

Day 4

Session/Activity	Activity time (minutes)	Cumulative time of session
Session 15: Country Presentations		
Session 16: Hazard-Specific Flash Flood Management: Glacial Lake Outburst Floods		
16.1 Glaciers, formation of glacial lakes, and the glacial landforms	10	10
16.2 Causes of glacial lake dam failure	10	20
16.3 Impacts of GLOF events	10	30
16.4 Measures to minimise GLOF risk	30	60
16.5 Briefing for the field trip	30	30

Session 15 Country Presentations

Objective

To give the participants an opportunity to share their experiences and knowledge on various activities for flash flood risk management

Activities

Ask the participants to give a short presentation on any aspect of flash flood risk management from their own country.

SESSION 15

Suggestions for the facilitator – planning ahead

A little preparation can help to make this activity a good success. Make sure that you advise the participants well ahead of time, possibly in the course requirements or even on the first day of the course, that they will have to make a presentation on Day 4. Advising the participants ahead of time will give them plenty of time to work on their presentations and to gather any materials that are required such as photos and documentation. When and as appropriate, encourage them to show how they are already using some of the concepts that they have learned in the first three days of the course.

The presentations can consist of a PowerPoint, a short video, or both. Be specific about how long the presentation should be; this will depend on the scheduling and the size of the class, but on average, country presentations are 30 minutes: 20 minutes for the presentation and 10 minutes for discussion.

There must be, at least one presentation from each country. If there are several participants from the same country they can join up for a team presentation, and if there are very many from the same country then different teams can each choose an aspect that they would like to elaborate.

The day before, collect the titles of the presentations and the names of the presenters and make a short list – this will make it easier to introduce them. Make sure that any audio-visual backup that is needed is available. Introduce the country presentation in alphabetical order by country and ask participants to present accordingly. If the facilitator feels that it is appropriate, the country presentations can be shared among the participants at the end of the training. In this case, decide what is the most appropriate medium for sharing the information (e.g., photocopies, CDs) and prepare the required number of copies.

Session 16 Hazard-Specific Flash Flood Management: Glacial Lake Outburst Floods

Time: 60 minutes

Objective

To introduce glacial lake outburst floods (GLOFs) and the measures that can be taken to minimise the risk they pose, including:

- ▶ The glacial landscape, glaciers, and the formation of glacial lakes
- ▶ Causes of glacial lake dam failure
- ▶ How to determine which glacial lakes are potentially dangerous
- ▶ The potential impacts of GLOFs
- ▶ Measures that can be used to minimise the risks posed by GLOFs

Activities

Activity 16.1: Glaciers, formation of glacial lakes, and the glacial landforms

Time: 10 minutes

Present the salient features of glaciers, how glacial lakes are formed, and the characteristics of the glacial landscape such as moraine, terminus, talus slope, ice cliff, crevasse, dead ice, and supra glacial lakes.

Activity 16.2: Causes of glacial lake dam failure

Time: 10 minutes

- Step 1** Present the causes of glacial lake dam failure. Differentiate between moraine dam failure and ice dam failure.
- Step 2** Discuss the methods used to determine whether a glacial lake is potentially dangerous.

Activity 16.3: Impacts of GLOF events

Time: 10 minutes

Discuss the possible impacts of GLOF events. Give examples from documented recent GLOF events such as, for example, the Dig Tsho GLOF of 4 August 1985.

Activity 16.4: Measures to minimise GLOF risk

Time: 30 minutes

Discuss the control measures that can be used to minimise the risk of GLOFs.

- Step 1** Highlight the methods that can be used to prepare an inventory of glaciers and glacial lakes, for early recognition of risk.

- Step 2** Describe the empirical scoring system for moraine-dammed glacial lake outburst hazard.
- Step 3** Discuss the methods that can be used to estimate the magnitude of a potential flood in order to estimate downstream flooding and implement appropriate mitigation measures downstream.
- Step 4** Discuss GLOF risk mapping. Explain how estimating the magnitude of past floods can be used as a basis for preparing for future hazard and risk. Discuss the methods that can be used to calculate the parameters of past floods such as velocity, depth, width, and discharge.

