3 Early Warning Systems, Monitoring, and GLOF Mitigation

Identification of potentially dangerous glacial lakes and recognition of risks associated with them, including ranking of the critical lakes, has become a priority task. Once the critical lakes are identified, the planners, developers, and scientists involved need to develop and implement appropriate measures to reduce the potential risks from these lakes. Measures include: monitoring, to provide an early indication of changes; early warning systems, to provide downstream residents and owners of infrastructure time to take avoidance action; and mitigation measures, to physically change the situation and thus reduce the risk.

Monitoring and early warning systems

The United Nations International Strategy for Disaster Reduction (UNISDR), in a 2006 report, defines early warning as "the provision of timely and effective information, through identified institutions, that allows individuals exposed to a hazard to take action to avoid or reduce their risk and prepare for effective response" (United Nations 2006).

Effective GLOF monitoring and early warning systems are an important part of disaster preparedness; they have the potential to greatly reduce loss of life and property. Any such system should involve application of remote sensing tools, such as the universally available earth observation satellite data, over-flight reconnaissance with small format cameras, telecommunication, and broadcasting systems.

Much progress has already been made in this area, particularly in Nepal and Bhutan. The National Action Plan for Adaptation (NAPA) to Climate Change prepared by the Royal Government of Bhutan has placed considerable emphasis on GLOF vulnerability reduction efforts. Similarly, the Government of India has brought out a 'National Communication on Climate Change Mitigation and Adaptation' which has also pinpointed GLOF vulnerability reduction efforts. However the results are not always without problems. Some examples of early warning systems are given in the following.

Early warning system in the Sutlej river basin, India

Some measures have been put in place in the Sutlej River basin for monitoring, forecasting, and early warning to deal with flash floods, especially from cloudbursts. As GLOFs are one of the causative factors in propagating flash floods downstream, these measures also act as an early warning system for a GLOF. Telemetry stations set up by the Snow and Hydrology Division of the Central Water Commission in Sumdo, at the confluence of the Parechu and Spiti rivers, and Khaab, at the confluence of the Spiti and Sutlej rivers, and by the Naptha-Jhakri project at Dubling, are intended to monitor any increase in the water level and to relay information. They were introduced in response to the gap in early warning that was felt after the floods in 2000, and also for the protection of hydropower projects. Similarly, a wireless network at Reckong Peo, used by security personnel with connections to border outposts, and the Doordarshan Satellite Earth Station and All India Radio Relay Centre, have been very useful in generating warnings and in communicating during emergencies (UNDP 2008).

Early warning system in the Tsho Rolpa and Tamakoshi valleys, Nepal

Lake Tsho Rolpa in the Tamakoshi sub-basin in eastern Nepal is fed by Trakarding glacier and is one of a small number of glacial lakes that have been studied in detail, including field investigations of the lake itself and the downstream area. This investigation led to a realisation in the 1990s that the risk associated with the lake, whose level had risen to the crest of its containing end moraine dam, was potentially serious (WECS 1993, 1994). It was feared that Rolwaling valley downstream of the lake could be inundated due to catastrophic outflow and that widespread loss of life and serious damage to local infrastructure, including potential damage to the 60 MW Khimti Hydroelectric Project, was a high probability (Reynolds1999).

Attempts to significantly reduce the risk of a GLOF occurring from Tsho Rolpa have been extensively documented. Although the early warning system(s) was initially to some extent successful, a serious problem arose as a result of interference from local people. Details of the early warning systems are given below.

