Chapter 3

Understanding Flash Flood Hazards

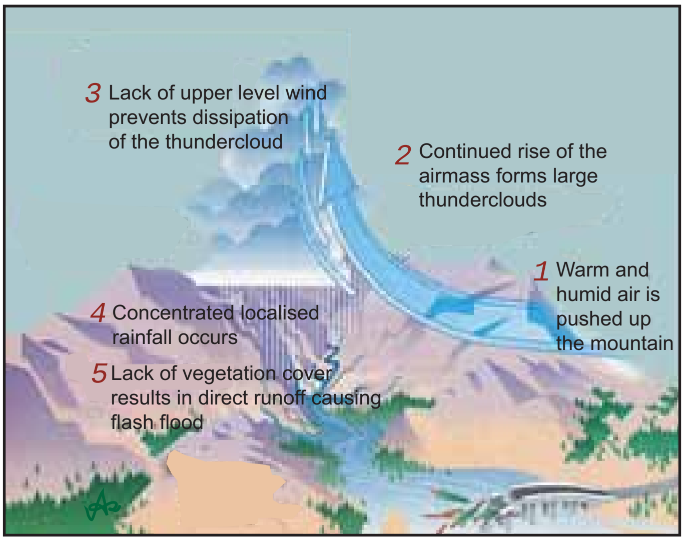
For proper flash flood management, practioners must understand the factors that cause flash floods. The main processes causing flash floods in the HKH region are intense rainfall, landslide dam outburst, and glacial lake outburst. This chapter describes the physical factors causing these and gives some examples.

3.1 Intense Rainfall Flood

Intense rainfall is the most common cause of flash floods in the HKH region. These events may last from several minutes to several days and may happen anywhere, but are more common in mountain catchments. The main meteorological phenomena causing intense rainfall are cloudbursts, a stationary monsoon trough, and monsoon depressions.

Cloudbursts

Cloudbursts are associated with the intensive heating of an airmass, its rapid rise, and the formation of thunderclouds. Interaction with local topography results in upward motion, especially where the atmospheric flow is perpendicular to topographic features. Particularly intense precipitation rates typically involve some connection to monsoon airmasses, which are typically heavily moisture laden and warm due to their tropical origin (Kelsch et al. 2001). Lack of wind aloft prevents dissipation of the thunderclouds and facilitates concentrated cloudbursts, which are often localised and limited to a small area. The cloudburst process is illustrated in Figure 8.



Source: Modified from Jarrett and Costa 2006

Figure 8: The mechanism of a cloudburst

Monsoon trough

Another type of intense rainfall is caused by the prolonged stationary position of an inter-tropical convergence zone (ITCZ), commonly called a monsoon trough, an elongated zone of low pressure system, along the mountain range. This type of meteorological phenomenon occurred in central Nepal on 19-20 July 1993, bringing record-setting rainfall to the upper region of the Mahabharat Range in the central part of Nepal (Figure 9). On 17 July the monsoon trough was not well defined. There was a large area of low pressure in western India. The low-pressure zone intensified slightly and a small cell of low pressure appeared over central Nepal, although of only low intensity (1004 hPa). On 19 July the sea level pressure over central Nepal was 1002 hPa and the monsoon trough was well established. This caused a heavy downpour over the central part of Nepal. On 20 July the monsoon trough remained in the same position but the low-pressure cell intensified to 1000 hPa. The heavy downpour continued throughout the day. On 20 July, Tistung station in central Nepal measured a record 24-hour rainfall of 540 mm, and the gauge recorded a maximum rainfall of 70 mm in one hour. The trough remained almost in the same place on 21 July, but the intensity of the low-pressure cell reduced to 1002 hPa; the rain continued but with less intensity. The situation gradually changed thereafter as the trough moved southward and the low pressure cell dissipated to a large area of 1004 hPa. This event of 1993 caused excessive flooding of the Bagmati River and its tributaries. The flood at the Bagmati Barrage site was estimated at 16,000 m^3/s (DHM/DPTC 1994). This discharge exceeded the design

