Chapter 9
Glacial Lake Outburst Floods and Damage in the Country

9.1 Introduction

Periodic or occasional release of large amounts of stored water in a catastrophic outburst flood is widely referred to as a **jokulhlaup** (Iceland), **a debacle** (French), an **aluvión** (South America), or a **Glacial Lake Outburst Flood** (GLOF) (Himalayas). A jokulhlaup is an outburst which may be associated with volcanic activity, a debacle is an outburst but from a proglacial lake, an **aluvión** is a catastrophic flood of liquid mud, irrespective of its cause, generally transporting large boulders, and a GLOF is a catastrophic discharge of water under pressure from a glacier. GLOF events are severe geomorphological hazards and their floodwaters can wreak havoc on all human structures located on their path. Much of the damage created during GLOF events is associated with the large amounts of debris that accompany the floodwaters. Damage to settlements and farmland can take place at very great distances from the outburst source, for example in Pakistan, damage occurred 1,300 km from the outburst source (Water and Energy Commission Secretariat (WECS) 1987b).

9.2 Causes of Lake Creation

Global warming

There is concern that human activities may change the climate of the globe. Past and continuing emissions of carbon dioxide (CO_2) and other gases will cause the temperature of the Earth's surface to increase—this is popularly termed 'global warming' or the 'greenhouse effect'. The 'greenhouse effect' gives an extra temperature rise.

Glacier retreat

An important factor in the formation of glacial lakes is the rising global temperature, which causes glaciers to retreat in many mountain regions.

During the so-called 'Little Ice Age' (AD 1550–1850), many glaciers were longer than today. Moraines formed in front of the glaciers at that time nowadays block the lakes. Glaciation and interglaciation are

natural processes that have occurred several times during the last 10 000 years and before.
As a general rule, it can be said that glaciers in the Himalayas have retreated about 1 km since the Little Ice Age, a situation that provides a large space for retaining melt water, leading to the formation of moraine-dammed lakes (LIGG/WECS/NEA 1988).

Röthlisberger and Geyh (1985) conclude in their study on 'glacier variations in Himalaya and Karakorum' that a rapid retreat of nearly all glaciers with small oscillation was found in the period from 1860/1900–1980.

Causes of glacial lake water level rise

The rise in water level in glacial lakes dammed by moraines creates a situation that endangers the lake to reach breaching point. The causes of water level rise in glacial lakes are given below.

- Rapid change in climatic conditions that increase solar radiation causing rapid melting of glacier ice and snow with or without the retreat of the glacier.
- Intensive precipitation events
- Decrease in sufficient seepage across the moraine to balance the inflow because of sedimentation of silt from the glacier runoff, enhanced by the dust flow into the lake.
- Blocking of ice conduits by sedimentation or by enhanced plastic ice flow in the case of a glacial advance.
- Thick layer of glacial ice (dead ice) weighed down by sediment below the lake bottom which stops subsurface infiltration or seepage from the lake bottom.
- Shrinking of the glacier tongue higher up, causing melt water that previously left the glacier somewhere outside the moraine, where it may have continued underground through talus, not to follow the path of the glacier.
- Blocking of an outlet by an advancing tributary glacier.
- Landslide at the inner part of the moraine wall, or from slopes above the lake level.
- Melting of ice from an ice-core moraine wall.
- Melting of ice due to subterranean thermal activities (volcanogenic, tectonic).
- Inter-basin sub-surface flow of water from one lake to another due to height difference and availability of flow path.

9.3 Bursting Mechanisms

Different triggering mechanisms of GLOF events depend on the nature of the damming materials, the position of the lake, the volume of the water, the nature and position of the associated mother glacier, physical and topographical conditions, and other physical conditions of the surroundings.

Mechanism of ice core-dammed lake failure

Ice-core dammed (glacier-dammed) lakes drain mainly in two ways.

- through or underneath the ice
- over the ice

Initiation of opening within or under the ice dam (glacier) occurs in six ways.

- Flotation of the ice dam (a lake can only be drained sub-glacially if it can lift the damming ice barrier sufficiently for the water to find its way underneath).
- Pressure deformation (plastic yielding of the ice dam due to a hydrostatic pressure difference between the lake water and the adjacent less dense ice of the dam; outward progression of cracks or crevasses under shear stress due to a combination of glacier flow and high hydrostatic pressure).
- Melting of a tunnel through or under the ice
- Drainage associated with tectonic activity
- Water overflowing the ice dam generally along the lower margin
- Sub-glacial melting by volcanic heat

The bursting mechanism for ice core-dammed lakes can be highly complex and involve most or some of the above-stated hypothesis. Marcus (1960) considered ice core-dammed bursting as a set of interdependent processes rather than one hypothesis.