The early warning systems

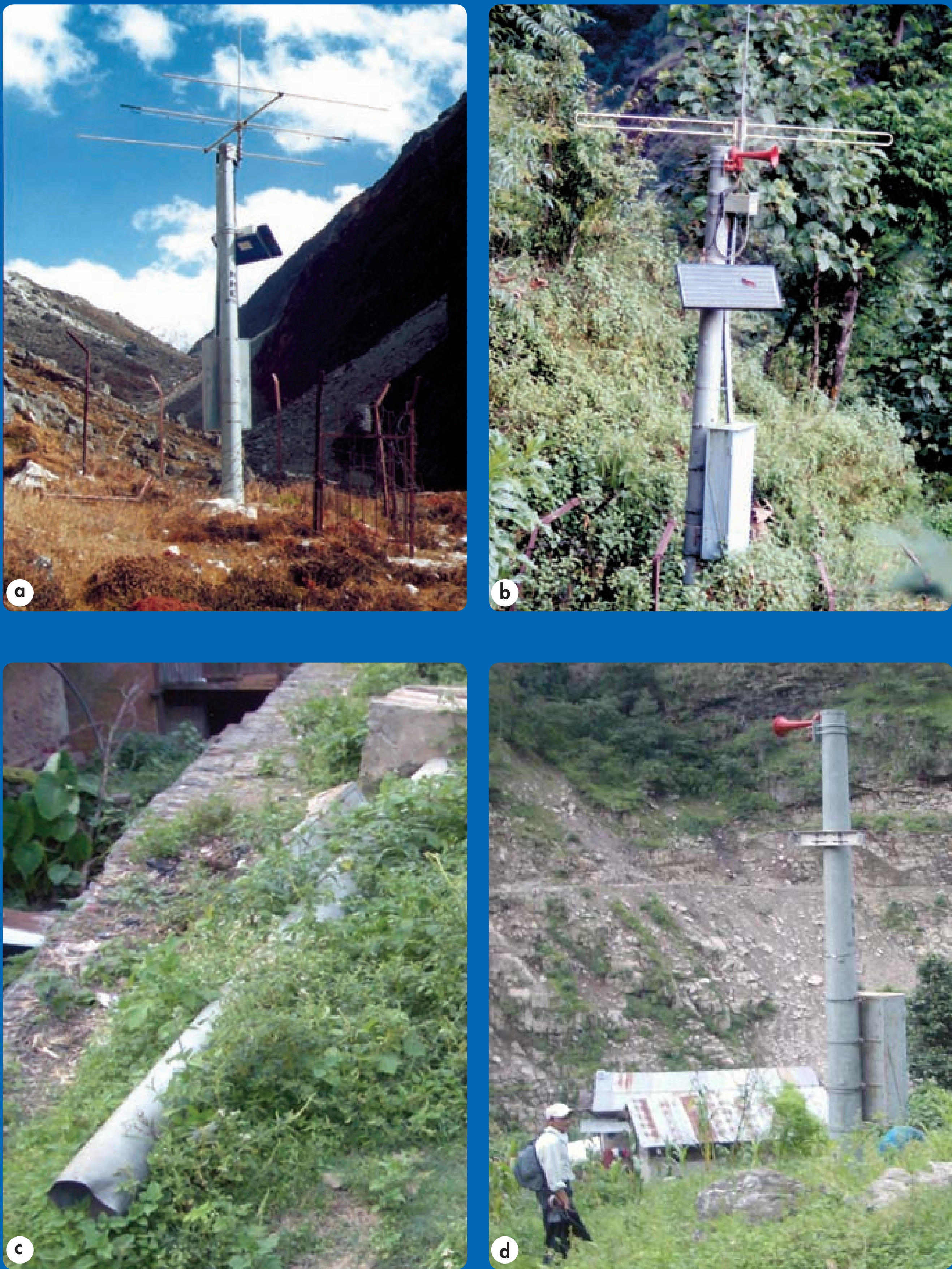
An intensive warning system is needed during short periods when construction projects are underway or for other reasons when a significant risk is identified. In June 1997, a manual early warning system was installed by the Nepal Government as an emergency measure for the local villagers and the Khimti Hydropower Project, under construction at that time. The emergency measure was needed in view of the rapid rate of deterioration of the moraine dam, and the construction activities of the Tsho Rolpa GLOF Risk Reduction Project (TRGRRP) which aimed to lower the lake level (see next section). Early warning systems were installed in the Rolwaling and Tamakoshi valleys. Army camps were established at the terminal moraine and at Naa village, the nearest village to the lake. Police posts were also established at Naa and Bedding villages. Each army camp and police post was provided with a high frequency radio transceiver; the army post at Naa also had a backup set. The police posts and the army camp in Naa were in regular radio contact with their respective headquarters in Kathmandu. The army posts were also provided with satellite telephones. The lakeside army post used one of the phones to contact the Disaster Prevention Cell at the Home Ministry twice a day to deliver status reports. In the event of a GLOF, Radio Nepal, the national broadcaster, would broadcast a warning (Reynolds, 1999; Bajracharya, et al., 2007).

