Chapter 12
Glacial Lake Outburst Flood Mitigation Measures, Monitoring and Early Warning Systems

There are several possible methods for mitigating the impact of Glacial Lake Outburst Flood (GLOF) surges, for monitoring, and for early warning systems. The most important mitigation measure for reducing GLOF risk is to reduce the volume of water in the lake in order to reduce the peak surge discharge.

Downstream in the GLOF prone area, measures should be taken to protect infrastructure against the destructive forces of the GLOF surge. There should be monitoring systems prior to, during, and after construction of infrastructures and settlements in the downstream area.

Careful evaluation by detailed studies of the lake, mother glaciers, damming materials, and the surrounding conditions are essential in choosing an appropriate method and in starting any mitigation measure. Any measure taken must be such that it should not create or increase the risk of a GLOF during and after the mitigation measures are in place. Physical monitoring systems of the dam, lake, mother glacier, and surroundings are necessary at different stages during and after the mitigation process.

12.1 Reducing The Volume of Lake Water

Possible peak surge discharge from a GLOF could be reduced by reducing the volume of water in the lake. In general any one or combination of the following methods may be applied for reducing the volume of water in the lake:

- controlled breaching,
- construction of an outlet control structure,
- pumping or siphoning out the water from the lake, and
- making a tunnel through the moraine barrier or under an ice dam.

Controlled breaching

Controlled breaching is carried out by blasting, excavation, or even by dropping bombs from an aircraft. One of the successful examples has been that reported for Bogatyr Lake in Alatau, Kazakhastan

(Nurkadilov et al. 1986). An outflow channel was excavated using explosives and 7 million cubic metres of water was successfully released in a period of two days. These methods, however, can give strong, uncontrolled regressive erosion of the moraine wall causing a fast lowering of the lake level. Lliboutry et al. (1977a, b, c) described a case from Peru of the sudden discharge of 6–10 million cubic metres of water after two years of careful cutting of a trench in the moraine wall.

Construction of an outlet control structure

For more permanent and precise control of lake outflows, rigid structures made out of stone, concrete, or steel can be used. However, the construction and repairs of the required mitigation works at high elevations, in difficult terrain conditions and in glacial lake areas far from road points and not easily accessed, will cause logistic difficulties. Therefore, preference should be given to construction materials available locally such as boulders and stones. The boulders on the moraine walls can be held in place by wire mesh ('gabion') and/or held down by appropriate anchors.

Open cuts in a moraine dam can be excavated during the dry season when a lake's water level is lower than during the wet season. Such a method is risky as any displacement wave arising from an ice avalanche can rip through the cut and breach the moraine. This method should be attempted where there is no risk of avalanches into the lake.

Pumping or siphoning out the water from the lake

Examples given by Lliboutry et al. (1977a, b, c) from Peru and the pumping programme for the control of Spirit Lake after the eruption of Mount St Helens in Washington State in the USA are very costly because of the large amount of electricity needed for the powerful pumps. The pumping facility consisted of 20 pumps with a total capacity of 5 $m^3 s^{-1}$ and the cost of the pumping plant, operation, and maintenance for about 30 months was approximately US $11 million (Sager and Chambers 1986).

In the Hindu-Kush Himalayan region, there is no hydroelectric power distribution at high altitudes nor a simple means of transporting fuel to high elevations. Many of the lakes are higher than the maximum flying altitude for helicopters.

The use of a turbine, propelled by the water force at the outside of the moraine dam, will lower the energy costs. The problem of coupling the turbine and the pumps has to be solved.

Siphons with manageable component size are attractive in that they are readily transportable, relatively easy to install, and can be very effective for smaller size lakes.

Making a tunnel through the moraine dam

Tunnelling through moraines or debris barriers, although risky and difficult because of the type of material blocking the lake, has been carried out in several countries. In Peru, Lliboutry et al. (1977a, b, c) reported problems related to tunnelling through a moraine dam which had been severely affected by an earthquake.

