4. GLOF in the Nepal Himalaya

4.1 Appearance of GLOF Disaster in Nepal

Though there were many GLOFs in Nepal in the past as mentioned hereunder, the detailed features of a GLOF itself were not well investigated because of its occurrence in the remote areas. Among the GLOFs which have occurred in Nepal, only two were investigated in detail. One was the flood of 1981 generated from the glacier lake on the Zhangzangbo glacier located at the head of a tributary of Boqu river (Sun Kosi in Nepal) in Tibet. The other was Dig Tsho GLOF occurred in 1985. The lake was formed on the Langmoche glacier in Khumbu region, East Nepal. The positions are respectively pointed by an arrow in Fig. 3. Both are typical moraine-dammed lakes. To understand a GLOF impact, let us review the Dig Tsho GLOF as an illustration.

Early afternoon on 4th August, 1985, on a fine day of the monsoon season, the nearly completed Namche hydropower plant was fully destroyed by a flood which occurred unexpectedly. No heavy rain had fallen on previous days. Investigations in the upstream reaches to identify the cause of the flood revealed that outburst of the Dig Tsho glacier lake dammed by the moraine was responsible for the flooding. According to Vuichard and Zimmermann (1987), the Dig Tsho lake had been separated from the mother glacier, Langmoche, by the glacier retreat and may have been formed within the last 25 years. One-third of the lake was covered by floating ice like ice-shelf on the upstream end of the lake, which is formed by the debris of avalanche falling along the steep glacier. The lake was dammed by the end moraine of 60 m height from the valley bed. The volume of water store in the lake was estimated to be about 6.75×10^6 m^3. The lake size was approximately 1.5 km in length, an average of 300 m in width and 18 m in maximum depth. The moraine-dam was assumed to be broken by an overtopping of 4-6 m-high wave, which was generated by the ice avalanche from Langmoche glacier with an estimated volume of $1\text{-}2 \times 10^5$ m^3 falling down into the lake. Finally lake water amounting to 5×10^6 m^3 in volume was released through the breach during 5 hours and 8.8×10^5 m^3 of the moraine materials was eroded at the breach. The maximum discharge was estimated to be 1,600 m^3/s at a point 2 km downstream from the lake. Released water rushed down with an average velocity of 4 to 5 m/s along the river in the reach between 25 km and 40 km in distance from the flood source, where the average gradient of the river bed is 0.06. The trace of the flood is still clearly seen in the satellite imagery. A close-up view of the end moraine breach is shown in Photo 3. The position is shown by No. 3 with an arrow in Fig. 4.

The surge including heavy debris inflicted serious damages along the rivers of the Langmoche Khola, Bhote Kosi and Dudh Kosi within a distance of 40 km from the flood source. The Namche hydropower plant at 12 km downstream, 30 houses, 14 bridges, trails and cultivation lands were washed away as well as three human lives and several livestock were lost. In addition, the GLOF also destroyed the fragile Himalayan nature by both erosion and sedimentation along the river course. The direct action of rushing water excavated river banks by lateral erosion and undercutting, which destabilized steep slopes on both sides of the rivers. Slope collapses and many landslides were generated, which damaged also the forest adjoining the river banks.

After suffering the destructive GLOF impact, many researchers had investigated the Dig Tsho

Photo 3 : Breach of the end moraine excavated by the Dig Tsho GLOF.

GLOF (Galay, 1985 ; Ives, 1986 ; Vuichard and Zimmermann, 1986 ; Vuichard and Zimmermann, 1987). Nepal Government also directed to study general features of a glacier lake and GLOF phenomena in Nepal as well as in the upstream area of the international rivers, Bhote Kosi coming from Tibet. (WECS Interim Report, 1987 ; LIGG, WECS and NEA, 1988).

No one had paid any attention to the existence of the GLOF phenomenon in the Nepal Himalaya before the Dig Tsho GLOF because the Zhangzangbo GLOF which had occurred four years ago in 1981 was considered to be a normal flood and not yet recognized as a GLOF then. The Dig Tsho GLOF was an eye-opening event for high rank officials, engineers, planners and technicians of His Majesty's Government of Nepal and concerned agencies of the water resource development sector. Since the Arun 3 hydropower project had advanced to a feasibility study level at that time, GLOF related anxiety crept into the Project.