In January 1998, MeteorComm and its partner, British Columbia Hydro International Ltd. (BCHIL) of Vancouver, signed a contract with the Government of Nepal, Department of Hydrology and Meteorology (DHM), to design, supply, install and commission an audible warning system downstream of Tsho Rolpa (www.MeteorComm – Wireless Communications Tsho Rolpa.mht). The project was financed by the World Bank (WB) at a total cost of US $ 1,032,000. This first early warning system installed at Tsho Rolpa and the villages of the Tamakoshi valley in May 1998 was intended to warn people living in downstream areas in the case of a GLOF event, and consisted of a GLOF sensing and warning system. The sensors would detect the occurrence of a GLOF and transmit relevant information to the transmitter station thus setting in motion the warning process. The warning would sound to alert the local people downstream. This system was fully automated and required no human intervention.

The GLOF sensing system consisted of six water level sensors installed along the right bank of the river channel immediately downstream of the lake outlet at Sangma Kharka; this was designed to detect the onset of a breach. Three sensors were connected by armoured and shielded cables to each of the two independently functioning transmitting stations (Figure 5a) located at a higher elevation and within 80 m of the sensors. Each sensor was located at a different elevation above the previous high water mark such that different sensors would be able to indicate any progressively rising river stages. Thus, the sensing system would detect the occurrence of a GLOF immediately and signal directly to all warning stations located downstream within two minutes of initiation of a flood. The remote station at Naa village had the dual function of forming part of the GLOF sensing system and providing local warning to the village residents.

The warning system consisted of 19 warning and relay stations installed at the 17 villages of the Rolwaling and Tamakoshi valleys (Figure 5b). The warning stations located in the villages had Meteor Communication Corporation (MCC) 545-transceiver units mounted on 4.67m self-supporting standard galvanised iron power poles. The antennae were mounted on extensions to the poles approximately 5 m above the ground. Lightning rods and solar panels were mounted on the same poles. MCC 545 units, with battery and relay for the horns, were mounted inside sheet metal boxes with lockable shelters, also attached to the poles. All cables were protected by plastic conduits, covered by galvanised sheet metal and strapped to the poles. Air-powered horns, designed to operate off charged air cylinders for a period of two minutes, with a reserve for an additional one to two minutes, were also mounted on the poles. The air horns could provide a sound of 80 dB up to a minimum distance of 150 m under the most adverse conditions. They were backed up by electric horns which could operate for four minutes. The GLOF warning systems were based on 'extended line of sight' (ELOS) VHF radio technology. The warning signal would be transmitted via ELOS ground wave signals from remote station to remote station down the valley. Thus, an early warning signal would be triggered automatically if a GLOF was detected.

Figure 5: **The Tsho Rolpa/Tamakoshi valley early warning system:** a) Sangma Kharka transmitter station outside lake Tsho Rolpa receives signals from sensors and transmits to other remote warning stations; b) the warning and relay station Gongar village, comprising solar panel, battery, antenna and amplifier with siren; c) destroyed siren pole at Sigati village; d) damaged siren at Bhorle village



A second component of the system was the installation of an MCC meteor burst master station located in Dhangarhi, western Nepal. A meteor burst station uses the ionised trails of meteors to extend the range of transmitted radio signals to over 1,600 kilometres (1000 miles). Several of the warning stations, as well as a sensing station, were designed to transmit and receive signals from the master station, to provide further redundancy to the system. The master station also monitored the status of the entire warning system. Thus, the master station provided a communication link between remote stations located in the Rolwaling and Tamakoshi valleys and the monitoring station in Kathmandu.

