breach by over-topping or by piping, whereas ice-dammed lakes drain underneath the ice.

3. GLOFS

The most active glaciers in Nepal and the adjoining region of Tibet in China are located in the eastern part of the region. There are numerous occurrences of glacier lakes in this region. The frequency and extent of GLOFs in the Himalaya have not yet been adequately documented. Only in the last decade has the phenomenon drawn scientific attention after the Zhangzangbo GLOF on July 11, 1981, and the Dig Tsho GLOF on August 4, 1985. But there is evidence (primarily in the form of extensive deposits in side valleys and breached terminal moraines) that GLOFs have occurred throughout the Himalayas; however, to date there is no detailed catalogue of the number and location of these past events. A few cases have been reported. Most of the known cases occurred along the major rivers in the Kosi Basin (in Nepal) and the Pumqu Basin in Tibet (China). Some of the recorded events are as follows.

- Historical GLOF in the Pokhara Valley, about 450 years ago.
- Destructive GLOFs along the Bhote-(Sun) Kosi in Nepal from Zhangzangbo Lake (Boqu River in Tibet, China) in 1964 and 1981.
- GLOF from Gelhaipuco Lake (Tibet) along the Arun River (Nepal) in 1964.
- GLOF from Phuchan Glacier Lake along the Tamur River (Nepal)in 1980.
- GLOF along the Bhote-(Dudh) Kosi in Nepal from Dig Tsho Lake on August 4, 1985.
- The Ayaco GLOF on the northern slope, west of Mt. Sagarmatha (Mt. Everest) in Pumqu Basin (Tibet, China) in 1968, 1969, and 1970.
- The Jinco GLOF in 1982 along the Yairuzangbo River in the Poique Basin (Tibet, China) (Arun Basin).
- The Taraco GLOF in 1935 in the Targyaling gully of the Poiqu Basin (in Tibet, China) and the Sun Kosi Basin (in Nepal).
- The Longda GLOF in 1964 at the source of the Trisuli River in Tibet.
- GLOF of Nare Glacier Lake (southern slope of Mt.Ama Dablam in Nepal) in 1977.
- The Chubung GLOF at the end of the Ripimo Shar Glacier in the Rolwaling Valley of Nepal on July 12, 1991.

4. IMPACT OF GLOFS

Sediment transport during GLOFs can be exceptionally high, with suspended sediment concentrations as high as 350,000mg/l (Indus River in Darband, Pakistan)(Hewitt 1983). Large quantities of material are eroded from terraces, valley walls, river banks, and previous fluvial deposits. 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 processes leave an extensive series of unstable slope sections, which are subject to intermittent movement, and become sources of river sediment over several years following the GLOF. The surge during GLOFs is of a devastating scale with a discharge of about 16,000 cumecs (the Zhangzangbo 1981 GLOF which occurred 23 minutes after the burst).

The main flood of the Zhangzangbo 1981 GLOF lasted about 60 minutes and the burst water volume was estimated at 19 million cubic metres, with about four million cubic metres of mixed materials adding to the debris flow process (XuDaoming 1985). The bulk density of the Jelhaipuco 1964 GLOF was about 1.45 tonnes per cubic metre and the total burst water volume was about 23.36 million cubic metres, which affected long stretches downstream along the Arun River in Nepal (LIGG/WECS/NEA 1988). During the Dig Tsho GLOF on August 4, 1985, along the Dudh Kosi, it was estimated that a volume of six to 10 million cubic metres of water drained from the lake within four hours, giving an average discharge of 500 cumecs, the initial peak discharge possibly exceeding 2,000 cumecs (Vuichard and Zimmerman 1987).

