Chapter 3: Landslide Dam Lakes and Glacial Lakes

The triggers of flash floods in the Hindu Kush Himalayas include catastrophic failure of landslide dams that retain landslide dam lakes, and of moraine or ice dams that retain glacial lakes. Flash flooding caused by landslide dam failure is a significant hazard in the region and is particularly common in the high rugged mountain areas of China, India, Nepal, and Pakistan (Zhu and Li 2000). The previous chapter looked at ways of preventing the formation of landslide dams by reducing the prevalence of landslides and debris flows. Another important approach to mitigating flash floods is to reduce the likelihood of dam failure, and/or to put in place warning and avoidance mechanisms to reduce the risk in the case of failure. In order to design appropriate measures, it is important first to understand the formation process, failure mechanism, and risk mitigation techniques for both types of lake.

Landslide Dam Lakes

Formation

Landslide dam lakes can be created as a result of a broad range of mass movements in different geomorphological settings. Dams form most frequently as a result of rock and earth slumps and slides, debris and mudflows, and rock and debris avalanches in areas where narrow river valleys are bordered by steep and rugged mountain slopes (Zhu and Li 2000). A lake then forms behind the dam as a result of the continuous inflow of water from the river (Figure 4). Only a small amount of material is needed to form a dam in a narrow valley, and even a small mass movement can be sufficient. This type of setting is common in geologically active areas such as the Hindu Kush