**Note to the
trainer**

Remember to briefly remind the class that measures such as land-use regulations and early warning systems, which were covered in previous sessions, also apply in the case of GLOFS.

Session 16 Resource Materials

RM 16.1: Glaciers and formation of glacial lakes

Glaciers

A glacier is a huge mass of flowing ice. Since in any given year, more snow falls than melts, snow layers pile up year after year and are compressed under their own weight. As the compression progresses the density increases and the compacted layer, now called ice, becomes impermeable to air. The density of ice ranges from 0.83 to 0.917 g/cm³. When the thickness of the snow and ice exceeds a certain critical value, the ice mass of the lower layers undergoes a plastic deformation, flows down to a lower elevation, and becomes thinner.

Moraine

The debris from both sides of the steep slope settles on the glacier surface and is carried downslope. The debris that piles up on both sides and at the end of the glacier are known as moraines. 'Terminal' or 'end moraines' are formed at the foot or terminal end of a glacier. Lateral moraines are formed on the sides of the glacier. Medial moraines are formed when two different glaciers, flowing in the same direction, coalesce and the lateral moraines of each combine to form a moraine in the middle of the merged glacier. Less apparent is the ground moraine, also called glacial drift, which blankets the underneath surface of much of the glacier below the equilibrium line (the imaginary line separating areas of positive and negative mass balance).

Glacial lakes

Glacial lakes (Figures 23 and 24) are the ponds which form when glaciers melt; they are usually found near the ends of glaciers. Since the structure of these lakes is not consolidated, they can be unstable. These lakes are created when glaciers surge; they can broadly be classified into three categories based on the composition of the dam:

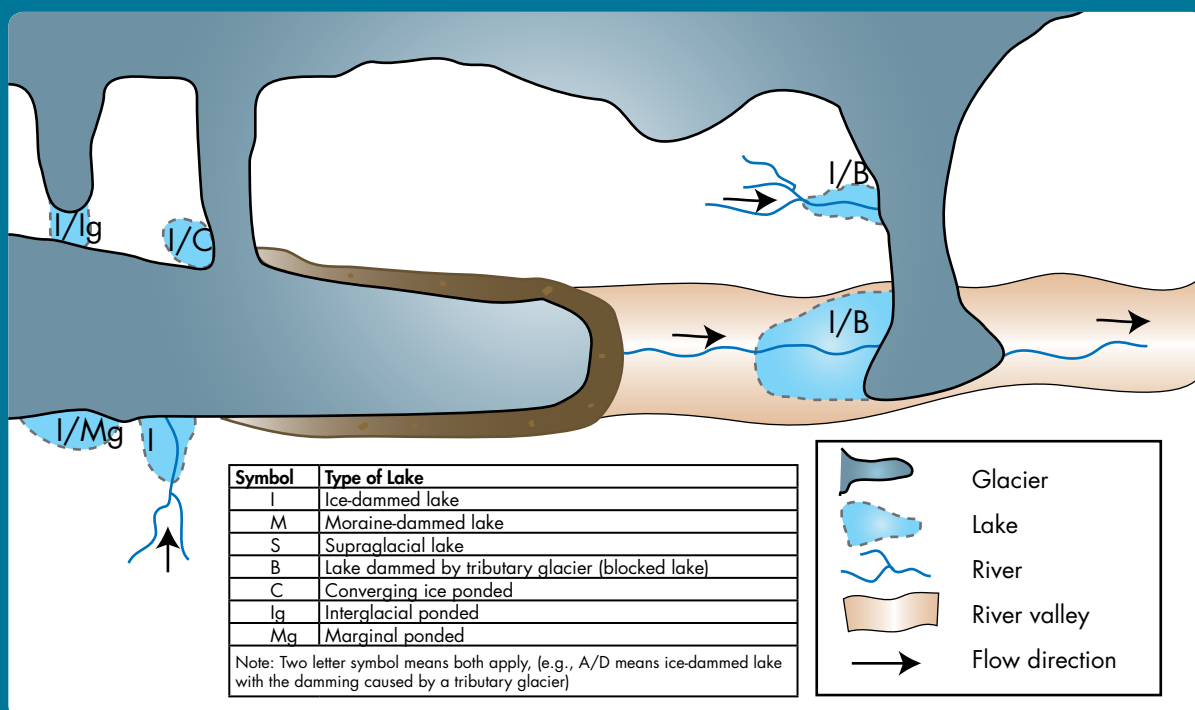
- moraine dammed lakes;
- glacial ice-dammed lakes;
- ice-core moraine dammed lakes.