The outcome

By 2002, four years after establishment, the early warning system was no longer operating (Figures 5c,d) despite the fact that it was a robust system commissioned with the latest technology. Lack of participation by the local communities and disruption of communications during Nepal's long period of political uncertainty, appears to have led to the system being ignored and then destroyed, with components being taken to use for other purposes locally. The people in the area thought that the lake had been reduced to a safe level and lost interest in the warning system. The tendency towards ignoring the importance of early warning was further intensified by the incidence of false alarms (Khanal et al. 2009).

Early warning system in the Upper Bhote Koshi, Nepal

Another example of an early warning system, similar to that of Tsho Rolpa, is in place in the Upper Bhote Koshi valley of eastern Nepal. The system was installed in 2001, mainly for the Upper Bhote Koshi Hydroelectric Project. It consists of two remote sensing stations with data loggers near the Friendship Bridge at the Nepal-China border that are designed to receive, analyse, and transmit data from sensors. If the water level increases significantly, the system will transmit warning signals to stations located at the intake and the powerhouse site of the power station. In this system, there are seven GLOF detection sensors at the Friendship Bridge, one ultrasonic water level measuring device, and six float type water level switches. It operates on short-burst VHF radio signals using meteor burst technology. Warning sirens are set off from compressed air horns which transmit a sound of 127 dB at a minimum distance of 33 m. There are five such stations along the river (Bajracharya et al. 2007), but the early warning system is only installed up to the border between Nepal and China. From there, there is only 6 minutes of warning time down to the Bhote Koshi hydropower station. To be really useful, the early warning system would need to be extended further upstream into China (TAR). As of 2009, the system was still fully functioning – presumably because of the interest of the hydropower project.

Poiqu basin (Sunkoshi – Bhote Koshi basin)

The inventory by Mool et al. (2005) indicated that the number of lakes in the Poiqu basin, TAR, China (Sunkoshi – Bhote Koshi basin), increased from 119 in the 1980s to 139 in 2000, with an increase of 22% in lake area. Nine potentially dangerous lakes were identified from analysis of multi-temporal satellite images and use of GIS tools, based on different criteria. It was recommended that the lakes be monitored regularly and detailed field studies undertaken. Ten sites were selected for installation of early warning systems, some located in Nepal. As of 2009, no systems have been installed.

Monitoring of Imja lake in the Everest region, Nepal

Imja glacial lake has been one of the fastest growing lakes in the Himalayas and ICIMOD has been monitoring the lake as a basis for devising an early warning system. A remote sensing system (using geo-ICT tools and techniques) was developed in cooperation with the Department of National Parks and Wildlife Conservation (DNPWC) and Keio University of Japan (Bajracharya 2009). Two monitoring devices or field servers – the Internet field observation robot (Figures 6a,b) – were installed on the lake shore at 5,000 masl and close to the nearest big settlement, Namche Bazaar, in 2007 by a team led by Keio University, with other researchers from the National Agricultural Research Centre, Japan. It was connected to the Internet in collaboration with the Asia Pacific Advanced Network (APAN) and Nepal Research and Education Network (NREN). The field servers capture time lapse images of the lake and Namche Bazaar (Figures 6c, d) and meteorological data. These are transferred in real-time by Wi-Fi to a server located in Japan at http://fsds.dc.affrc.go.jp/data4/Himalayan/ (Asia Disaster Report 2007).