A landslide adjacent to the lake and subsequent partial abrasion on the ice can cause the draining of ice core-moraine-dammed lakes by overtopping as the water flows over, the glacier retreats, and the lake fills rapidly.

Mechanism of moraine-dammed lake failure

Moraine-dammed lakes are generally drained by rapid incision of the sediment barrier by outpouring waters. Once incision begins, the hustling water flowing through the outlet can accelerate erosion and enlargement of the outlet, setting off a catastrophic positive feedback process resulting in the rapid release of huge amounts of sediment-laden water. Peak discharge from breached moraine-damaged lakes just downstream from the moraine can be estimated from an empirical relationship developed by Costa (1985) (Figure 9.1) The onset of rapid incision of the barrier can be triggered by waves generated by glacier calving or ice avalanching, or by an increase in water level associated with glacial advance.

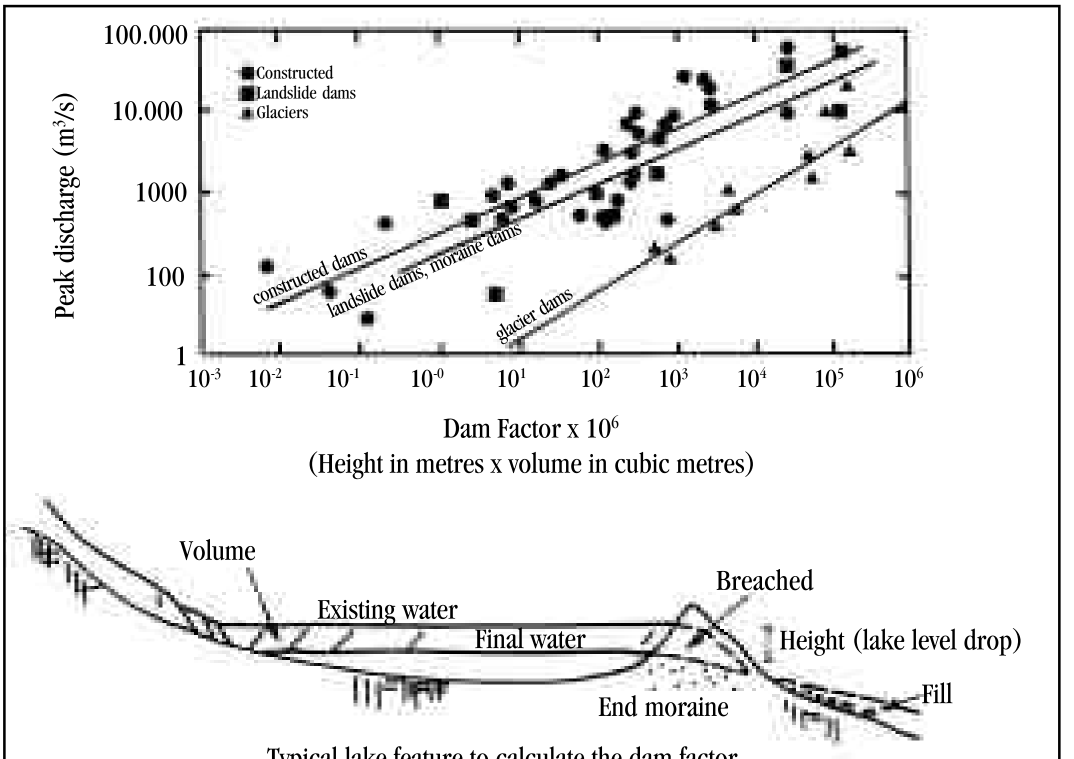

Figure 9.1: Peak discharge* from breached moraine-dammed lakes can be estimated from an empirical relationship developed by Costa (1985)

Dam failure can occur for the following reasons:

- melting ice core within the moraine dam,
- rock and/or ice avalanche into a dammed lake,
- settlement and/or piping within the moraine dam,
- sub-glacial drainage, and
- engineering works.

Melting ice-core

The impervious ice core within a moraine dam melts, lowering the effective height of the dam, thus allowing lake water to drain over the residual ice core. The discharge increases as the ice core melts, and as greater amounts of water filter through the moraine, carrying fine materials. The resulting regressive erosion of the moraine dam ultimately leads to its failure.