Most of the glacial lakes in the HKH are moraine dammed. When the glacial dams break, huge amounts of water from the glacial lake are released downstream in a sharp flood wave. This flood wave is usually released with so much force that it can wash away infrastructure found along the river banks. This destructive flood is known as a glacial lake outburst flood (GLOF).

The formation of glacial lakes

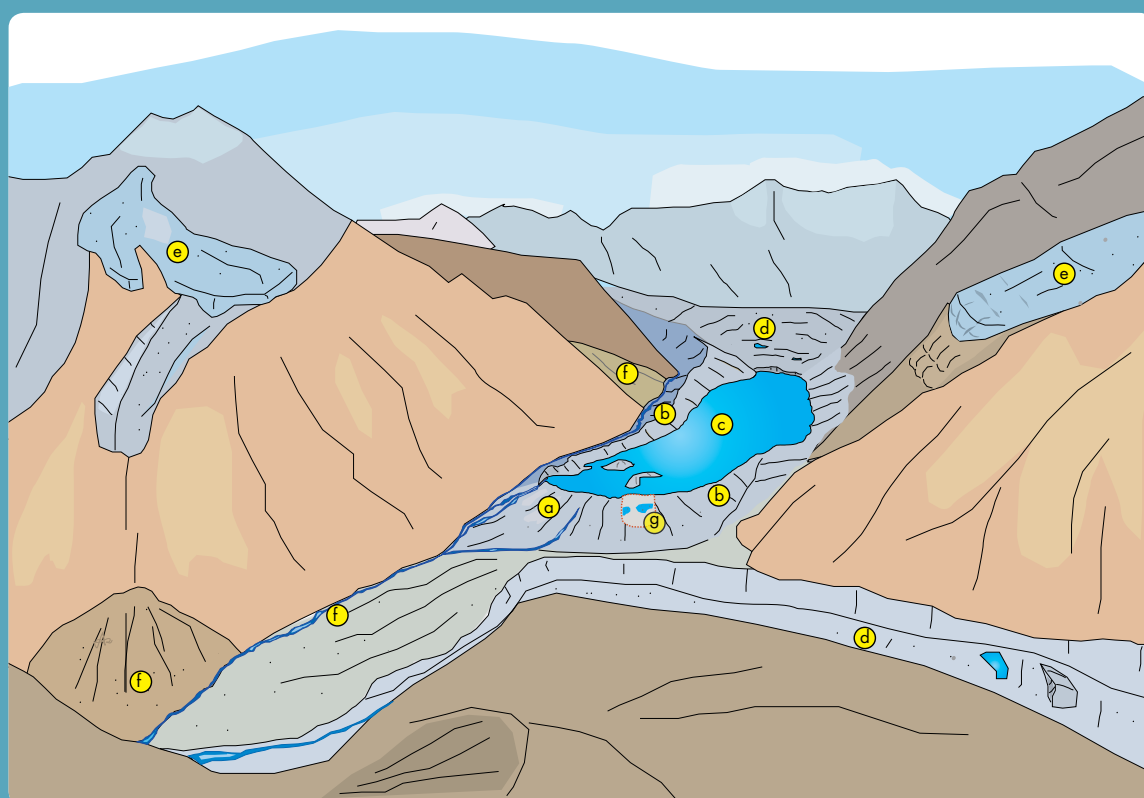
The formation and growth of glacial lakes is closely related to deglaciation. Shrinkage of glaciers is a widespread phenomenon in the HKH region at present and is closely associated with climate change. The glacial retreat that has been observed in recent decades is generally attributed to an anthropogenic increase in the concentration of greenhouse gases in the atmosphere and the overall warming that is attributed to it. Valley glaciers are typically dotted with supra-glacial ponds; in a warming environment these grow bigger and merge with each other. This process is accelerated by the rapid retreat of glaciers. As glaciers retreat, they leave large voids behind, and the melt water that is trapped in these depressions forms lakes. Figure 25 shows the rapid growth of the Tsho Rolpa Lake in Nepal as an example.