The World Wildlife Fund (WWF) – Nepal is also conducting a climate change impact assessment of the Everest region, especially Imja Tsho and downstream areas. In partnership with the Department of Hydrology and Meteorology, a simulation has been made of an Imja Tsho GLOF using a dam-break model. A detailed survey of Imja Tsho, and hazard mapping for

Figure 6: **Monitoring of Imja glacial lake:** a) field server the lake (2009); b) solar panel for field server (2009); c) part of image from field server at lake (26 June 2009); d) part of image from field server at Namche Bazar (1 Jan 2010)

communities at risk related to rockfalls and landslides, are also planned. The Information Centre established by WWF Nepal at Ghat, near Lukla provides relevant information.

ICIMOD carried out GLOF simulation studies for Dig Tsho and Imja Tsho in Nepal, and Lunana lake in Bhutan (Bajracharya et al. 2007), and GLOF modelling studies including socioeconomic vulnerability assessments for Zangzangbo, Imja, Tsho Rolpa, and Thulagi lakes in their downstream areas in 2009 (Khanal et al. 2009, unpublished report).The studies provide a basis for ascertaining the arrangements that would be needed for setting up early warning systems in the valleys. A good first approximation was made for land and settlement classification according to four defined levels of risk. This facilitated an estimate of potential losses that can be anticipated in the event of a worst case GLOF occurrence.

Early warning system in the Lunana region, Bhutan

The Lunana area at the head of the Pho Chhu River in west-central Bhutan has been of considerable concern to the Bhutanese authorities. The Luggye Tsho GLOF of 7 October1994 caused heavy damage to the Dzong at Punakha and 23 deaths (Richardson and Reynolds 2000).

A manually-operated early warning system has been placed in the Lunana region by the Flood Warning Section (FWS) of the Department of Energy (DoE). Two staff members from the FWS are stationed in the Lunana lake area. They are equipped with wireless sets and satellite telephones to report lake water levels on a regular basis and to issue warnings to downstream inhabitants. Several gauges have also been installed along the main river as well as at the lakes. These are monitored at various stations at different times depending on the distance from the station and base camp. The station is in regular contact with other wireless stations in the downstream areas along the Puna Tsang Chu, including the villages and towns of Punakha, Wangduephodrang, Sunkosh, Khalikhola, and Thimphu (Bajracharya et al. 2007).

The Japan International Cooperation Agency (JICA) and the Gross National Happiness Commission (GNHC) signed an agreement for the study of GLOF phenomena in Bhutan. This aims to build a network for sharing satellite data for research, to complete an inventory of historical glacial lake expansions, to conduct a detailed analysis of hazardous lakes, to assess risk factors and triggers of GLOFs, and to recommend effective countermeasures, such as deployment of early warning systems. The project will also be extended to cover the Mangde Chu basin, and to recommend mitigation measures (Kuensel Online, 11 June 2009).

Mitigation measures

Potential outburst flood hazards can be alleviated by various techniques. The primary objective is to reduce the risk of a flood from the lake. However, coordinated measures to protect life and property in the downstream area must also be undertaken. It is imperative to have monitoring systems in place prior to, during, and after the construction of infrastructure so that settlements in the downstream area are protected against unintentional creation of hazards. Mitigation measures to effect risk reduction can be structural or non-structural. In the following, mainly structural measures are discussed.

The most common structural mitigation measures are aimed at reducing the volume of water in the lake. Reduction of the volume of water in the lake should reduce the potential peak surge discharge as well as the hydrostatic pressure exerted on the moraine dam, and is the most effective mitigation measure. There are different ways to achieve this that can be used alone or in combination:

1. Controlled breaching of the moraine dam
2. Construction of an outlet control structure
3. Pumping or siphoning the water from the lake
4. Tunnelling through the moraine barrier or under an ice dam

Mitigation measures must be brought into play in such a way that no unintentional increase in danger occurs. Since moraine dam stability is a major part of the problem, it follows that artificial disturbance of the dam itself during construction activity could actually increase the degree of danger while mitigation measures are being put into place. Thus, choice of an appropriate method for each individual lake is critical. This necessitates careful evaluation of the lake, glacier, damming materials, and surrounding landscape. Physical monitoring systems for the dam, lake, glacier, and surroundings are necessary at all stages of the mitigation process.