The main impact of GLOFs downstream is extensive loss of human lives and cattle, loss of infrastructures, destruction of land (that cannot be reclaimed for several years), and interruption of tourism in mountainous areas. The GLOF on July 11, 1981, from Zhangzangbo Lake along the Boqu (Bhote-Sun Kosi) River in Tibet (China) destroyed the diversion weir at the Sun Kosi Hydro Project in Nepal, as well as two bridges, and tore out extensive sections of the Arniko Highway (Nepal to China highway), resulting in damage amounting to US$ three million. The GLOF on August 4, 1985, from Dig Tsho Lake along the Bhote-Dudh Kosi destroyed the nearly completed Namche Small Hydel Project (estimated cost of the damage, US$ one and a half million), numerous footbridges, and trekking trails, as well as causing extensive loss of life. Even the very small Chubung GLOF on July 12, 1991, destroyed six houses and a number of river banks in Beding village, Rolwaling Valley. Similar impacts have been reported about other events from time to time.

The Need for Investigation of Mitigation Measures

For the prediction of GLOFs, identification of GLOF-prone areas, as well as investigations of the possible (actual) occurrences and consequences, are necessary. The accuracy of prediction of GLOFs may range from a high degree of reliability to a level of uncertainty. Compilation of an inventory of glaciers and glacier lakes, using remote sensing technology, is the first step to identifying GLOF-prone areas. Careful monitoring of climatic changes, area, glacier behaviour, mechanical condition of dam material and surroundings, subsurface hydrology in and around the lake area, as well as seismic and tectonic activities in the region, is required.

The impact of a GLOF surge can be mitigated by reducing the volume of water in the glacier lakes in order to reduce the peak surge discharge. This can be achieved by controlled breaching; construction of an outlet control structure; pumping water out of a lake; and construction of a tunnel through the moraine barrier, or under an ice dam. Protecting infrastructures against the destructive impact of the GLOF surge and monitoring systems prior to, during, and after construction of infrastructures and settlements are necessary. Preventive measures, such as blasting masses of loose rock and ice, can be taken to ensure that avalanches do not slide into lakes.

After the 1985 Dig Tsho GLOF and its severe impact, the GLOF phenomenon in the Nepal Himalayas drew the attention of many organisations. As a result, various studies were conducted. In this context, the Water and Energy Commission Secretariat (WECS) of His Majesty's Government of Nepal started the first ever systematic GLOF study, which is still continuing. In 1987, a joint Nepal-China study team successfully conducted field research on glaciers and glacier lakes in the Arun and Bhote-(Sun) Kosi basins within Tibet (China). Within Nepal, field investigations of the Dig Tsho, Imja, Tsho Rolpa, and Lower Barun glacier lakes have been completed to date. The major constraints to GLOF studies in Nepal, however, are lack of funds, field manpower, and adequate equipment.

Remote Sensing for Study of GLOFs

Remotely-sensed data, such as satellite data and aerial photographs, are very useful in the study of GLOFs. Glaciers and glacier lakes, as well as GLOF study field investigations using conventional methods, require extensive time, funds, and resources together with hardship in conducting field work. Glaciers and glacier lakes are generally in remote areas and accessibility is limited by the tough and difficult terrain. The use of remotely-sensed data reduces the extent of field work required and expedites the preparation of surveys. The multi-stage approach to the use of remotely-sensed data and field investigation increases the work capacity and accuracy. An inventory of glaciers and glacier lakes can be carried out very quickly and correctly, using satellite images and aerial photographs, and the physical conditions of the area can be accurately evaluated. Instructions for data compilation and assemblage for the World Glacier Inventory have been issued by the Temporary Technical Secretariat for the World Glacier Inventory, Swiss Federal Institute of Technology, Zurich (ETH-Z) (Muller, Caflish, and Muller 1977). For regional and semi-detailed works, satellite images are suitable, from which one can judge which area is of interest for detailed study. For a detailed inventory study, aerial photographs of a larger scale (1:50,000 to 1:10,000), complemented by maps, are necessary.