Figure 23: Types of glacial lakes



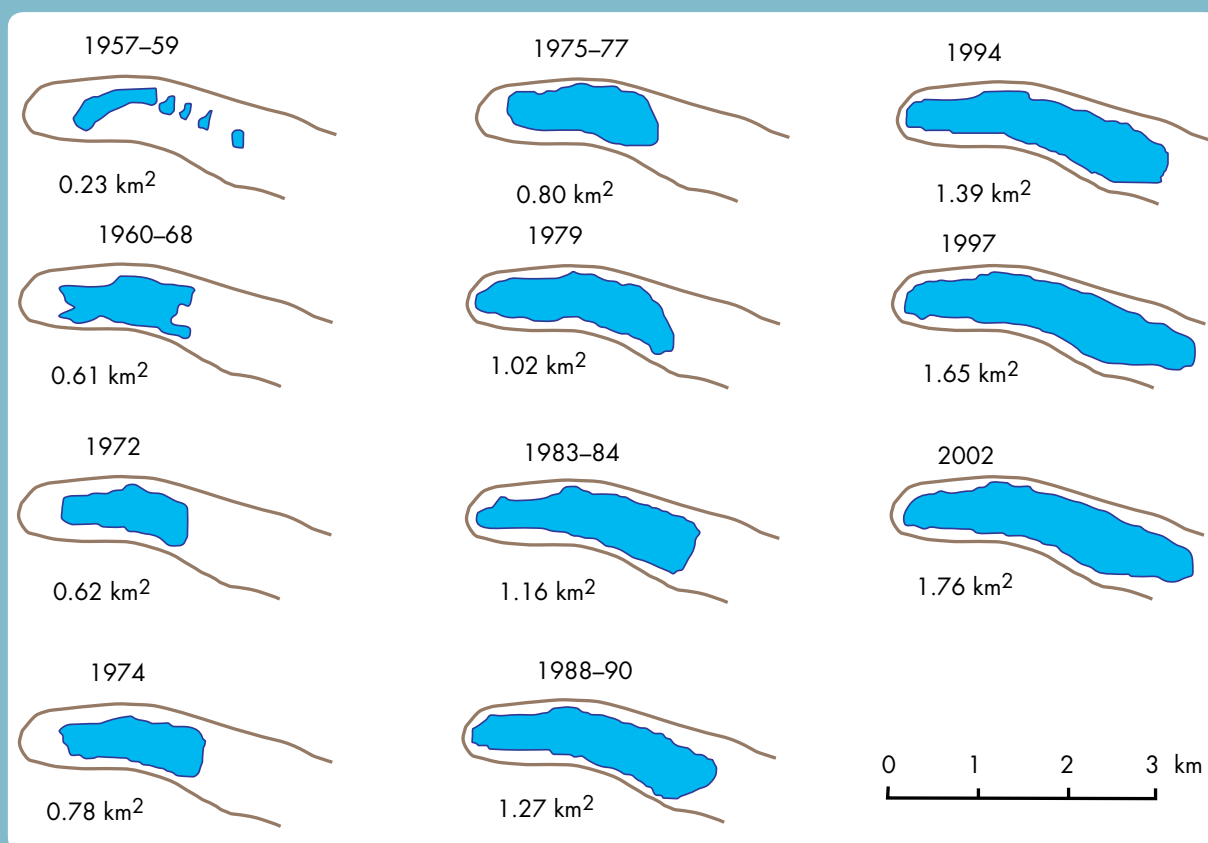
Source: Shrestha (2008)