Overtopping by displacement waves

Lake water is displaced by the sudden influx of rock and/or ice avalanche debris. The resultant waves overtop the freeboard of the dam causing regressive and eventual failure.

Settlement and/or piping

Earthquake shocks can cause settlement of the moraine. This reduces the dam freeboard to a point that the lake water drains over the moraine and causes regressive erosion and eventual failure.

Sub-glacial drainage

A receding glacier with a terminus grounded within a proglacial lake can have its volume reduced without its ice front receding up-valley. When the volume of melt water within the lake increases to a point that the formerly grounded glacier floats, an instantaneous sub-glacial drainage occurs. Such drainage can destroy any moraine dam, allowing the lake to discharge until the glacier loses its buoyancy and grounds again.

Engineering works

Artificial measures taken to lower the water levels or to change dam structures may trigger catastrophic discharge events. For example, in Peru in 1953, during the artificial lowering of the water level, an earth slide caused 12m high displacement waves, which poured into a trench, excavated as part of the engineering works and almost led to the total failure of the moraine dam.

9.4 Surge Propagation

As GLOFs pose severe threats to humans, man-made structures, agricultural fields, and natural vegetation it is important to make accurate estimates of the likely magnitude of future floods. Several methods have been devised to predict peak discharges, which are the most erosive and destructive phases of floods. The surge propagation hydrograph depends upon the type of GLOF event, i.e. from moraine-dammed lake or from ice-dammed lake (Figure 9.2). The duration of a surge wave from an ice-dammed lake may last for days to even weeks, while from a moraine-dammed lake the duration is shorter, minutes to hours. The peak discharge from the moraine-dammed lake is usually higher than from ice-dammed lakes.

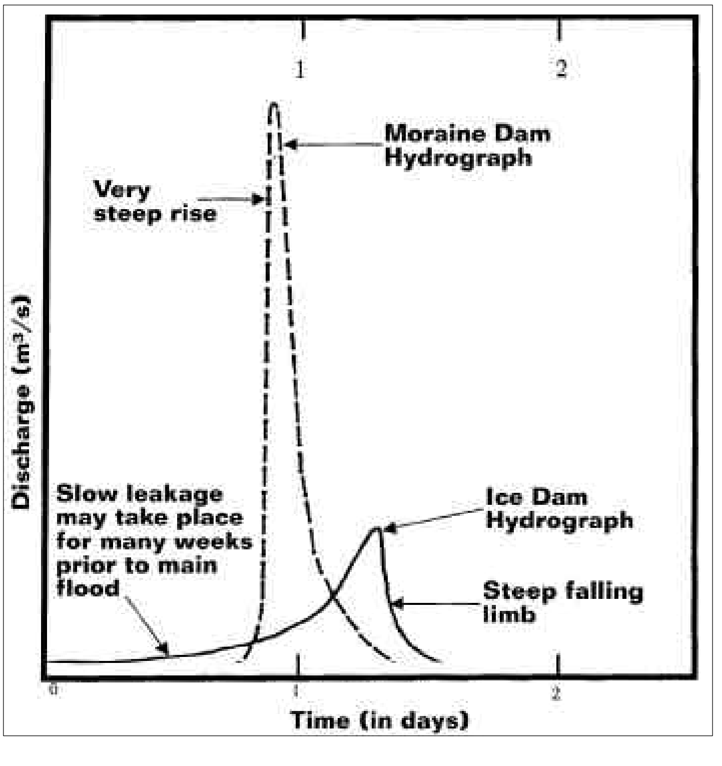

Figure 9.2: Difference in release hydrograph between moraine- and ice-dammed lakes

The following methods have been proposed for estimation of peak discharges.

1) Clague and Mathews formula

Clague and Mathews (1973) were the first to show the relationship between the volume of water released from ice-dammed lakes and peak flood discharges.

$Q_{max} = 75(V_0*10^{-6})^{0.67}$

where
Q_{max} = peak flood discharge ($m^3 s^{-1}$)

V_0 = total volume of water drained out from lake (m^3)

The above relationship was later modified by Costa (1988) as the peak discharge yielded from the equation was higher than that measured for Flood Lake in British Columbia that occurred in August 1979:

$Q_{max} = 113(V_0*10^{-6})^{0.64}$

Later Desloges et al. (1989) proposed:

$Q_{max}=179(V_0*10^{-6})^{0.64}$

This method of discharge prediction is not based on any physical mechanism, but seems to give reasonable results.