Glaciers and lakes can be identified and studied by visual interpretation methods, using satellite images and the knowledge of image interpretation keys - colour, tone, texture, pattern, association, shape, shadow, etc. In a standard FCC image, glaciers appear white to light-blue in colour, of variable sizes, with linear and regular shapes, having fine to medium textures. The distinct linear and dendritic patterns associated with the slopes and valley floors of high mountains covered with snowfields can be distinguished from glaciers. Shallow to deep lakes in the mountains, if not frozen, appear light-blue to blue; clean, deeper lakes appear black, and frozen lakes appear white. Sizes are generally small, having circular, semi-circular, or elongated shapes with fine texture and are generally associated with glaciers (in the case of a high-lying area), or rivers (in the case of a low-lying area). Lakes that have already burst in the past can be identified from the drainage character associated with the lake. The channel path, along which glacial lake outburst flooding has occurred, shows distinct light-tone widths along the banks, due to bank erosion and deposition at different places along the river. The loose material transported and deposited along the streams has higher spectral reflectance compared to the surroundings, which appear relatively lighter and brighter.

The main problem connected with the use of satellite images is cloud cover and surface snow cover. In the High Himalaya, most of the year, a large area of the ground surface is frozen, which makes it difficult to differentiate lakes and ground snow cover. The image with the least snow cover is suitable for quick and correct identification of glaciers and glacier lakes. Only during the summer and monsoon seasons of the year will there be least snow cover. However, there will be cloud cover, which obstructs the view. One should be careful to select images with no cloud cover and the least snow cover in the study area, in order to guarantee accurate interpretation of the images. In future, remote sensing data, such as radar, might solve the cloud cover problem. Multi-date satellite images are indicative of the changes occurring in the area of interest and the recent advances in satellite remote sensing technology with better spacial, spectral, and temporal resolutions, as well as stereo capabilities, will benefit GLOF research. Since aerial photographs of the high Himalayan Region are not easily available, satellite images (such as SPOT) are a limited tool for a reliable glacier lake inventory and GLOF study. However, ground truth collection and field instrumentation for detailed information are also necessary.

5. BIBLIOGRAPHY

Bjornsson, H., 1992. "Jokulhlaups in Iceland: Prediction, Characteristics, and Simulation." In *Annals of Glaciology*, (16), 95-106 pp. International Glaciological Society.

Ding Yongjian and Liu Jingshi, 1992. "Glacier Lake Outburst Flood Disasters in China." In *Annals of Glaciology*, (16), 180-184 pp. International Glaciological Society.

Feng Qinghua, 1991. "Characteristics of Glacier Outburst Flood in the Yarkiant River, Karakorum Mountains." In *Geo Journal*, 25: 2/3, 255-263 pp.

Hewitt, K., 1983. "Snow and Ice Conditons in the Upper Indus Basin: A review and Bibliography." Wilfrid Laurier University: Canada. Unpublished Report.

Ives, J.D., 1986. *Glacier Lake Outburst Floods and Risk Engineering in the Himalaya.* Occasional Paper No. 5, 42 p. Kathmandu: ICIMOD.

Kulkarni, A.V., 1991. "Glacier Inventory in Himachal Pradesh Using Satellite Images." In *Photonirvachak (Journal of the Indian Society of Remote Sensing)*, Vol.19, No. 3.

*LIGG/WECS/NEA, 1988. *Report on the First Expedition to Glaciers and Glacier Lakes in the Pumqu (Arun) and Poiqu (Bhote-Sun Kosi) River Basins, Xizang (Tibet), China: Sino-Nepalese Investigation of Glacier Lake Outburst Floods in the Himalaya*, 192 p. Beijing, China: Science Press.

Lliboutry, L., 1977a. "Glaciological Problems Set by the Control of Dangerous Lakes in Cordillera Blanca, Peru, II: Movement of a Covered Glacier Embedded within a Rock Glacier." In *Journ. Glaciol.*, 18: 79, 255-273 pp.