Tunnelling can only be carried out through competent rock beneath or beside a moraine dam. The costs of such a method are very high. Unfortunately, not all moraine dams are suitable for tunnelling.

The construction of tunnels would pose difficulties in the Himalayas due to the high cost of transporting construction materials and equipment to high elevations.

12.2 Preventative Measures Around the Lake Area

Any existing and potential source of a larger snow and ice avalanche, slide, or rockfall around the lake area which has a direct impact on the lake and dam has to be studied in detail. Preventative measures against the instabilities of the moraine dam and the surrounding area, such as removing masses of loose rocks to ensure there will be no avalanches into the lake, will reduce to some extent the danger of GLOF.

12.3 Protecting Infrastructure Against the Destructive Forces of the Surge

The sudden hydrostatic and dynamic forces generated by a rapid moving shock wave can be difficult to accommodate by conventionally designed river structures such as diversion weirs, intakes, bridges, settlements on the river banks, and so on. It will be necessary to build bridges with appropriate flow capacities and spans at elevations higher than those expected under GLOF events. The Nepal–China highway, after reconstruction, has arched bridges well above the 1981 GLOF levels. Also, the road has been moved to higher levels and has gabion protection at the base of the embankments. Settlements should not be built at or near low river terraces but at heights well above the riverbed in an area with GLOF potential. Slopes with potential or old landslides and scree slopes on the banks of the river near settlements should be stabilised. It is essential that appropriate warning devices for GLOF events be developed in such areas.

12.4 Monitoring and Early Warning Systems

A programme of monitoring GLOFs throughout the country should be implemented using a multi-stage approach, multi-temporal data sets, and multi-disciplinary professionals. Focus should first be on the known potentially dangerous lakes and the river systems on which infrastructure is developed. Monitoring, mitigation, and early warning system programmes could involve several phases as follow.

- Detailed inventory and development of a spatial and attribute digital database of the glaciers and glacial lakes using reliable medium- to large-scale (1:63,360 to 1:10,000) topographic maps
- Updating of the inventory of glaciers and glacial lakes and identification of potentially dangerous lakes using remote-sensing data such as the LANDSAT TM, IRS1C/D, LISS3, SPOT XS, SPOT PAN (stereo), and IRS1C/D PAN (stereo) images
- Semi-detailed to detailed study of the glacial lakes, identification of potentially dangerous lakes and the possible mechanism of a GLOF using aerial photos
- Annual examination of medium- to high-resolution satellite images, e.g. LANDSAT TM, IRS1D, SPOT, and so on. to assess changes in the different parameters of potentially dangerous lakes and the surrounding terrain
- Brief over-flight reconnaissance with small format cameras to view the lakes of concern more closely and to assess their potential for bursting in the near future
- Field reconnaissance to establish clearly the potential for bursting and to evaluate the need for preventative action
- Detailed studies of the potentially dangerous lakes by multi-disciplinary professionals
- Implementation of appropriate mitigation measure(s) in the highly potentially dangerous lakes.
- Regular monitoring of the site during and after the appropriate mitigation measure(s) have been carried out
- Development of a telecommunication and radio broadcasting system integrated with on-site installed hydrometeorological, geophysical, and other necessary instruments at lakes of concern and downstream as early warning mechanisms for minimising the impact of a GLOF
- Interaction/cooperation among all of the related government departments/institutions/agencies / broadcasting media, and others for detailed studies, mitigation activities, and preparedness for possible disasters arising from GLOF events

The methodology for the inventory of glaciers and glacial lakes, the use of geographic information systems (GIS), and the remote sensing techniques and identification of potentially dangerous lakes are explained in Chapters 4–6 and 11.

12.5 Mitigation Measures, Monitoring, and Early Warning Systems Applied in the Country

Mitigation measures to prevent the bursting of the lake were implemented in 1996 on Raphstreng Tsho only. Initially a number of methods was suggested:

- siphoning,
- pumping, and
- excavation of a channel.

