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 he 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 the water out 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 system 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 problems, of coupling the turbine and the pumps have 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 have to be taken such as removing masses of loose rocks to ensure there will be no avalanches into the lake.

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 Land Observation Satellite (LANDSAT) Thematic Mapper (TM), Indian Remote Sensing Satellite (IRS)1C/D Linear Imaging and Self Scanning Sensor (LISS)3, Stéréo Système Probatoire d'Observation de la Terre (SPOT) multi-spectral (XS), SPOT panchromatic (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, ans 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.

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

Tsho Rolpa is the only glacial lake on which detailed study and mitigation measures are carried out in Nepal. Detailed field investigations of the lake, mother glacier, lake surroundings, and downstream area in the Rolwaling and Tama Koshi Valleys have been studied by different organisations/institutions. In the occurrence of a GLOF from Tsho Rolpa Lake, the resulting flood could cause damage up to 100 km downstream from the lake, threatening about 10,000 human lives, thousands of livestock, agricultural land, bridges, including some components of the Khimti Hydroelectric Project and other infrastructures. Siphons and early warning systems were tested and further studies were carried out to evaluate suitable mitigation measures and their cost.

Test siphon

The Netherlands–Nepal Friendship Association used siphons to test mechanisms and materials for lowering the level of Tsho Rolpa Lake in 1995. The method worked smoothly for some time, but later, due to lack of regular maintenance, the joint couplings broke frequently. The siphon method was successful but to lower the lake water to the level desired, the number of siphon pipes had to be increased substantially.

Implementation of an early warning system

Following panic created by the media in the summer of 1997 in the Rolwaling and Tama Koshi Valleys, His Majesty's Government of Nepal (HMGN) implemented an early warning system at the end of June 1997 to provide timely warning to the people. An army camp was established on the lakeside at the village of Naa, approximately 3 km downstream from the lake. A police post was also established at Naa and another police post was established in Beding, approximately 9 km downstream from the lake. Each of the army and police posts was provided with a HF radio transceiver and the army post at Naa had a back-up set. The two police posts and the army post in Naa were in regular radio contact with their respective headquarters in Kathmandu. In addition the two army posts were provided with satellite telephones. The army post at the lakeside used one of the phones to contact the disaster prevention cell at the Home Ministry twice a day to deliver a status report. In the event of a GLOF, Radio Nepal, the national broadcaster, would broadcast a warning. Radio Nepal can be received in most places along the valleys that are at risk.

The glacial lake outburst flood (GLOF) early warning system

The first flood warning system in the country was installed in May 1998 to warn the people living downstream from Tsho Rolpa Glacial Lake, in the potential GLOF hit area along the Rolwaling and Tama Kosi Valleys as well as at the Khimti Hydroelectric Project (BC Hydro 1998). The Department of Hydrology and Meteorology (DHM) implemented the project and the technical design of the system was by BC Hydro International Limited. It was financed by the World Bank. The total cost of the whole system was US $1,032,000. The operation of the warning system has been satisfactory. There have been a few false alarms due to short circuits caused by moisture in the electrical system.

The GLOF warning system can be essentially divided into two general components: the GLOF sensing system, which detects the occurrence of a GLOF and initiates the warning process, and the downstream warning system, which conveys this warning to communities at risk. These are linked by the signal transmission system. The GLOF warning system transmits its signals in two ways. All stations in the system can transmit signals from one to another using the extended line of site (ELOS) mode of the meteor burst transceivers. In addition, five stations in the GLOF warning system have the capability of transmitting radio signals to a master station located at Dhangadi in western Nepal. From the master station, the messages are relayed either to other stations forming the warning system or to a data monitoring station in Kathmandu. A second data monitoring station is located at the confluence of the Khimti and Tama Koshi.