In addition to reducing the volume of lake water, there are other preventative measures around the area that can help reduce the likelihood, or impact of, a GLOF. These include removing masses of unstable rocks to guard against avalanches or rockfalls hitting the lake surface and causing a surge wave, and protecting infrastructure in the downstream area. Engineering work as a part of hazard reduction efforts, especially in such remote and high altitude areas, is very expensive, however.

Some examples of programmes, projects, and interventions related to mitigation measures that have been applied to reduce the impact of GLOF risk in the Himalayan region are described below.

Bhutan

The earliest awareness of glacial lakes in Bhutan dates from the 1960s (Gansser 1966). After the Luggye Tsho GLOF event of 7 October 1994 in Punakha Wangdue valley, emphasis was placed on GLOF risk mitigation. The Royal Government of Bhutan sent an Indo-Bhutan team of experts to the Lunana area in 1995 to investigate any residual risk. The team recommended immediate mitigation measures for Raphstreng Tsho, including an attempt to lower the lake's water level as soon as feasible. Funding was provided by the Government of India with consulting by Water and Power Consultancy Services (India) Ltd (WAPCOS). The original plan was to reduce the lake level by 20 m in the first phase. WAPCOS found that this would actually take seven to eight years, but that lowering of the lake level by only four metres would also significantly reduce the risk of overtopping. Controlled opening of the moraine dam was carried out by manually widening the outlet channel with crowbars, pickaxes, and spades. Although a method of pumping to reduce the lake level was attempted initially, it was discarded as both ineffective and too expensive for such a remote region. Despite numerous constraints, such as having to work with manual tools, and obstructions caused by huge boulders in the channel bed, the water level in the main lake was lowered by 0.95 m, and in the two subsidiary lakes by 0.94 m and 1.5 m, by October 1995 (Häusler and Leber 1998; ICIMOD 2001b). The lowering continued until the lake level was reduced by four metres in 1998 (UNDP-ECHO 2007a).

Phase 2 of the Raphstreng Tsho Outburst Flood Mitigation Project began in 1999 supported by Austro-Bhutanese Cooperation. The main aim was to assess the geo-risks of Raphstreng Tsho and Thorthormi Tsho in the Lunana area. The activities involved fieldwork with an integrated multi-disciplinary approach using remote sensing, geological, hydro-geological, and geophysical methods to interpret the subsurface characteristics of the moraine dam (Häusler et al. 2000; Mool et al. 2001b). The investigations indicated that the risk of an outburst from Raphstreng Tsho was low, but the risk from Thorthormi Tsho was high (Häusler et al. 2000).

Thus a project for 'Reducing climate change-induced risks and vulnerabilities from glacial lake outburst floods in the Punakha-Wangdue and Chamkhar valleys' was initiated by UNDP to run from 2008 to 2012 in conjunction with the Department of Geology and Mines, the Department of Energy (Ministry of Economic Affairs), and the Disaster Management Division (Ministry of Home and Cultural Affairs). The Global Environment Fund (GEF) has provided US$ 3.5 million; the project is mainly examining the effectiveness of structural risk reduction measures. Activities cover risk reduction measures for Thorthormi glacial lake, including artificial lowering; hazard zonation mapping in

"Installing an automatic early warning system (EWS) to reduce the impact of a glacial lake outburst flood (GLOF) in the Punatshangchu basin has become urgent, according to participants of an inception workshop on the regional climate risk reduction project in Punakha. The plan to establish an automatic EWS has not taken off yet, although the government in early 2009 said that automatic sirens would be set up in the villages down from the Lunana area, which would warn people at the first hint of any impending floods in the area. The earlier plan was to install an automatic sensor a few kilometers upstream of Phochu to detect the first flood and five sirens along the area....... . To make EWS comprehensive, there will now be two sensors at two locations: one at Lunana and the other 25-30 km upstream of the Phochu. United Nations Development Programme's (UNDP) Kinley Penjor said UNDP would develop a soft package to prepare or train people in the valleys to make EWS effective. He said 'after the machinery is in place, it's important for people to know what to do and how to respond to climate induced GLOF.' " (Kuensel Online 18 Jan 2010)