All these methods were suggested basically to reduce the level of water in the lake by 20m initially, but it was later worked out that 4m was sufficient. Considering the site conditions, it was found that the excavation of a channel was the best suited method for mitigating GLOF hazards from Raphstreng Tsho.

A detailed topographic survey of Raphstreng Tsho and its two subsidiary lakes was carried out, on a scale of 1:2,000 with 2.5m contour intervals. L-sections and cross-sections of the existing natural channel through which the water from Raphstreng Tsho was going to Pho Chu were prepared. These sections were used to estimate the quantity of excavation required to lower the lake. The water level of the main lake is at 4,348.79 masl. It joins subsidiary lake I at a level of 4,348.50 masl after travelling 5m along the channel. The outlet of subsidiary lake I is at an elevation of 4,348.15 masl and is 70m away from Raphstreng outlet. The water from the subsidiary lake I outlet flows through a narrow channel 8–15m wide for 60m, joins subsidiary lake II at an elevation of 4,343.9 masl, and flows out through its outlet at 4343.4 masl. The outlet of subsidiary lake II is 180m away from the main lake along its flow path. From this section the water follows the natural channel and joins the Pho Chu.

The sequence of excavation activities is given below.

- The outlet of subsidiary lake II was excavated first to lower the level of this lake.
- In the next step, the channel between the two subsidiary lakes was excavated. Once this had reached the desired depth, the outlet of subsidiary lake I was cut to allow the water to flow out.
- Then the channel between subsidiary lake I and the main lake was excavated. When this was completed, the outlet of the main lake was excavated to let the water flow out, thus reducing the level of the lake by 4m.

Flood mitigation measures (Phase I—1996)

The scope of the work for the 1996 expedition was to carry out the immediate mitigation measures for the biggest lake (Raphstreng Tsho) as recommended by the joint expedition team of 1995. The project was funded by the Government of India, and Water and Power Consultancy Services (India) Ltd (WAPCOS) was appointed to provide consultants. The Indo-Bhutan expedition team comprised experts from the Department of Geology and Mines (DGM), the Department of Roads (DOR), the Survey of Bhutan and the Royal Bhutan Army (RBA), the Geological Survey of India (GSI), and WAPCOS.

The team was to carry out a site survey and investigation to firm up the various parameters to be used for the preparation of design and cost estimates of civil work planned for preventing a possible outburst of the glacial lakes in Lunana. The survey and investigation carried out comprised hydro-meteorological and topographical surveys and geotechnical, geological, and foundation investigations.

Due to the urgency to lower the lake level of Raphstreng Tsho, the civil work for this purpose was carried out simultaneously. The initial proposal, to siphon together with excavating the spillway to reduce the lake level by 20m, was found unfeasible, so an alternative solution had to be found. Based on the reconnaissance study it was decided that the existing channel through which the lake water was flowing into the Pho Chu would be used for lowering the lake water level. The excavation work was done using manual tools like crowbars, shovels, spades, pick axes, and so on. The team reached Lunana on 7 July 1996 and actual excavation of the channel started on 12 July. The total number of person days used at this site until 19 October 1996 was 67 848 (WAPCOS 1997). During this period the water level in the main lake (Raphstreng Tsho) was lowered by 0.95m, in the lower subsidiary lake I by 0.94m, and in the subsidiary lake II by 1.5m (Figure 12.1). The report of WAPCOS 1997 recommended that lowering of the lake by 20m was not absolutely necessary and that lowering it by 4m should be sufficient. To implement this recommendation of lowering the lake water level by 4m, work was carried out in 1997 and 1998.

Raphstreng Tsho outburst flood mitigation project (Lunana) Phase II—1999

After a fact finding mission (Phase I), actual fieldwork (Phase II) under Austro-Bhutanese cooperation was planned as the Raphstreng Tsho Outburst Flood Mitigation Project. The main aim of the project was to assess the geo-risks of the Raphstreng/Thorthormi Tsho area (Häuslar et. al. 2000). An integrated multi-disciplinary approach was adopted using remote sensing, geological, hydro-geological, and geophysical methods. IRS-1D PAN digital data for 3 January 1999 with a ground resolution of 5.8m was acquired.