The signal transmission system

The GLOF warning system is based on the installation of two independent meteor burst remote warning stations (MBRWS) in larger communities, and the installation of one MBRWS in smaller communities. In both cases the warning signal is transmitted via ELOS ground wave signals from a remote station to a remote station down the valley. A warning station based on ELOS ground signals does not require a master station, instead it relies on the signal being passed downstream from one station to the next. ELOS technology can reliably send signals approximately 30 km to the next station. To increase the reliability of the system, each station must be able to 'see' at least two stations within the next 30 km downstream. Thus, if one of these stations fails, the signal can bypass that station and still reach the next station downstream. The spacing of villages at risk satisfies this requirement along most segments of the system. For signal relay purpose, three additional stations were installed where they otherwise would not have been required for community risk purposes. In the vicinity of Simigaon, two remote stations were installed near the valley confluence to ensure adequate reliability that the warning signals would be transmitted beyond this sharp bend in the line of sight. A third relay station was installed at Birkot, subsequent to installation of the warning system, as system tests showed that the station at Gumu Khola would not reach Naya Pul, its second downstream station. In addition to being programmed to receive and transmit ELOS communication signals, remote station technology has been programmed to send and receive meteor burst signals at five stations. This provides additional reliability in the event of failure of two or more successive stations as well as permitting system monitoring from Kathmandu. Monitoring of the warning system is centred in Kathmandu with a back-up data monitoring centre in Khimti. The meteor burst stations cannot directly transmit data to close proximity (say Kathmandu), therefore a master station had to be located in Dhangadi, which transmits data to Kathmandu.

The glacial lake outburst flood sensing system

The GLOF sensing system consists of six sensors with three connected to each of the two remote stations with meteor burst and ELOS capability. The six GLOF sensors are located along the right bank of the river channel just downstream from Tsho Rolpa Lake. The sensors are connected by armoured and shielded cables to two transmitting stations installed within 80m of the sensors. Three sensors are connected to each station and the transmitting stations function independently of one another. Each of the six GLOF sensors is located at a different elevation above the previous high water mark. Thus operation of the different sensors should be indicative of the rising river stages. The sensors and the transmitting stations are spaced laterally along the river to minimise the chances of damage by rockfall or other damage. The sensors transmit signals directly to the remote warning station located in Naa as well as to each other. This remote station at Naa has the dual function of forming part of the GLOF sensing system and providing local warning to the residents of Naa. The warning logic is programmed into the remote station transmitters. A warning would only be transmitted downstream if the control logic determined that a GLOF warning situation existed. The sensor transmitters also send a radio signal to the master station for subsequent relay to communities. The redundancy of transmitting the GLOF warning signal directly to Naa increases the reliability of the GLOF sensing system significantly.

The glacial lake outburst flood warning system

The remote warning stations located in the villages have a Meteor Communication Corporation (MCC) 545 transceiver unit mounted on a 4.67m self-supporting standard galvanising iron power pole. The antenna is mounted on an extension to the pole and is approximately 5m above the ground. An air powered horn, back-up electric horn, lightening rod, and solar panel are also mounted on this pole. The MCC 545 unit, battery, and relay for the horn are mounted inside a sheet metal, lockable shelter attached to the pole. All cables are protected by plastic conduit, covered by galvanised sheet metal and strapped to the pole.

The air horn is designed to operate off a charged air cylinder for a period of 2 min with a reserve for an additional 1–2 min in the event of it being previously operated (false alarm). The electric back-up horn will operate for a period of 4 min. The air horn provides a sound amplitude of 80 dB up to a 150m range under the most adverse conditions. The early warning system consists of 19 warning stations, located at 17 villages along Rolwaling and Tama Koshi Valleys. The automated sirens will warn the villages in case of a GLOF from Tsho Rolpa Glacial Lake.

Mitigation measures at Tsho Rolpa Lake

A detailed multidisciplinary study on the stability of the moraine dam was conducted and an appropriate method for lowering the lake level was chosen. In August 1997, a formulation team visited the lake and recommended that the lake level be lowered by 3m by cutting an open channel in the southwest part of the end moraine (DHM 1997c). The Netherlands Government funded this project and a grant agreement was signed in August 1998 between the Netherlands and HMGN. Table 12.1 outlines the general project features.