Lliboutry, L.; Arnao, B.M.; Pautre, A.; and Schneider B., 1977b. "Glaciological Problems Set by the Control of Dangerous Lakes in Cordillera Blanca, Peru, I: Historical Failures of Morainic Dams, Their Causes, and Prevention." In *Journ. Glaciol.*, 18: 79, 239-290 pp.

Lliboutry, L.; Arnao, B.M.; and Schneider B., 1977c. "Glaciological Problems Set by the Control of Dangerous Lakes in Cordillera Blanca, Peru, III: Studies of Moraines and Mass Balances at Safund." In *Journ. Glaciol.*, 18: 79, 275-290 pp.

Muller, F., 1970. "Inventory of Glaciers in the Mount Everest Region, Perennial Ice and Snow Masses: A Guide for Compilation and Assemblage of Data for World Inventory." In *UNESCO Technical Paper on Hydrology*, No. 1, 47-45 pp.

*Muller, F.; Caflish, T.; and Muller, G., 1977. *Instructions for Compilation and Assemblage of Data for a World Glacier Inventory.* Zurich: Temporary Technical Secretariat for World Glacier Inventory, Swiss Federal Institute of Technology.

Reynolds, J.M., 1992. "The Identification and Mitigation of Glacier-related Hazards: Examples from the Cordillera Blanca, Peru." In McCall et al. (eds.), *Geohazards Natural and Man-made*, 13, 143-157 pp. Chapman and Hall.

Sugden, D.E. and John, D.S., 1990. "Short and Medium-term Glacier Fluctuations." In *Glaciers and Landscape: A Geomorphological Approach*, Chapter 6, 102-128 pp. London: Edward Arnold (a division of Hodder and Stoughton).

Vuichard, D. and Zimmerman, M., 1987. "The 1985 Catastrophic Drainage of a Moraine-dammed Lake, Khumbu Himal, Nepal: Cause and Consequence." In *Mountain Research and Development*, 7: 2, 91-110 pp.

Vuichard,D. and Zimmerman, M., 1986. "The Langmoche Flash Flood, Khumbu Himal, Nepal." In *Mountain Research and Development*, 6: 1, 90-94 pp.

WECS, 1986. *Preliminary Study of Glacier Lake Outburst Floods (GLOFs) in the Nepal Himalaya: Phase 1 Interim Report*. Report No. 4/1/200587/1/1, Seq. No. 252. Kathmandu: Water and Energy Commission Secretariat.

WECS, 1993. *Preliminary Report on the First Field Investigation on the Lower Barun Glacier Lake*. Report No. 3/4/080893/1/1, Seq. No. 428. Kathmandu: Water and Energy Commission Secretariat.

WECS, 1987. *Erosion and Sedimentation in the Nepal Himalaya: An Assessment of River Process*. Report No. 4/3/010587/1/1, Seq. No. 259. Kathmandu: Water and Energy Commission Secretariat.

WECS, 1987. *Dudh Kosi River 1985 GLOF Study Survey Report*. Report No. 4/3/040587/1/1, Seq. No. 257. Kathmandu: Water and Energy Commission Secretariat.

*XuDaoming, 1985. *Characteristics of Debris Flows Caused by Outbursts of Glacier Lake in Boqu River in Xizang, China, 1981*, 24 p. Lanzhou Institute of Glaciology and Cryopedology, Academia Sinica (unpublished manuscript).

Yamada, T., 1991. *Preliminary Work Report on Glacier Lake Outburst Flood in the Nepal Himalayas*. Report No. 4/1/291191/1/1, Seq. No. 387, 30 p. Kathmandu: Water and Energy Commission Secretariat.

Yamada, T., 1992. *Report on the First Research Expedition to Imja Lake*. Report No. 3/4/120892/1/1, Seq. No. 412, 20 p. Kathmandu: Water and Energy Commission Secretariat.