Himalayas where earthquakes occur and slopes are steep. These areas contain abundant landslide source materials such as sheared and fractured bedrock materials. Large landslide dams are often caused by complex landslides that start as slumps and transform into rock or debris flows or avalanches. The lake formed along the Hunza River by a massive landslide in Attabad, Pakistan, in January 2010 is one of the more striking recent examples of a landslide dam lake in the region.

Landslide dam outburst floods (LDOF) and modes of dam failure

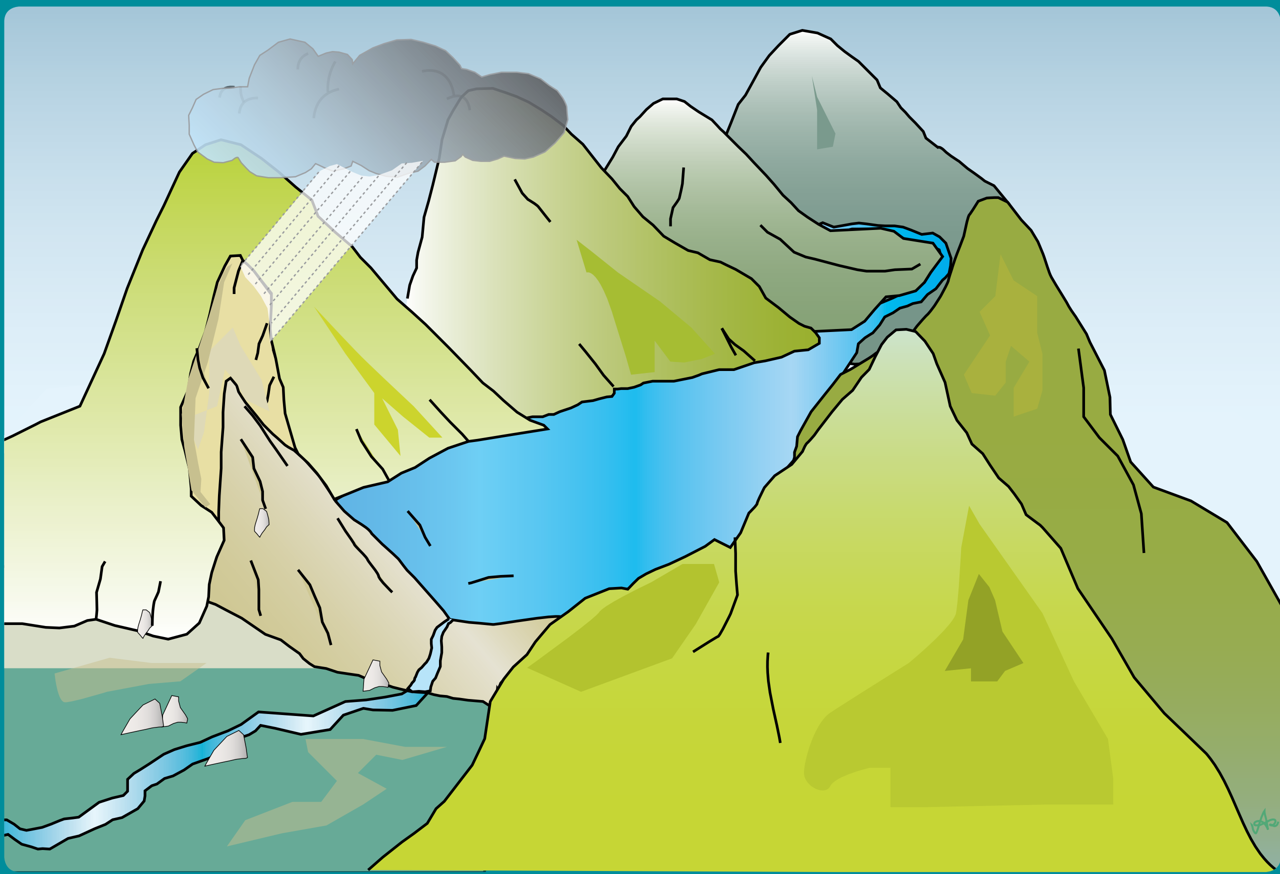
A dam failure is a complex hydrologic, hydraulic, and geological phenomenon which is controlled primarily by the failure mechanism and characteristics and properties of the dam (Uhlir 1998). In many cases, the breach occurs as a result of fluvial erosion of the debris or landslide material, with erosion starting at the toe of the dam and moving progressively upstream to the lake. Piping (the presence of sloping tube-like features in the soil often marked by seepage) can also lead to internal structural failure of the dam. However, the most common cause of failure is overtopping by the lake water. Sometimes, piping and undermining of the dam can cause partial collapse followed by overtopping and breaching. A landslide dam with steep upstream and downstream faces and high pore-water pressure is also susceptible to slope failure. If the dam has a narrow cross-section or the slope failure is progressive, the crest of the dam can fail, again leading to overtopping and breaching. Sometimes, lateral erosion of the dam by the stream or river can cause failure.