Figure 24: Schematic view of typical glacial lakes found in the HKH: a) end moraine; b) lateral moraine; c) glacial lake; d) glacier terminus; e) hanging glacier; f) talus slope; g) dead ice



Source: Shrestha (2008)

Figure 25: Development of the Tsho Rolpa glacial lake



Source: Shrestha (2008)

RM 16.2: Causes of glacial lake dam failure

Moraine dam failure

Moraine dams can be breached in a number of ways, the mechanisms of dam failure can be classified into two broad categories:

- breaches caused by the erosion of dam material;
- breaches caused by the sudden collapse of a portion of the dam (as in the case of earthquakes or geo-technical failures, for example).

A moraine dam may collapse as a result of some external trigger or because of internal failure. A huge displacement wave can cause the water to overtop the moraine; the displacement wave can be caused by a rockslide or by an avalanche of snow or ice from the glacier terminus or by hanging glaciers falling into the lake. The displacement wave can cause a large breach that leads to dam failure (Ives 1986).

The types of failure caused by erosion of the terminal moraine can be further classified as caused by:

- overtopping of the dam due to a progressive rise in the lake level or by creation of a surface wave by a landslide, a rock fall, an icefall, ice calving, or wind waves;
- piping through the dam material;
- intensive rain which rapidly fills up the lake and eventually overtops or pipes through the moraine.

Richardson and Reynolds (2000) analysed 26 GLOF events in the Himalayas in the twentieth century and concluded that a majority of the moraine dam failures were triggered by overtopping usually as a consequence of a displacement wave triggered by ice avalanches into the lake from hanging or calving glaciers.

Ice-dam failure

Ice is the softest type of rock and, in the conditions found in the Himalayas, it is also usually very close to its melting point. Ice-dammed lakes are mechanically very unstable, since the ice dams can be compromised by:

- flotation of the ice dam;
- pressure deformation;
- melting of a tunnel through or under the ice; and
- drainage associated with tectonic activity.

Methods to determine whether glacial lakes are potentially dangerous

Methods to determine whether a glacial lake is potentially dangerous or not, can range from simple desk-based investigations to complicated methods, involving highly specialised field tests. In general, potentially dangerous lakes can be identified based on the following:

Volume and rise in the water level of the lake. An outburst of a relatively small lake may not have a significant impact. Lakes smaller than 0.01 km³ in volume are not considered potentially dangerous. The dynamics of the water level are also important, since an increase in the water level increases the hydrostatic pressure on the moraine dam and may cause it to collapse.

Activity of a glacial lake. Rapidly increasing lake size indicates the high probability of a GLOF. Similarly, when the lake boundary and outlet position are dynamic, high risk is also indicated.

Position of the lake. Potentially dangerous lakes are generally located at the lower end of the ablation area of the glacier near the end moraine. Only when the parent glacier is sufficiently massive can it give rise to lakes that are large enough to be dangerous. Large lakes should be regularly monitored with the help of multi-temporal satellite imaging and field investigations.

Condition of the moraine dam. The condition of the moraine damming the lake determines how stable the lake is. The possibility of outburst due to collapse of the moraine dam increases if:

- the dam has a narrow crest area;
- the dam has steep slopes;
- the dam is ice cored;
- the dam is located high above the valley floor;
- there are instabilities in the slopes of the dam;
- there is seepage through the moraine dam.

Condition of parent glacier and glaciers on the periphery. The terminus of the parent glacier (that is in contact with the lake) can experience calving due to the development of thermokarsts on the lower part of the terminus and exploitation of crevasses on the glacier. When a large fragment of ice drops from this terminus into the lake, it can cause a displacement wave that has sufficient intensity to travel across the lake and cause water to overtop the moraine dam. Similarly, when the parent glacier presents at a steep angle or when it is located on a side valley it can cause ice avalanches into a lake. Such ice avalanches can cause displacement waves capable of overtopping moraine dams.