Young, G.J., 1980. "Monitoring Glacier Outburst Floods." In *Nordic Hydrology*, (11), 285-300 pp.

Zhang Xiangsong, 1992. "Investigation of Glacier Bursts of the Yarkant River in Xinjiang, China." In *Annals of Glaciology*, (16), 135-139 pp. International Glaciological Society.

Zimmerman, M.; Bichsel, M.; and Kienholz, H., 1986. "Mountain Hazard Mapping in the Khumbu Himal, Nepal With Prototype Map, Scale 1:50,000." In *Mountain Research and Development*, 6: 1, 29-40 pp.

* Only the references marked with an asterisk are mentioned in the text.

Plates

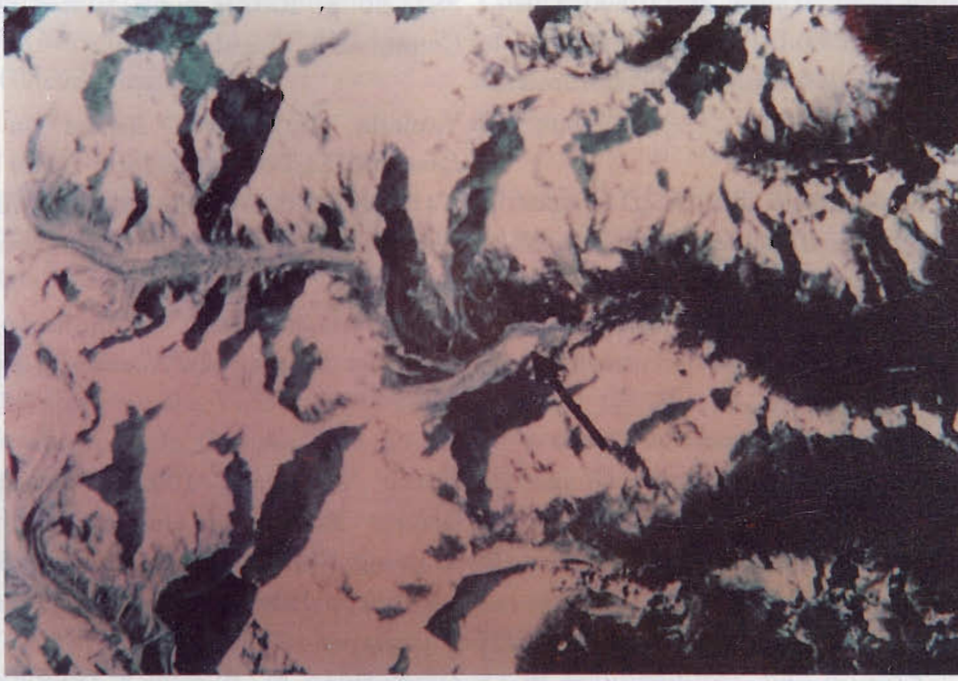


Plate 1: A portion of the Space Lab 1 Mission STS-9 Metric Camera Colour Infrared Photograph (taken on December 2, 1983) of the Barun Valley, showing the newly developed Lower Barun Glacier Lake (indicated by an arrow) at the lower part of the Lower Barun Glacier. This lake is not shown on the topographic map based on 1950s aerial photographs.

Plate 2: A portion of the Landsat MSS image E2284-04041 dated November 2, 1975. (1) Tsho Rolpa Glacier Lake and (2) Dig Tsho Glacier Lake.

Plate 3: A portion of the Space Lab 1 Mission STS-9 Metric Camera Colour Infrared Photograph (taken on December 2, 1983). (1) Tsho Rolpa Glacier Lake which has been developed on a larger scale than in 1975 (note the scales are different in all the images given here; please take the surrounding features for comparison) and (2) Dig Tsho Glacier Lake.