2) Mean versus maximum discharge method

If the volume of water released by a flood and the flood duration are known, the mean and peak discharges can be calculated. Generally the flood duration will not be known in advance. Hence, this method cannot be used to determine the magnitude of future floods. Observations of several outburst floods in North America, Iceland, and Scandinavia have shown that peak discharges are between two to six times higher than the mean discharge for the whole event.

3) Slope area method

This method is based on measured physical parameters such as dimensions and slope of channel during peak flood conditions from direct observations or geomorphological evidence.

$Q_{max} = vA$

The peak velocity is calculated by the Gauckler–Manning formula (Williams 1988)

$v = r^{0.67} S^{0.50}/n$

where
v = peak velocity
S = bed slope for a 100m channel reach
n = Manning's roughness coefficient
r = hydraulic radius of the channel

$r = A/p$

where
A = cross-sectional area of the channel
p = perimeter of the channel under water

For sediment floored channels, bed roughness is mainly a function of bed material, particle size, and bed form or shape and can be estimated from:

$$n = 0.038D^{0.167}$$

where
D = average intermediate axis of the largest particles on the channel floor.

Desloges et al. (1989) compared the results from all the three methods for a jokulhlaup from the ice-dammed Ape Lake, British Columbia. All the methods gave comparable results.

- The Clague and Mathews method gave a calculated peak discharge of 1680 ± 380 $m^3 s^{-1}$.
- The mean versus maximum discharge method gave 1080–3240 $m^3 s^{-1}$.
- The slope area method gave 1,534 and 1,155 $m^3 s^{-1}$ at a distance of 1 and 12 km from the outlet respectively.

These general relationships are useful for determining the order of magnitude of initial release that may propagate down the system. However, to predict the magnitude of future floods, the first method should be applied, because volume of lake water can be estimated in advance.

Attenuation of a peak discharge of 15,000–20,000m s^{-1} has been reported for the Poiqu River in Tibet (Sun Koshi in Nepal) within a distance of 50 km (XuDaoming 1985).

9.5 Sediment Processes During a Glacial Lake Outburst Flood

During a GLOF, the flow velocity and discharge are exceptionally high and it becomes practically impossible to carry out any measurement. Field observations after a GLOF event have shown a much higher sediment concentration of rivers than before the GLOF event (Electrowatt Engineering Service Ltd 1982; WECS 1995a). WECS (1995a) calculated the volume of sediment as $22.5*10^4$ m^3 after the Chubung GLOF of Nepal in 1991. A high concentration of 350,000 mg^{-1} during a GLOF in the Indus River at Darband in 1962 is reported by Hewitt (1985).

Figure 9.3 gives a hypothetical GLOF illustration showing discharge and variation in sediment concentration (WECS 1987a). The total sediment load is generally accepted as the wash load, which moves through a river system and finally deposits in deltas. In Bhutan, no measurements have been undertaken on total sediment during GLOF events, however, rough estimates of total load during torrents can be made assuming a high sediment concentrations (WECS 1987b). During a GLOF event, stones the size of small houses can be easily moved (WECS 1987b). The relationship between flow velocity and particle diameter can also be used to calculate the size of boulders that can be moved during such events.

9.6 Socioeconomic Effects of Glacial Lake Outburst Floods

The impacts of GLOF events downstream are extensive in terms of damage to roads, bridges, trekking trails, villages, agricultural land, natural vegetation, as well as the loss of human lives and infrastructure. The sociological impacts can be direct when human lives are lost, or indirect when the agricultural lands are converted to debris filled lands and the village has to be shifted. The records of past GLOF events in the Himalayas show that once every three to ten years, a GLOF has occurred with varying degrees of socioeconomic impact. Therefore, the most appropriate mitigating methods must be applied after conducting a proper hazard assessment study based on possible economic loss evaluation.

Glacial lakes were formed by the retreat of glaciers. Most of these lakes are dammed by moraines. These moraine dams if unstable could fail and give rise to GLOF events, having a devastating effect downstream. During recent decades there has been a rapid retreat of glaciers all over the world. It has been observed that the glaciers in Bhutan are retreating at a rate of about 30–40m $year^{-1}$ (Section 7.3), new lakes are being formed, and the size of existing lakes attached to glaciers is increasing.