4. 2 Causes of a Moraine-dammed Lake Burst

Moraine-dam materials are solely the debris consisting of large boulders, gravel, sand, silt and clay which are not yet consolidated. Some moraine contains dead glacier ice. Ice is the softest rock on earth and is usually very close to or equal to the melting point in the Himalayan regions. Thus, a glacier lake dammed by a moraine essentially exists in quite an unstable condition.

A moraine-dammed glacier lake could burst in two ways : (i) a dam break due to some triggering effect and (ii) self-destruction due to the aging of the moraine-dam.

4. 2. 1 External Triggers for a Lake Burst

Lake water overtopping a moraine carries sufficient energy to easily break a moraine-dam. Once a breach is created on the moraine-dam, it leads to a positive feedback to the lake-burst. Running water excavates and erodes the breach deeper and wider, which brings about further increase in the release of running water. The overtopping of lake water is caused by a big wave, which is generated by the huge mass falling down into the lake, such as a snow or glacier avalanche from the steep slope beside the lake and also advancing, sliding and calving of the mother glacier into the lake. Earthquake should also be considered as an external trigger contributing to a lake -burst.

4. 2. 2 Self-destruction of a Moraine-dam

Self-destruction of a moraine-dam is caused by the spontaneous failure of a well weathered dam slope and leakage from the networks of drainage conduits developed in the dam. The dam break is closely correlated with the water level of a lake, i. e. the amount of hydrostatic pressure exerted on the dam wall. The size and shape of the conduits may change from season to season and year after year by being frozen / disappearing during the winter and being re-opened / newly created during the summer. Also, a small conduit occasionally grows to a large conduit due to erosion by water. These drainage conduits tend to weaken the dam as a whole whereby the dam collapses spontaneously due to water pressure without any particular triggering action.

4. 3 General Characteristics of GLOF

GLOF could be regarded as a sort of debris flow with great devastating power because of the inclusion of heavier debris in flood water than would be the case in a normal flood. The flood carries the moraine materials from the breach. Rushing water erodes remarkably both banks of the river and causes landslides from the steep slopes along the river channel. As a result, flood water includes a great amount of debris ; in the case of 1964 Gelhaipuco GLOF, the bulk density was estimated to be about 1.47 t/m^3 derived on the basis of the flood trace marks and sediment deposits on the river bed (LIGG, WECS and NEA, 1988). According to Xu (1988), the total amount of debris involved in the flood was estimated to be about four million m^3 in the Zhangzangbo GLOF which happened along the Boqu river (Sun Kosi in Nepal). A debris of 3 million m^3 is estimated in the case of Dig Tsho GLOF (Vuichard and Zimmermann, 1987). The impact pressure of a debris flow was, for instance, derived to be 171 t/m^2 and 32.4 t/m^2 by estimated breaking stresses of the Phulpin bridge piers and the sluice gate at Sun Kosi hydropower plant, respectively, in connection with the Zhangzangbo GLOF.

According to the inhabitants, their impressions of the Zhangzangbo GLOF were described as rumbling of thunder accompanied by and vibration akin to that generated by an earthquake, smog and foul-earth smell in the valley probably emanating from the rich organic debris included in it and a flow head of 20-30 m height looking like a rapidly moving wall. The same testimonies were bought in the case of Dig Tsho GLOF also (Ives, 1986).

A moraine-dam burst results in a greater rate of water release as compared to that due to an ice dam burst, since the release of water from an ice-dammed lake continues over several days or possibly weeks but the bursting of a moraine-dammed lake is immediate. The peak discharge occurs within several 10 minutes at the breach. The initial discharge rate is extremely high ; the hydrograph of a moraine-dammed GLOF is sharper than that of an ice-dammed GLOF.