Physical condition of the surroundings. When the mountain slopes around the lake are unstable, there is always a possibility of mass movements and snow avalanches, both of which can cause displacement waves that can overtop the moraine dams. Smaller lakes located at high altitudes can also sometimes pose a danger to a glacial lake located at a lower altitudes. When the high altitude lakes outburst they can drain into the lower altitude ones and the additional water can cause overtopping and consequent failure of the moraine dam.

RM 16.3: Impacts of GLOF events

There have been at least 35 recorded GLOF events in the HKH region: 16 in China, 15 in Nepal, and 4 in Bhutan; and there have been some reports of floods of glacial origin in India and Pakistan. Many of the GLOFs in China occurred in the southern part of the Tibetan Plateau, where rivers drain into Nepal. One of the most remarkable GLOF events was the Zhangzanbo lake GLOF of 11 July 1981. The lake burst because of a sudden ice avalanche which caused a large wave, and a 50 m deep and 40–60 m wide breach formed in the moraine. This GLOF created a great change in the landforms downstream by erosion and sedimentation, and caused considerable damage to the highway below the lake up to the Sunkoshi power station. It destroyed the Friendship Bridge between Nepal and China and two other bridges, one in Tibet and one in Nepal. The flood also caused heavy damage to the diversion weir of the Sunkoshi hydropower station.

One of the region's most well documented GLOF events was the Dig Tsho GLOF of 4 August 1985. Dig Tsho Lake is located at the headwaters of the Bhotekoshi River in Nepal. The GLOF destroyed the nearly complete Namche Hydropower Project and the total damage was estimated at US \$1.5 million.

RM 16.4: Measures to minimise GLOF risk

Early recognition of risk

The most effective way to minimise the risk of a GLOF hazard is to be aware of the risk early so that appropriate measures can be taken in a timely and cost-effective manner.

The first step is to prepare an inventory of the glaciers and glacial lakes in the region. While preparing the inventory of glacial lakes, parameters that can be derived remotely can be entered as attributes. Then the GIS software can be programmed to screen for potentially dangerous lakes in the area of interest.

RGSL (2003) has suggested criteria for defining the GLOF hazard of glacial lakes (Table 12), and a hazard rating based on an empirical score (Table 13). A glacial lake scoring higher than 100 is potentially dangerous and an outburst can occur at any time. Glacial lakes should be monitored regularly to refine and update the status of the criteria which is listed below.

Table 12: Empirical scoring system for moraine-dammed glacial lake outburst hazard (RGSL 2003)

Criteria affecting hazard/score	0	2	10	50
Volume of lake	N/A	Low	Moderate	Large
Calving risk from ice cliff	N/A	Low	Moderate	Large
Ice/rock avalanche risk	N/A	Low	Moderate	Large
Lake level relative to freeboard	N/A	Low	Moderate	Full
Seepage evident through dam	None	Minimal	Moderate	Large
Ice-cored moraine dam with/without thermokarst features	None	Minimal	Partial	>Moderate
Compound risk present	None	Slight	Moderate	Large
Supra/englacial drainage	None	Low	Moderate	Large

Source: Shrestha (2008)

Table 13: Hazard rating on the basis of the empirical scoring system (RGSL 2003)

0	50	100	125	150+
Zero	Minimal	Moderate	High	Very High
An outburst can occur any time				

Source: Shrestha (2008)

Volume of lake. The volume of the lake can be established by bathymetric surveying for which there are two common methods. The first is to measure the depth directly when the lake is frozen. A grid of measurement points is pre-determined and depth sounding measurements

are made through holes bored through the ice layer at these points. The measurement points are interpolated to get the total volume of the lake. Another method which is recently gaining in popularity uses echo-sounders. This method can give a relatively dense measurement in a short time. The volume thus derived can be related to the surface area of the lake and after a number of measurements the relationship of volume to area can be established.