There have been several cases of GLOFs in Bhutan, but only one has been recorded in detail. Records for the other cases are based on verbal information gathered from elderly people many years after the flood took place.

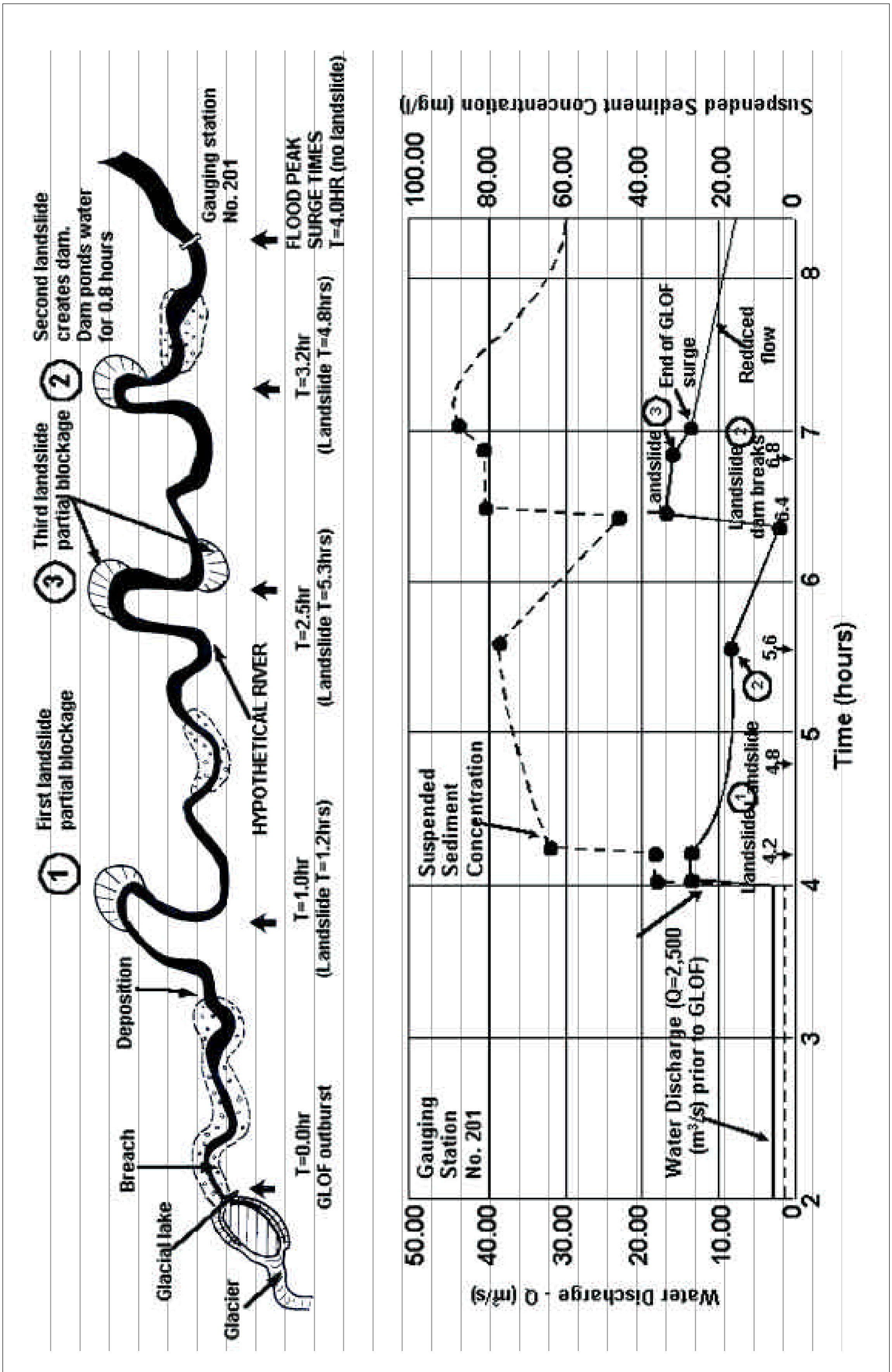

Figure 9.3: Hypothetical GLOF illustration showing discharge and variation in sediment concentration (WECS 1987a)

9.7 Brief Review of Glacial Lake Outburst Flood Events and Damage Caused

The 1957 GLOF

The 1957 GLOF affected the Punakha–Wangdue Valley, which destroyed part of Punakha Dzong. Gansser (1970) attributed this flood to the outburst from Tarina Tsho, western Lunana.