The flow velocity of water caused by GLOF is dependent on the magnitude of flood and the gradient of the river bed. Mean velocity is reported to be 9.8 m/s in the 1981 Zhangzangbo GLOF with an average gradient of 0.03 (Xu, 1988) and 4-5 m/s in the 1987 Dig Tsho GLOF with an average gradient of 0.06 (Vuichard and Zimmermann, 1987).

The magnitude of a GLOF and the damage inflicted by it depend on the following parameters

1) surface area of the lake
2) volume of stored water in the lake,
3) releasing rate of water mass,
4) natural features of a river channel, and
5) status of infrastructure and habitation in the downstream area.

The area of the lake, S, is an essential parameter influencing the rate of release of water through the breach. If the breach is excavated to a depth H, the volume of lake water, SH, could be potentially released through the breach. This potential volume may be closely related to the rate of water release. The rate initially determines the flood hydrograph. The total volume of released water may depend on the volume of stored water in the lake and determines the GLOF size. The attenuation of a flood wave is also important for assessment of the extent of GLOF disaster downstream. The attenuation is strongly influenced by natural features of a river channel such as the gradient of the river bed and width of the river. Fig. 2 shows an example of GLOF attenuation, which was investigated in the Zhangzangbo GLOF (Xu, 1988). In general, the extent of GLOF disaster may be limited to a reach of 10 km and even up to a maximum of 100 km downstream from the flood source. The scale of damage fully depends on the status of infrastructure and habitation along a GLOF path. If no or few, no serious damage happens. GLOF is only natural phenomenon like an avalanche in a deep and remote mountain.

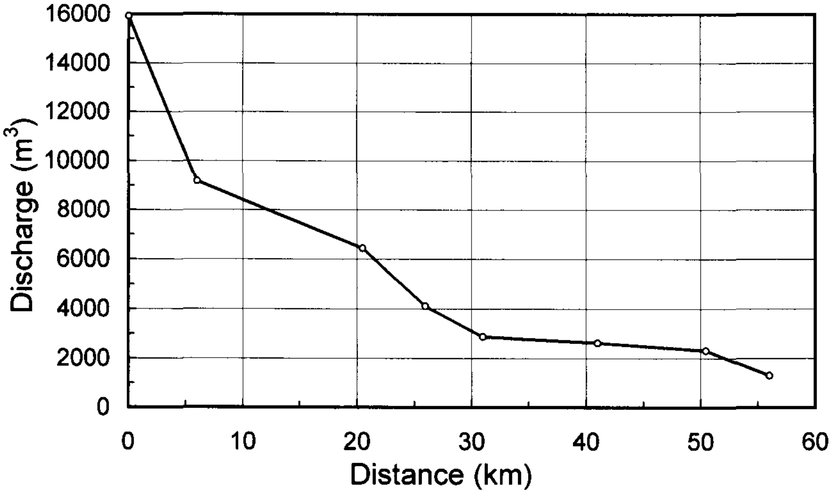

Fig. 2 : Attenuation of GLOF hydrograph in the case of Zhangzangbo GLOF in the Sun Kosi on 1981 (after Xu, 1985 ; modified).

4. 4 Record of GLOFs in Nepal

Since GLOF is quite a natural phenomenon corresponding to the retreating processes of a glacier, the event might have frequently taken place in the past in the country. After the Dig Tsho GLOF, the glacier lakes and the past GLOF events were intensively investigated by a Sino - Nepalese Joint Expedition in the glacierized areas not only in Nepal but also in Tibet. The upper watersheds of the Arun, Tama Kosi and Sun Kosi rivers are located in Tibet, China. These international rivers are called Bhote Kosi in Nepal. The past GLOFs were identified by means of satellite imageries, field visits to glacier lakes and collections of GLOF information from inhabitants living in the Himalayan highland along the rivers. Table 2 shows a list of GLOF events which happened in Nepal. The list has been mainly compiled from the results of the Sino - Nepalese Joint Expedition carried out in 1987 (LIGG, WECS and NEA, 1988). In addition, the recent report of GLOF occurrence in the Rolwaling Valley (Damen, 1992) and in the upper reach of the Must Chu, a tributary of the Kali Gandaki (personal communication with C. Hottelet) are added to the list. The latter lake is located on a nameless debris covered glacier ; Mr. Kondo visiting the lake in 1995 found the trace of the outburst (personal communication with T. Kondo). Unfortunately he did not take any photos.