LDOF risk mitigation measures

Both structural and non-structural measures can be used to reduce the risk associated with landslide dam failure.

Non-structural measures (discussed in Module 2) include estimation of downstream flooding, estimation of past floods, early warning systems, and so on.

Figure 4: Formation of a landslide dam lake



One of the most efficient structural measures is to lower the water level of the lake. Construction of spillways is the simplest approach. Pipes, tunnels, outlets, and diversions can also be used to control discharge (Zhu and Li 2000) and help drain the water. For example, Tangjianshan Lake, formed as a result of a landslide precipitated by the 12 May 2008 Wenchuan earthquake in China, was successfully drained by construction of a sluiceway 13 m wide, 10 m deep, and 475 m long (Zhuang 2010). In some cases, extensive blasting measures have been used to excavate new river channels through landslide dams (Zhu and Li 2000). However, it is not always possible to construct a drainage path, the unstable nature of the dam material can lead to collapse of the channel, and, in the worst cases, the channel construction itself can destabilize the dam and cause it to breach catastrophically.

Glacial Lakes

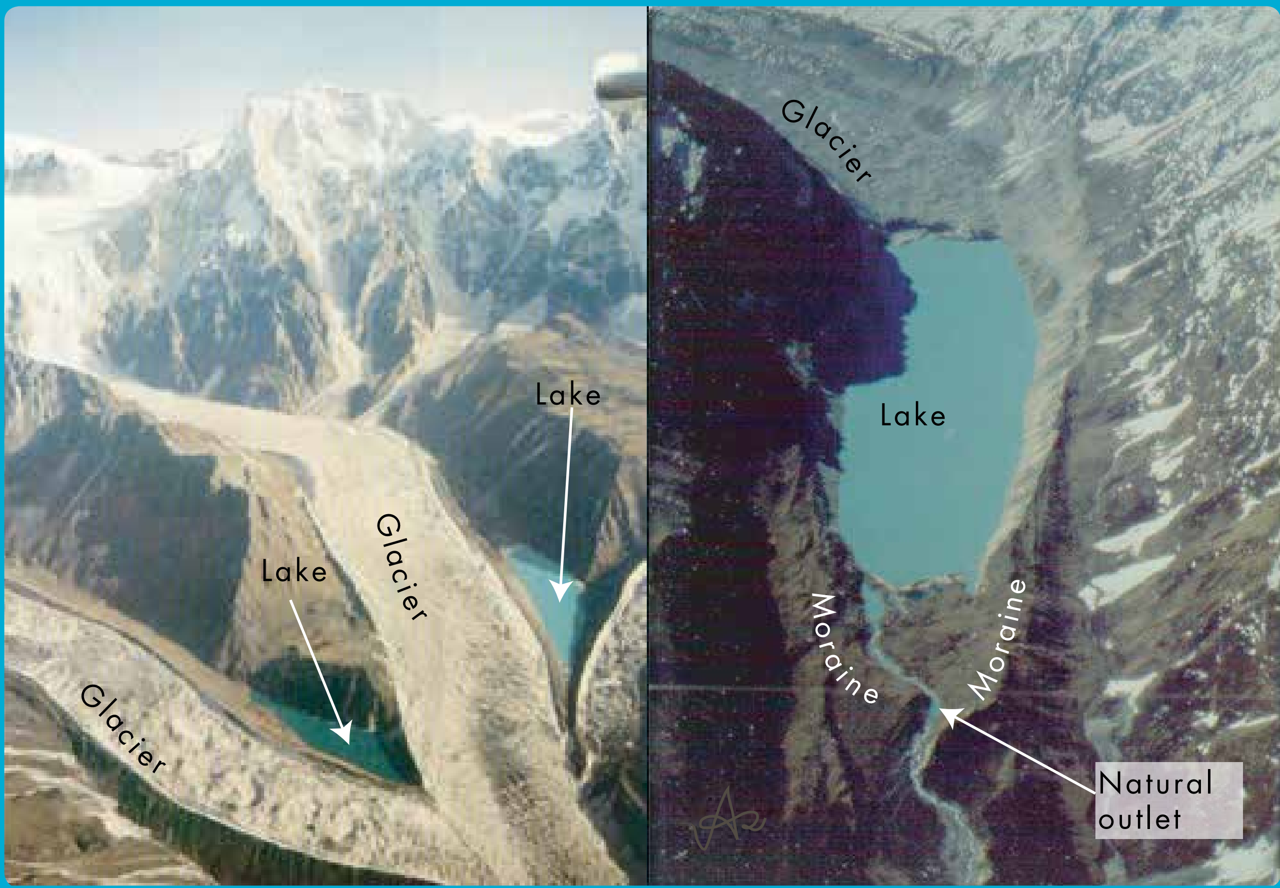
Formation

The ways in which glacial lakes can form and their distribution in the Hindu Kush Himalayan region are described in some detail in Ives et al. (2010) and ICIMOD (2011). They can be divided into two broad categories on the basis of the damming materials: moraine-dammed glacial lakes and ice-dammed glacial lakes. Moraine-dammed lakes usually form between the glacier terminus and the exposed end moraine as a glacier tongue thins and retreats (Figure 5). Ice-dammed lakes can form on the surface of a glacier and between a glacier and valley wall. Lakes can also form below or within glaciers but these are difficult to identify using normal mapping approaches and in practice no mitigation measures are possible.

Glacial lake outburst floods (GLOF) and modes of dam failure

Moraine dams are composed of unconsolidated boulders, gravel, silt, and sand and are thus often weak and susceptible to collapse. As glaciers retreat, the volume (and thus weight) of the water in the lake increases,

Figure 5: Formation of glacial lakes: lateral moraine dammed lake with ice (left) and end moraine dammed lake (right)



increasing the pressure on the dam. Moraine dammed lakes generally breach as a result of overtopping or piping, or a combination of the two (Mool 1995). Overtopping can be precipitated by a fall of ice (or rock) into the lake water, or by a sudden inflow of water from an outburst of a small lake higher up.