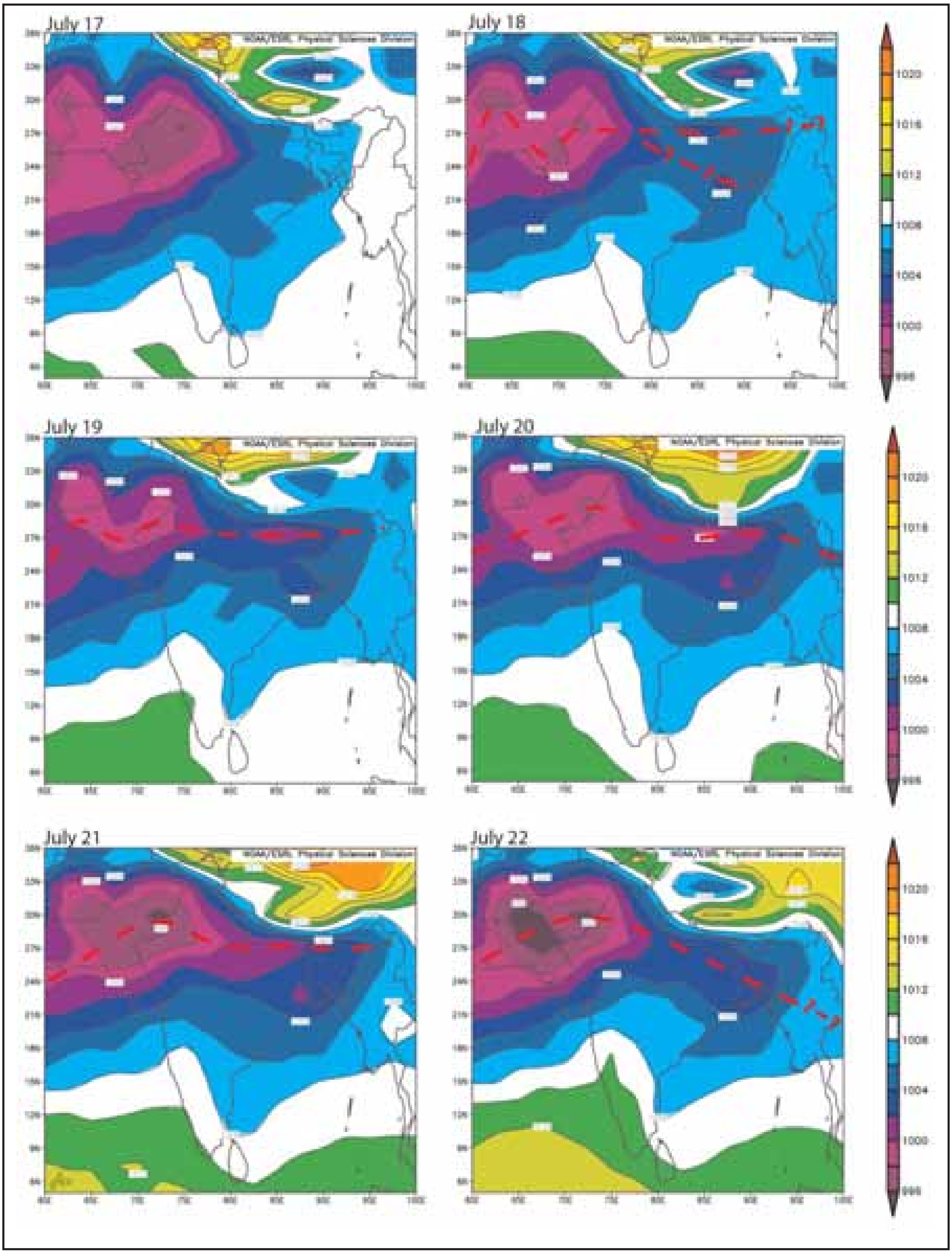
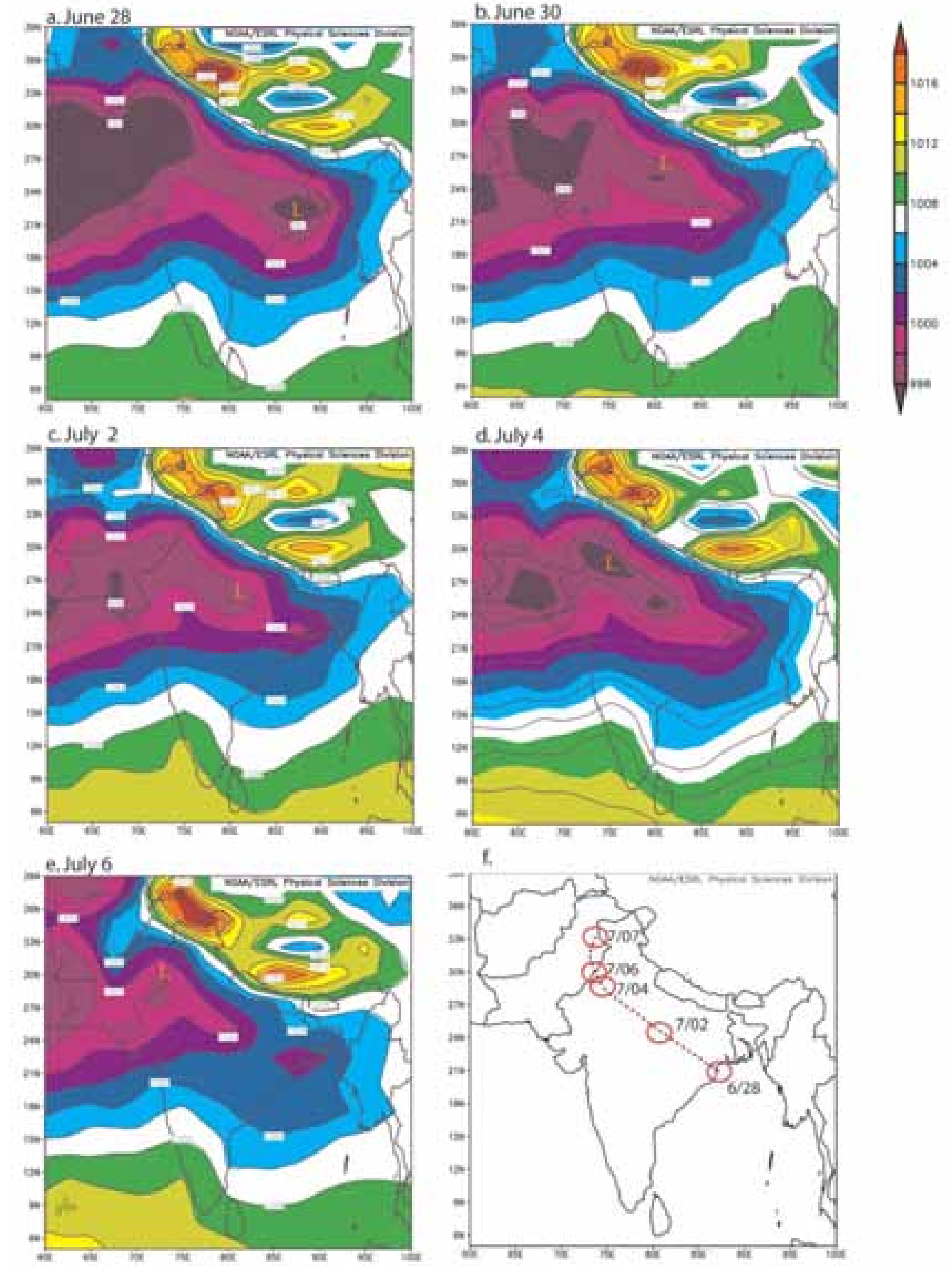