Chamkar chu in Bumthang; and the expansion of an early warning system along the Punakha-Wangdue valley. In addition, there are plans for improvement of national, regional, and local capacities to avert climate change-induced disaster in the Punakha-Wangdue and Chamkhar valleys. The project should demonstrate practical measures to reduce the risks associated with the Thorthormi glacial lake and facilitate replication of the lessons learned in other high-risk areas, both within and outside Bhutan (Kuensel Online, 7 December 2009; www.managingclimaterisk.org).

Proposals have also been made for Samdingkha to have a siren tower, given its high vulnerability to GLOFs. Two possible locations were identified: Siren 1 below Lorina village on the right side of Pho Chu facing Samdingha and about 60 m from the river level; and Siren 2, about 200 m above the suspension bridge. Both locations provide a good view of the vulnerable areas.

A GLOF hazard zonation plan for the Puna Tshang Chu valley from Khuruthang in Punakha to Kalikhola Lhamoyzinkha is among various risk management measures the Department of Geology and Mines (DGM) has prepared with the Netherlands Climate Assistance Programme (NCAP) (Karma et al. 2008; Kuensel Online 7 December 2009).

Nepal

The Tsho Rolpa Mitigation and Early Warning Programme was the first glacial lake outburst flood operation to include civil engineering structures in the entire HKH region. The early warning measures are described in some detail above. The preliminary investigation of Tsho Rolpa and its downstream section of the Rolwaling valley was undertaken by WECS in 1993 (WECS, 1993, 1994; Mool, 1995). Investigations in subsequent years led to a recommendation for immediate action, as well as for long-term measures. As an immediate measure, Wavin Overseas B.V., Holland, installed siphons over part of the terminal moraine in May 1995. This was primarily to test the use of siphons at high altitude. The project was undertaken in cooperation with the Netherlands-Nepal Friendship Association. The siphon system consisted of three inlet pipes submerged in the lake and connected to a single pipe with a discharge outlet located at a stable part of the outer flank of the moraine. Though the test siphons were installed successfully, the induced outflow was far below that required to ensure reducing the lake level by the targeted three metres, and it appeared that they might never exceed inflow of additional glacier and snow melt.

In the second phase of the mitigation measures, supported by a contribution of $2.9 million from the Dutch Government, an open channel was cut through the moraine dam and a four-metre deep artificial spillway succeeded in lowering the lake level by three metres. The spillway construction was completed by the Tsho Rolpa GLOF Risk Reduction Project of the Department of Hydrology and Meteorology in June 2000.

Pakistan

The high altitude, fragile environment, and isolated nature of Pakistan's Northern Areas poses special constraints and challenges for mitigating natural hazards such as glacial lake outburst floods.

The glacial lakes in this area are predominantly ice-dammed lakes resulting from local glaciers that have thickened and advanced in recent decades (Hewitt 2009). They must be differentiated from the supra-glacial and moraine-dammed lakes that are the principal concern of this report. Five GLOF events were reported during the first half of 2008 in the Gojal area of the Hunza valley and substantial damage to infrastructure and arable land was reported due to GLOF events in association with the Ghulkin and Passu glaciers. There is no regular early warning system in the Hunza river basin, and the local people use traditional methods, such as lighting torches and firing weapons, to warn the villagers of flash floods.

Risk reduction measures taken in Gojal include excavation, channelling, and spillway development. (UNDP-ECHO 2007b). A local village community used a siphoning technique to drain the lake associated with the Ghulkin glacier and reduce the threat posed by a potential outburst flood. A lateral moraine was excavated to set up the siphon (Roohi et al. 2008).