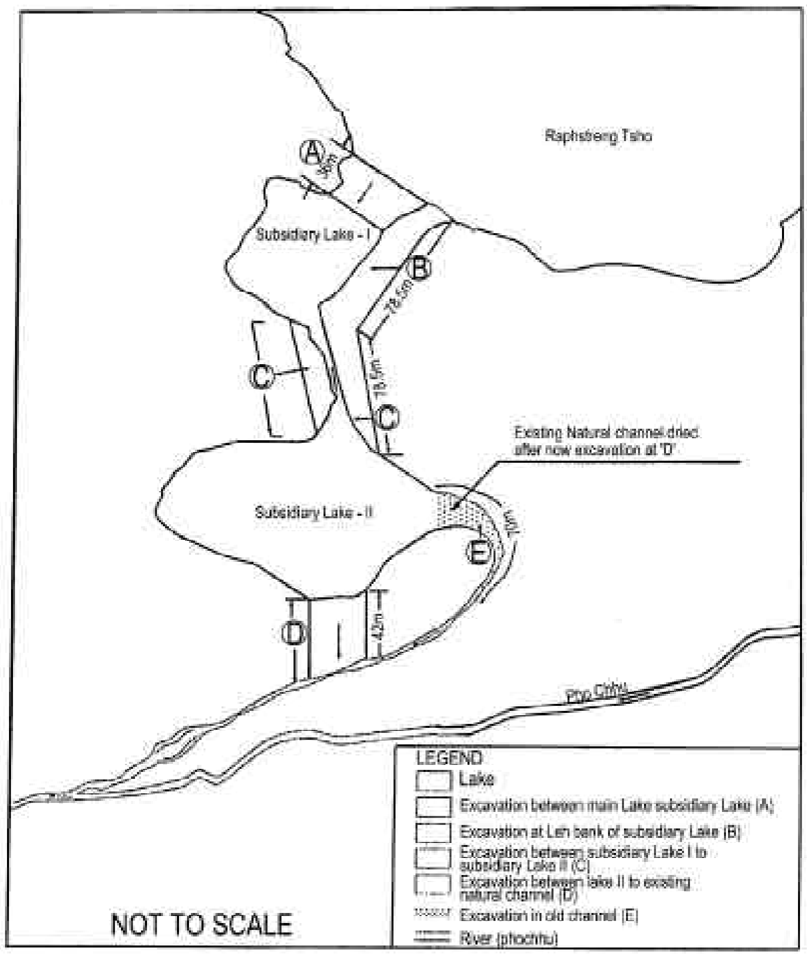

Figure 12.1: Schematic sketch of excavation work carried out for the mitigation of Raphstreng Tsho in 1996

ERDAS/IMAGINE software was used to generate the required satellite image maps: on a scale of 1:2500 for monitoring the decay of glaciers, at a scale of 1:5,000 for a base map for field work, and a 3-D digital elevation model (DEM) for geomorphological and geological interpretation.

From the hydrological studies conducted a hypothesis was postulated that (i) seepage water is not pure glacial melt, (ii) local ice must be expected along the flow path, (iii) in a multi-source groundwater system lake water is not the major contributor, and (iv) in multi-genetic moraines a very stable piping system exists. It is concluded that if this hypothesis is proved, the seepages will not weaken the morainic dam (Häuslar et al. 2000).

Sub-surface radar, geoelectric resistivity, and seismic investigation were used to interpret the sub-surface nature of the moraine dam. The findings from these investigations were that the end moraine of Raphstreng Tsho is not an ice core dam. It is concluded that the present day risk for an outburst from Raphstreng is low, but the risk of an outburst of Thorthormi Glacial Lake in the future is considered high and it could occur in 15–20 years considering the present trend of climate change (Häuslar et al. 2000). Häuslar and Leber (1998) proposed that special risk engineering at Lugge Tsho outlet and a more sound GLOF risk assessment east of Thanza be carried out.