1960 GLOF

This flood also destroyed part of Punakha Dzong due to the bursting of some lakes in eastern Lunana. It is said to have lasted for five days and there are no written records on this flood.

1994 GLOF

The most recent flood occurred on 7 October 1994 due to a partial burst from Lugge Tsho located in eastern Lunana, which caused loss of life and property along the Punakha–Wangdue Valley and damaged part of Dzongchung of Punakha Dzong (Watanabe and Rothacher 1996).

From the survey conducted on 20–23 October 1994, a total of 91 households was affected by the flood in the Lunana region (Geological Survey of Bhutan 1994). Twelve houses were damaged, 5 water mills were totally washed away, and 816 acres of dry land were damaged (and some was washed away and others were partially covered by silt and sand). There was major damage to pasture land which affected the people in the region because they are dependent on their yaks for their livelihood. A total of 965 acres of pasture land was washed away or covered by sand and silt. Livestock (16 yaks) were carried away by the flood. Food grains lost totalled about 6 tonnes, which can be considered as a huge amount for the people living in these regions. Some of the field photographs taken after the GLOF events are shown in Plates 9.1– 9.17.

Plate 9.1: Lugge Tsho Glacial Lake two weeks after the GLOF of 7 October 1994
(Yeshi Dorji)

Plate 9.2: Lugge Tsho Glacial Lake in contact with the tongue of Lugge Glacier. The photograph was taken two weeks after the GLOF of 7 October 1994. The tonal difference indicates the fresh surfaces on the slope after the first (7 October) and the second (17 October) events.
(Yeshi Dorji)

Plate 9.3: The occurrence of dead ice within the moraine of Lugge Tsho
(D.R. Gurung 1999)

Plate 9.4: The end moraine of Lugge Glacier slumps and fine sand indicating that it is underlain by dead ice.
(D.R. Gurung 1999)

Plate 9.5: The U-shaped valley looking downstream and Tenchey, Dota, and Tshoju Villages The sand deposited by the flood of 1994 is still seen in between Dota and Tshoju where only a little grass has grown.
(Yeshi Dorji)

Plate 9.6: Thanza Village and erosion downstream caused by the flood of 1994.
(Tshering Tashi, NEC)

Plate 9.7: Tshoju Village is just behind, the photograph was taken facing southeast. It shows the lacustrine deposit and sand deposited by the flood of 1994.
(Yeshi Dorji)

Plate 9.8: The debris brought down by the flood and deposited in the riverbed below Lhedi Village which destroyed the pasture land of Lunaps; a few trees were seen in the riverbed.
(Yeshi Dorji 1994)

Plate 9.9: Damage caused by the flood of 1994 to one of the oldest and most sacred temples in Punankha.
(Helvetas)

Plate 9.10: Erosion caused by the flood on the right bank of the Mochu above Punakha Dzong.
(Helvetas 1994)

Plate 9.11: A log being brought down by the flood of 1994 and the scene below Wangdue Phodrang Bridge.
(Helvetas 1994)

Plate 9.12: Punakha Dzong three days after the disaster of 1994. Also shown is the confluence of the Phochu and the Mochu below the Dzong and scars of the back flow water after it had joined the Mochu and dammed the flow above the Dzong.
(Phuntso Norbu 1994)

Plate 9.13: Thorthormi Glacier, Lugge Glacier, Lugge Hanging Glacier just above the right lateral moraine of Lugge and Druckchung Glaciers, Lugge Tsho, and Thorthormi Tsho. Also showing is the trench formed by water flowing from Lugge Hanging Glacier into Thorthormi Lake. The breach point of Lugge is also seen on the left lateral moraine of Lugge.
(Phuntso Norbu October 1994)

Plate 9.14: Supraglacial lakes being formed in Thorthormi Lake and erosion caused by the 1994 flood on the left lateral moraine.
(Phuntso Norbu 1994)

Plate 9.15: Raphstreng Lake with a frozen surface. Also shows first subsidiary lake. This was taken from a chopper before the mitigation measures for Raphstreng were undertaken.
(Yeshi Dorji March 1995)

Plate 9.16: Raphstreng Lake, right lateral moraine, glacial snout, the new excavated outlet, and erosion caused by the flood of 1994 along the main river bed.
(Phuntsho Norbu 1999)

Plate 9.17: Gangri Tsho and deep V-shaped cut at the outlet indicating that the lake had breached earlier.
(Karma 1998)