Table 12.1: General outline of Tsho Rolpa Migitigation Project	
Donor country	The Netherlands
Donor's representative in Nepal	Netherlands Development Agency (Neda)
Grant amount	NGL 5,977,263.60 (US $2,988,625)
Implementing agency	DHM
Duration of project	4 years (August 1998 to December 2002)
Completion of construction	30 June 2000 (lake level lowered by 3 m)
HMGN contribution (Years 3 and 4)	US $115 414
International technical advisor (ITA)	Reynolds Geo-Sciences Ltd (RGSL), UK
Contractor (design/build)	Butwal Power Company Ltd (BPC)
Contractor (civil construction)	Himal Hydro and General Construction Ltd (HH)

The objective of lowering the lake water by 3m immediately and tangibly is to reduce the risk of breach through the natural moraine dam. This GLOF risk reduction system consists of a lined channel constructed through the western end moraine (DHM 1998b). Some information about the project construction are given below.

- The channel will pass through a depression in the moraine commonly referred to as the Horseshoe Lake (Figures 12.1 and 12.2).

Figure 12.1: Aerial view of end moraine area of Tsho Rolpa Glacial Lake showing the mitigation project construction site (photograph source: DHM 2000)

Figure 12.2: Closer view of Tsho Rolpa Glacial Lake mitigation construction site (photograph source DHM 2000)

- The channel will be 6.4m wide at the bottom.
- The bottom elevation of the channel at the gate structure will be 4.2 below datum.
- The channel bottom will be flat upstream of the gate structure and will have a gradation of 0.3% downstream of the gate.
- The channel sides will be sloped at 2H:1V.
- A gate structure will be located in the channel (Figure 12.3).
- There will be three gates, each 2m wide and capable of being opened 1.5m above the channel bottom.
- The 20m of the channel upstream of the gates will be lined with gabion mattresses extending 1m above datum. The gabion mattresses will be underlain by (in turn) a geotextile, 100 mm of sand, a geomembrane, a geotextile, and a further 100 mm of sand (Figure 12.3).
- The channel is designed to convey the design flood flow of 14.6 $m^3 s^{-1}$ and the extreme flood flow of 30 $m^3 s^{-1}$.

The work was 90% complete when the construction was halted for the winter shut-down in October 1999 (DHM 2000). The construction work began again in April 2000. The status of construction work as of 30 June 2000 is given below.

- All construction work in the canal area was complete by the middle of May.
- The filling of the canal section between the gates and the cofferdam began at the end of May.
- Between 1 and 6 June, several tests for canal stability, stability of the downstream moraine slope, and flow conditions were conducted by releasing the ponded water.

- After 6 June the filling of the canal upstream with water began and continued until June 8 (Figure 12.4).
- The official beginning of drawdown was at 11 am on 8 June. The daily drawdown rate was maintained well below the allowed 25 cm. By late June a drawdown of 3m was achieved (Figure 12.5).
- After drawdown the unlined portion of the canal was given the specified configuration.
- The downstream part of the moraine, where the new flow took place, was closely monitored for the possibility of erosion. No erosion occurred on the slope. Some toe erosion of talus slopes opposite the moraine occurred.

Figure 12.3: Gate structure with partially erected gates. In the foreground geomembrane and geotextile are being laid (photo credit: Shrestha 2000)

Figure 12.4: Synoptic view of mitigation construction activity at the end moraine of Tsho Rolpa Glacial Lake to reduce the lake water level (photo credit: Shrestha 2000)

- The moraine slopes were monitored for possible failure due to drawdown of the lake water. No abnormal activities were seen.
- Due to water flowing over the moraine slope the location of the third bridge, as planned initially, had to be abandoned. Later, after much discussion with the local people, a decision was made to construct the bridge just downstream of the gate and to improve the approach trail to the bridge.

While the lowering of the lake by 3m is expected to reduce the risk of GLOF, it is not a permanent solution. The formulation mission also postulated a second project, the Tsho Rolpa GLOF Permanent Remediation Project (TRPRP), that would have the objective of lowering the water level in the lake by a further 17m (giving a total of 20m). Lowering the water level by 20m is considered sufficient to permanently eliminate the possibility of a GLOF emanating from Tsho Rolpa Lake. Among other options, BPC has investigated the possibility of a 20m lake level lowering by micro-tunnelling through the southern lateral moraine (Neda 2000).

Figure 12.5: Downstream view of outlet canal and gate structure (photo credit: Shrestha 2000)