Calving risk from ice cliffs. The status of the terminus of the parent glacier should be routinely monitored in the field. The geometry and size of the terminus can give useful information as to whether it will imminently give rise to large displacement waves. High overhanging ice-cliffs can calve, potentially giving rise to large displacement waves. A debris or ice apron in front of the ice-cliff reduces the chances that it will generate a large displacement, even when ice calving occurs. Often ice termini have a series of crevasses. The terminus and crevasses can be monitored by time lapse photography. High-resolution satellite imagery can provide some information on the crevasses, and field surveys can provide information on the height of the ice cliff.

Ice/rock avalanche risk. Ice avalanches from hanging glaciers and rock avalanches from weathered slopes can cascade into lakes where they can cause large displacement waves capable of overtopping moraine dams causing dam failure. Ice and rock avalanche areas have to be monitored regularly for early detection of possible avalanches. This can be done through a combination of visual inspection on the ground and high-resolution satellite imagery. The dynamics of the lake water level also have to be observed continuously. This can be done by establishing a lake water level measuring station. The water level data from the station can be monitored regularly by a gauge reader, or it can be read automatically using a level pressure sensor and data logger. The water level observations can be supplemented by discharge measurements, which give important additional information on the outflow from the lake.

Lake level relative to freeboard. High water level and low freeboard means that even a relatively small displacement wave can overtop the moraine dam. The dynamics of the lake water level have to be observed continually. This can be done by establishing a lake water level measuring station. The station can have a simple level gauge monitored regularly by a gauge reader, or an automatic recorder with a water level pressure sensor and data logger. The water level observation can be supplemented by discharge measurements, which will give important information on the outflow of the lake.

Seepage evident through dam. Seepage through a moraine dam may indicate that piping is taking place inside the dam; this is serious since piping is a precursor to dam failure. Seepage can also be due to rapid melting of dead ice inside the moraine dam; this is also serious since it can lead to the formation of voids inside the dam which can cause the dam to collapse. The height of the seepage outlet and seasonal fluctuations in the quantity of seepage need to be monitored. Seepage due to the infiltration of precipitation is seasonal and does not pose a serious threat to the integrity of the dam.

Ice-cored moraine dam with or without thermokarst features. Thermokarsts are voids in the moraine dam caused by rapid melting of buried ice blocks. Thermokarsts reduce the structural stability of the moraine dam and make it more vulnerable to the hydrostatic pressure of the lake water. Slumping and subsidence due to the collapse of thermokarst may cause overtopping of a moraine dam and lead to its collapse. Features on the moraine such as slumping and subsidence have to be monitored regularly. Monitoring can be accomplished visually or by conducting a detailed topographic survey of the concerned area. Specialised techniques such as ground penetrating radar surveys or electro-resistivity surveys give a three-dimensional map of the buried ice.

Compound risk present. This criterion is subjective and is based on visual observations. The risk is based on the behaviour and characteristics of the end and lateral moraines and the lake surroundings. Assessment of risk involves consideration of deepening and enlargement of ponds on the moraines, presence of ponds at higher altitude above the lake, shifting and enlargement of outlet channels, etc.

Supra or englacial drainage. Parent glaciers generally contain several supra-glacial lakes and englacial channels. Occasionally these ponds drain through englacial channels into the glacial lake. Similarly, lakes at higher altitude can drain into the glacial lake. If the volume of the water released is significant, it might cause overtopping of the moraine dam. Supra-glacial ponds and high altitude lakes need to be monitored regularly. Satellite images can provide multi-temporal information on the development of supra-glacial ponds and high altitude lakes in the surrounding areas.

Estimation of peak outflow discharge

Sophisticated computer models can estimate the peak discharge of a GLOF. Due to limited resources and expertise, it is not always possible to undertake a detailed modelling exercise. Simple methods can also provide reasonably good estimates of the outburst magnitude.

Costa and Schuster (1988) suggest the following equation for predicting peak outflow discharge from a GLOF:

$$Q = 0.00013(P_e)^{0.60}$$

where Q is peak discharge in m^3/sec , and P_e is potential energy in joules.