The list states the date of the GLOF event, the name of the lake which has burst, the cause of the outburst if identified, and a brief description of the damage in each GLOF occurrence. Distribution of the identifiable lakes that have burst in the past are shown by solid circles on the map in Fig. 3. Some of the GLOFs occurred two or three times from the same glacier lake. Among the twelve lakes burst in the past, six glacier lakes are located in Tibet. That is because the rivers Arun, Tama Kosi, Sun Kosi and Trisuli originate from Tibet. It is notable that approximately 95

Table 2 : List of glacier outburst floods happened in the past in Nepal.

No	Date	River basin	Name of lake	Cause of GLOF	Remarks and Damages
1	450 yrs ago	Seti Khola	Machhapuchhare	ice-cored moraine collapse	Pokhara covered by 50-60 m thick debris
2	Aug. 1935	Sun Kosi (Targyailing Gully)	Taraco	moraine collapse due to seepage	66,700 m^2 of wheat field, livestock, etc.
3	21 Sep. 1964	Arun	Gelhaipco	moraine collapse due to glacier sliding into the lake	dam breach 40 m deep and 23 million m^3 of water draining out. Bulk density of 1.45 t/m^3. highway and 12 trucks etc.
4	1964	Sun Kosi	Zhangzangbo	moraine collapse due to Seepage	no remarkable damages
5	1964	Trisuli	Longda		
6	1968	Arun (Zongboxan river)	Ayaco	the lake bursting three times in 1968, 1969 and 1970	road, concrete bridge etc.
7	1969	Arun	Ayaco		
8	1970	Arun	Ayaco		
9	3 Sep. 1977	Dudh Kosi	Nare	ice-cored moraine collapse	mini-hydro plant, road, bridges, farm land
10	1980	Tamur	Punchan		one village destroyed ; villager migrated after GLOF
11	11 July 1981	Sun Kosi	Zhangzangbo	moraine collapse due to glacier falling into the lake	dam breach 50 m deep and 40-60 m in width ; max drainage being 16,000 m^3 ; 19 million m^3 of water drained out. Arniko Highway, friendship bridge, Sun Kosi hydropower station, farm land etc.
12	27 Aug. 1982	Arun	Jinco	moraine dam collapse due to glacier sliding into the lake	1600 heads of livestock, 187,000 m^2 of farm land, houses of eight villages washed away
13	4 Aug. 1985	Dudh Kosi	Dig Tsho	moraine collapse due to glacier ice avalanche	Namche hydropower station, 14 bridges, trails, cultivated land etc.
14	12 July 1991	Tama Kosi	Chubung	moraine dam collapse of Ripimo Shar glacier	houses, farm land etc.
15	May 1995	*Kali Gandaki*	?	*Tsarang Chu upstream in Mustang*	