Plate 4: A portion of the MOS-1 MESSER image E11358-04580-0 dated November 8, 1988. (1) Tsho Rolpa Glacier Lake is larger in size than in Plates 2 and 3; (2) Dig Tsho Glacier Lake after the burst on August 4, 1985. The GLOF mark is clearly visible as a white linear feature along the drainage line, downstream from the lake.

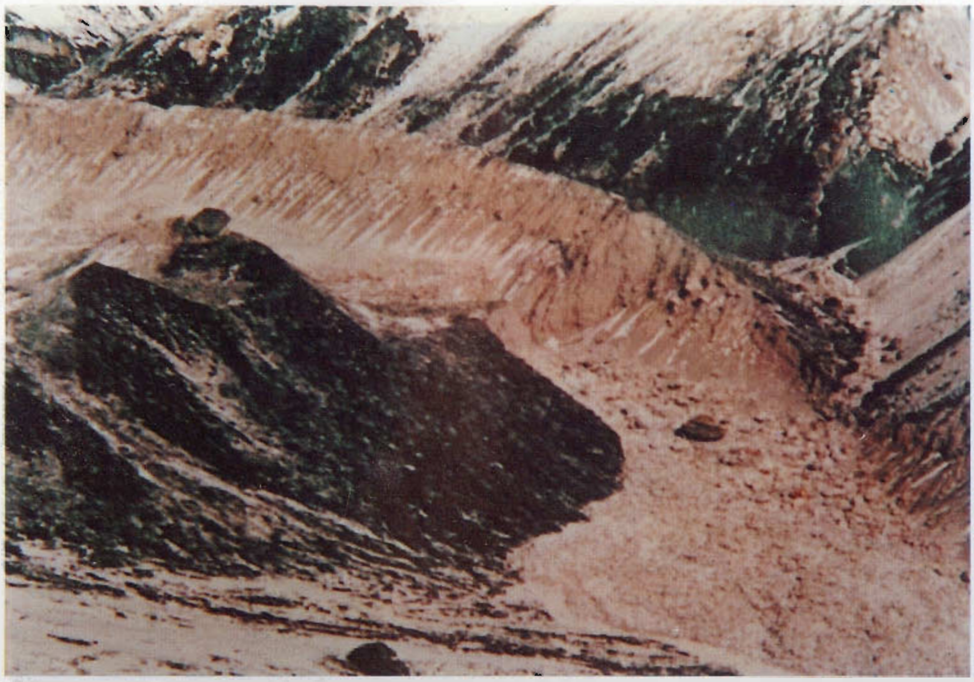
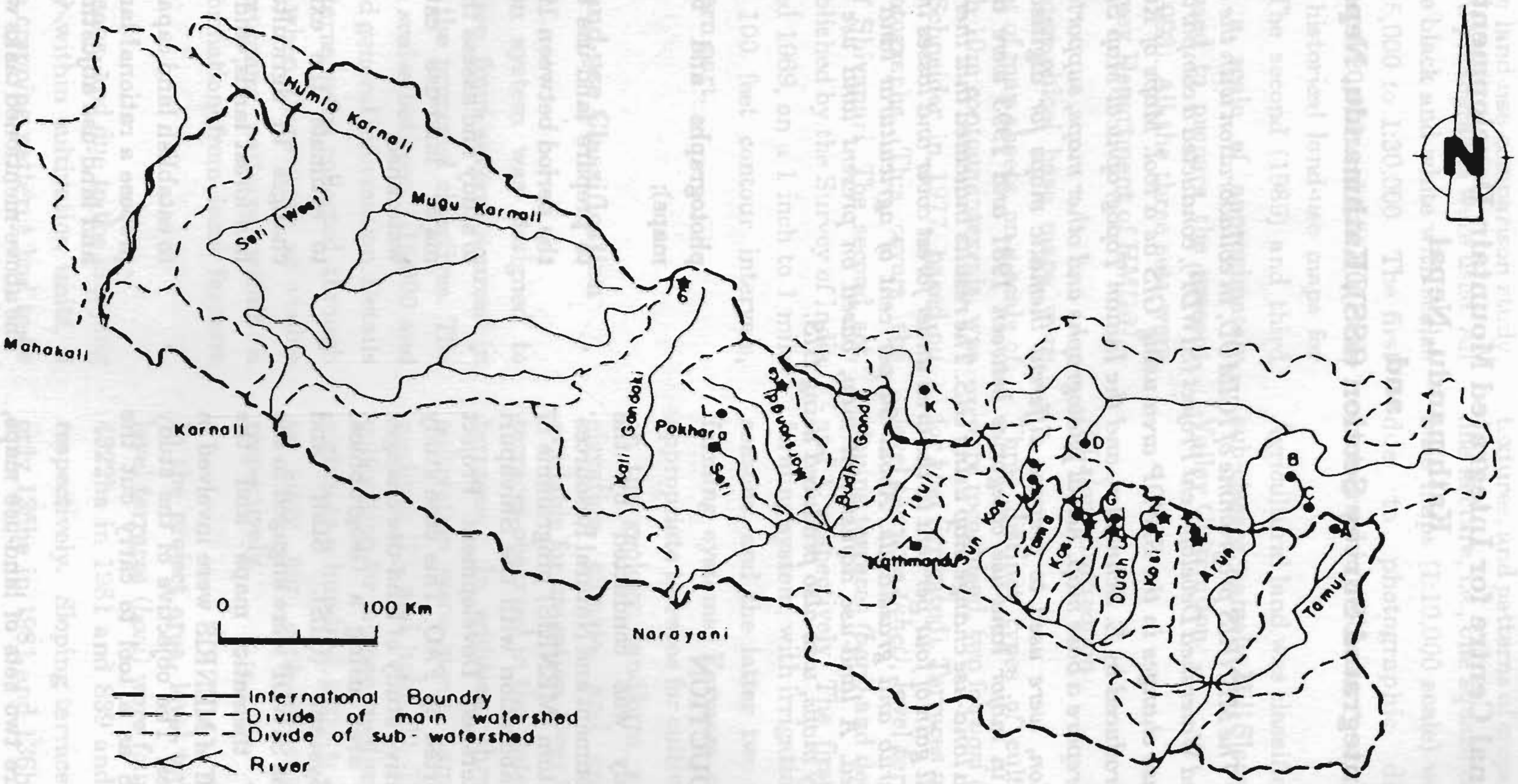