P_e is the energy of the lake water behind the dam prior to failure and can be calculated using the equation:

$$P_e = H_d \times V \times \gamma$$

Popov (1991) suggests the following equation be used to predict flash flood peak discharge due to an outburst:

$$Q = 0.0048V^{0.896}$$

The peak discharge depends on the volume of the glacial lake (V). The lake volume is generally not available unless a detailed bathymetric survey has been previously conducted. The surface area of the lake, however, can be easily derived from maps and satellite imagery. The volume can then be calculated using the following formula suggested by Huggel et al. (2002):

$$V = 0.104A^{1.42}$$

The peak outburst depends on the nature of the outburst, i.e., the duration of the outburst, the nature of the outburst hydrograph, and the size and geometry of the dam breach. A simple approach is to assume a triangular breach hydrograph and to assume that the duration of the outburst is 1,000 seconds. Huggel et al. (2002) suggest that most outbursts last between 1,000 and 2,000 seconds, and that the peak discharge can be estimated as:

$$Q = \frac{2V}{t}$$

Estimation of the area at risk by a GLOF event

The hazard assessment should include a rough estimate of the area that can potentially be affected by a lake outburst. A worst-case scenario is generally assumed for delineating the area that could be affected. The runout (travel) distance of an outburst is related to the amount of debris that is mobilised. Outburst floods with a higher content of solid material form debris flows and stop abruptly, whereas GLOFs, that consist predominantly of water attenuate, more gradually. For a rough estimate of the maximum area that can be affected, the peak discharge is used to estimate the overall slope of the outburst flood (the average slope between the starting and the end points of an outburst event).

GLOF risk mapping

GLOF risk mapping is an important tool to help predict the area likely to be impacted by a GLOF, to estimate the vulnerability of those areas, and to help in the planning mitigation measures. Detailed descriptions of GLOF risk mapping can be found in Shrestha et al. (2006) and Bajracharya et al. (2007a, 2007b). The process involves estimating the discharge hydrograph at the outlet (breach). This can be done using dam break models or by simple calculations assuming the breach size and the lake drawdown rate. The hydrograph is routed through the river reach to find the peak discharge and flood height at the locations of interest. An inundation map is prepared by overlaying the flood height over the terrain map.



Briefing for the Field Trip

Time: 30 minutes

Objectives

To share information about the upcoming field trip, including

- ▶ the objectives of the trip
- ▶ the list of planned activities
- ▶ practical information
- ▶ tips on required preparation

Activities

Take some time to properly orient the participants on the upcoming field trip. Make sure to mention the following.

- Discuss the objectives of the field trip.
- Point out each field visit site on a map, and explain how far it is and the route that will be taken.
- Describe the special or unique features of each field site and relate these feature to the success or failure of past flash flood risk management activities.
- Describe the activities that the participants are going to observe, and what they are going to do in the field.
- Go over the logistics of the field trip: time of departure, time of arrival at different places, length of stay, and what is expected at each site.
- Clearly mention any necessary preparation that needs to be made beforehand; list practical items that may be required: comfortable clothing, shoes for trekking, sun glasses, sun block, insect repellent, and other items as needed.

Suggestions for the facilitator

Preparation

A little prior preparation can help to make the field trip a success. Note the following:

- If at all possible, visit the sites of the field trip beforehand.
- Select places where different flood risk management measures have both been successful and unsuccessful.
- Once you have decided on a location, make sure to advise the community in-charge and others that you will be working with that you will be coming and when.
- Prepare a short description of the places to be visited, the events or activities to take place there, and any other necessary information such as the distance and the time to get there.
- Give a short presentation in which you describe the different places that the group will be visiting and point out what flood-related points of interest need to observe in each place.
- Distribute a copy of the short description of the locations to be visited to each participant after the briefing on the field trip.

(continues)

Suggestions for the facilitator (continued)

Logistics

The following necessary items for the field trip should be provided by the facilitator:

- Travel arrangement plans
- Accommodation plans
- Maps printed in large size (e.g., Google maps) and/or satellite images
- Drawing paper (A1 size) and camera
- Drawing materials such as marker pens, pencils, tape, and erasers

Remember to advise the local facilitator, if one is needed.