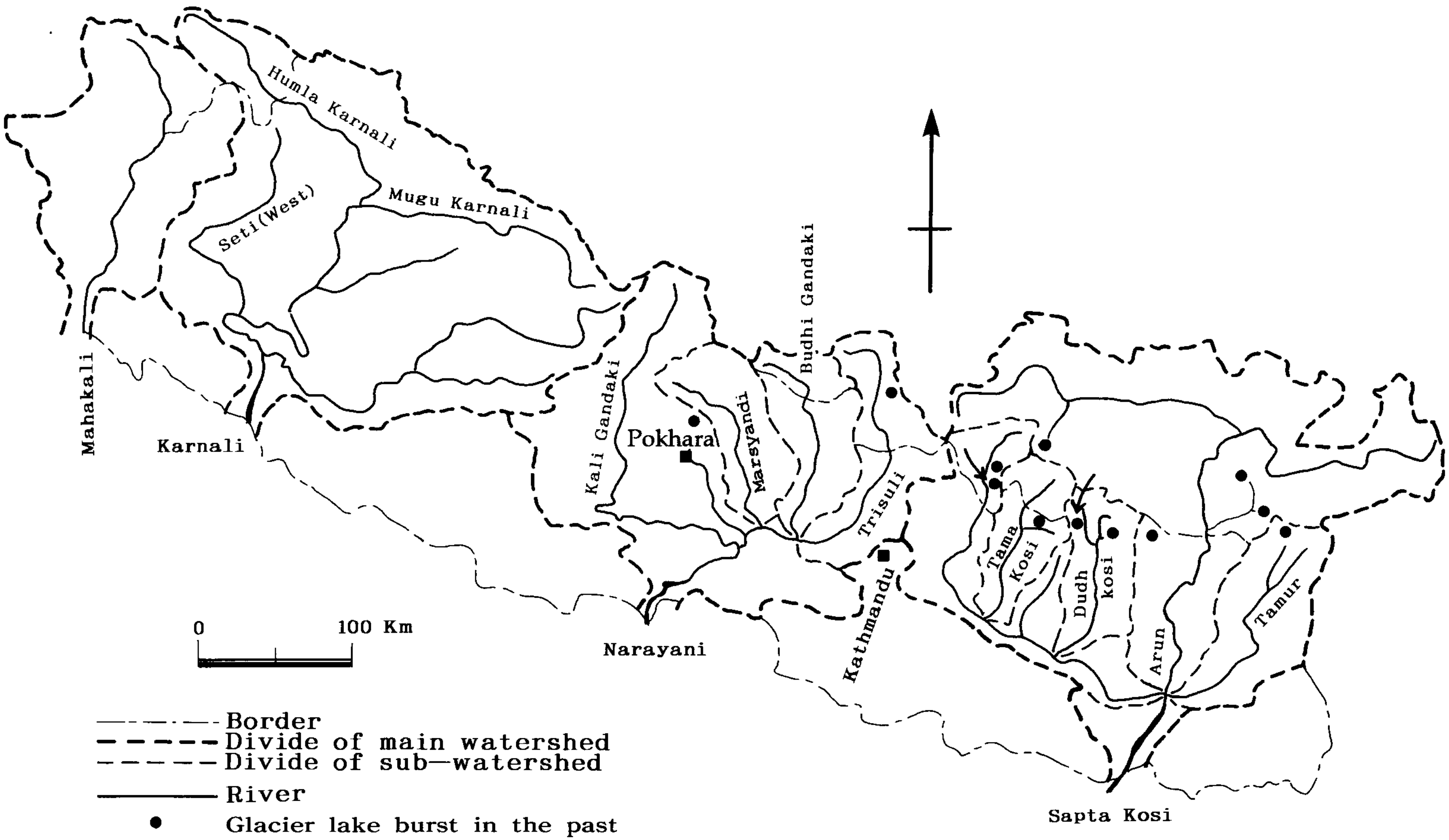

Fig. 3 : Position of glacier lakes that burst in the past. The map indicating drainage basins of the main rivers in Nepal by dotted lines. Arrow pointing the source position of Dig Tsho- and Zhangzangbo-GLOF.

% of the catchment area of the Arun 3 Project site lies in Tibet. The records are only collected in eastern and central Nepal Himalaya and also in the Tibetan side of the drainage basins of the rivers Arun, Tama Kosi, Sun Kosi and Trisuli. No systematic inspection has been carried out yet for the entire area related to GLOF. More records may be added to this list if inspection will progress in the future.

The country has encountered GLOF disasters at least 13 times since the mid-1960s as shown in Table 2. Except for the records 1 and 2 in the Table, GLOFs have occurred after the 1960s. The frequency appears to be more than once every three years, which seems to be a very frequent rate compared with other natural disasters. Thus, GLOF has been regarded as one of the most severe natural disasters now arising in Nepal. The most careful attention should be paid to control GLOF in the development of water resources in the vicinity of glacierized areas in the Nepal Himalaya.