Ice-dammed lakes drain underneath the ice. On occasion a pocket of water can burst within the ice. Water within the glacier's internal plumbing may build up pressure to such a point that the hydrostatic pressure exceeds the constraining cryostatic pressure and the water is able to rupture through the glacier ice. Internal water pockets may burst into existing sub-glacier draining, increasing the discharge to produce a characteristic flow (Sinha 1998).

In 1994, a catastrophic flood from the moraine dammed Luggye Tsho glacial lake in northern Bhutan produced a flood wave that was more than 2 m high at 200 km from the source (Richardson and Reynolds 2000).

GLOF risk mitigation measures

As with landslide dams, both structural and non-structural measures can be used to reduce the risk associated with moraine dam failure. The biggest difference is that glacial lakes can be identified and the risk assessed in a planned way, as the glaciers and moraines have a fixed position, unlike landslide dams which are unpredictable. Thus more time is available to plan and implement measures to reduce the likelihood of moraine dam failure. The approaches to and difficulties of GLOF risk assessment in the Hindu Kush Himalayan region are discussed in Ives et al. (2010).

Non-structural measures are discussed in Module 2 and Shrestha et al. (2011). They include risk assessment; planning measures that reduce exposure and vulnerability; awareness raising and flood preparedness training; and lake monitoring, early warning, and evacuation.

Structural measures aim to reduce the volume of water in the lake in order to reduce the potential peak discharge as well as the hydrostatic pressure on the dam. The four main approaches – controlled breaching of the moraine dam, construction of an outlet control structure, pumping or siphoning the water from the lake, and tunnelling under the moraine or ice dam (Ives et al. 2010; Kattelmann and Watanabe 1996) – are described briefly below. The challenge with all the approaches is that the moraine dam is inherently unstable, and disturbance of the dam during construction could itself precipitate collapse. At the same time, construction at the altitudes where glacial lakes are found is challenging, as is transportation of the appropriate equipment to these often very remote and poorly accessible sites. A high degree of technical and engineering skill is required, and investigation and planning must be meticulous. For this reason, structural mitigation is only an option for a very small number of lakes.

Blasting. If glacial lakes are at an early stage in formation and the water volume is small, it may be possible to blast the dam. However, careful precautions must be taken, in particular, total evacuation of the downstream area before blasting.

Construction of a spillway or open channel. Construction of a spillway or open channel is one of the most common techniques used to lower the water level in glacial lakes. However, the risk of rapid erosion of the spillway and uncontrolled release of water is substantial (Grabs and Hanisch 1993, cited in Kattelmann and Watanabe 1996). An artificial spillway has been used to lower the level of Tsho Rolpa glacial lake in Nepal since 2000. Precise engineering efforts are needed to implement such types of technique.

Siphoning. Siphoning out the lake water has a lower risk of inducing catastrophic failure and is more appropriate for remote areas. In theory, lake levels could be lowered by as much as five metres with a simple siphon under Himalayan conditions (Grabs and Hanisch 1993, cited in Kattelmann and Watanabe 1996). The number of siphons could be chosen to give the desired rate of lowering of the water level, taking into account the rate of inflow during the summer monsoon and melt seasons (Kattelmann and Watanabe 1996). Siphons were installed successfully in Tsho Rolpa lake in 1995, but the induced outflow never reached a level that exceeded the inflow, so ultimately the effort was unsuccessful (Box 6). However, siphoning might still offer a useful option under different conditions.

Box 6: **Siphoning out Tsho Rolpa glacial lake**

The purpose of installing siphon pipes was to test their performance in the high altitude environment with freezing conditions in winter. The test siphons worked satisfactorily with some maintenance, although the amount siphoned out was insufficient. The test showed that with sufficient funds, siphoning could be an option for lowering the water level (Rana et al. 2000).

Drilling and tunnelling. Another possibility is to drill or tunnel through the moraine dam and install a pipe to drain the water from the lake. Drilling is problematic, however, due to the inhomogeneous and poorly consolidated structure of the dam material and the risk of piping occurring along the casing installed during drilling (Grabs and Hanisch 1993). Another option for releasing lake water is to construct a tunnel into the lake from an adjacent deeper lying valley. Tunnels have been built through solid rock into glacial lakes in Norway and Switzerland (Kattelmann and Watanabe 1996), but the approach is impractical in the Himalayas with their weak geological structure and remoteness.