Plate 5: View of the breached end moraine of the Dig Tsho Lake during the August 4, 1985 GLOF. The lake has almost drained (WECS).

Plate 6: Surge wave from the GLOF of Dig Tsho Glacier Lake on August 4, 1985, eroding the right bank of the Bhote-Dudh Kosi at Namche Small Hydel Project. The shock waves developed at obstructions such as river banks, points of contraction, bends, and boulders ranging from 5 to 10 m in height. Velocities were exceptionally high. Namche Small Hydel Project was completely destroyed by the GLOF (WECS).

MAP SHOWING THE GLACIER LAKES OUTBURST AND IDENTIFIED AS PRIORITY FOR STUDY BY WECS



International Boundry
Divide of main watershed
Divide of sub-watershed
River

• GLACIER LAKES BURST IN THE PAST:

A = Phuchan (1980)
B = Jinco (1982)
C = Gelhalpuco (1964)
D = Ayico (1968, 1969, 1970)
E = Barun Khola (?)
F = Nare (1977)
G = Dig Tsho (1985)
H = Chubung (1991)
I = Taraco (1935)
J = Zhangzangbo (1964, 1981)
K = Longda (1964)
L = Behind Machhapuchhare (about 450 years ago)

★ PRIORITY LAKES FOR THE STUDY BY WECS:

1 = Lower Barun
2 = Imja
3 = Dig Tsho
4 = Tsho Rolpa
5 = Thulagi
6 = Glacier lake at Mustang Himal