Figure 9: Position of the monsoon trough during the flash floods of 1993 in central Nepal

Data source: http://www.cdc.noaa.gov/composite/Day/ (Accessed 2 June 2007)



Data source: http://www.cdc.noaa.gov/composite/Day/ (Accessed 4 June 2007)

Figure 10: Synoptic maps (a-e) and location of the monsoon depression (f), which caused flash floods in Pakistan in 2007

discharge of the barrage and caused out-flanking on both sides, which caused great damage to the canal intakes, inundated hectares of land, washed out several villages, and killed 1,275 people, with many others missing or injured. The same event heavily damaged hydropower facilities, as the penstock pipe of the Kulekhani hydropower plant was washed away by debris flow in Jurikhet Khola. The intake of Kulekhani II was completely destroyed by the debris flow of the Mandu Khola River. Several other rivers and rivulets including Kamala, Manusmara, Palung, Agra, Belkhu, and Malekhu were flooded and villages, agricultural fields, bridges, and roads washed away.

Flash flood due to monsoon depressions

Intense monsoon depressions seldom reach the mountain areas during the monsoon season. When they do, it is the result of a strong westerly wave over northern Kashmir, which causes heavy to very heavy rainfall in the lower Kashmir and Jammu Valley, resulting in devastating flash floods. One such event took place in July 2005 and caused a large flood in the Chenab River in Pakistan. A monsoon low developed in the Bay of Bengal on 28 June 2005 (Figure 10). It took a west-northwest course and reached the vicinity of Pakistan on the evening of 7 July 2005. A westerly wave moving across Kashmir and the northern parts of Pakistan interacted with the monsoon depression and rejuvenated it. This depression moved into Punjab and Kashmir and caused heavy rainfall in the upper catchment of the Chenab River. Due to the steep mountain catchment, the river flooded quickly. The discharge in the Chenab River and its tributaries Jammu Tawi and Munawar Tawi were heavily swelled, and discharges at Marala (the first gauging station in Pakistan) reached 5300m^3/s. This flood wave washed away bridges and inundated the foothills of Jammu Valley in Sialkot, Pakistan, causing huge damage to infrastructure downstream.

3.2 Landslide Dam Outburst Flood

Due to weak geological formations, active tectonic activities, highly rugged topography, and heavy rainfall, landslides and debris flow are common phenomena in the HKH region, causing severe loss of lives and property. In addition to their direct impact, landslides and debris flows trigger flooding. If large amounts of material from landslides or debris flows reach a river they can temporarily block its flow, creating a reservoir in the upstream reach (Figure 11). The 1911 earthquake triggered a rock slide that blocked the Mrgab River in southeastern Tajikistan, forming a still-existing natural dam 600m high. Lake Sarez, formed by the dam, is 60km long with maximum depth of 550m and volume of approximately 17km^3 (Schuster and Alford 2004).

As the reservoir level rises due to river flow and overtops the dam crest, sudden erosion of the dam can cause an outburst. Overtopping can also be caused by secondary landslides falling into the reservoir. Internal instability of the dam might trigger an outbreak even without overtopping. Outburst events are generally random and cannot be predicted with any precision. Such a flood, commonly known as a landslide dam outburst flood (LDOF), scrapes out beds and banks causing heavy damage to the riparian areas and huge sedimentation in downstream areas.

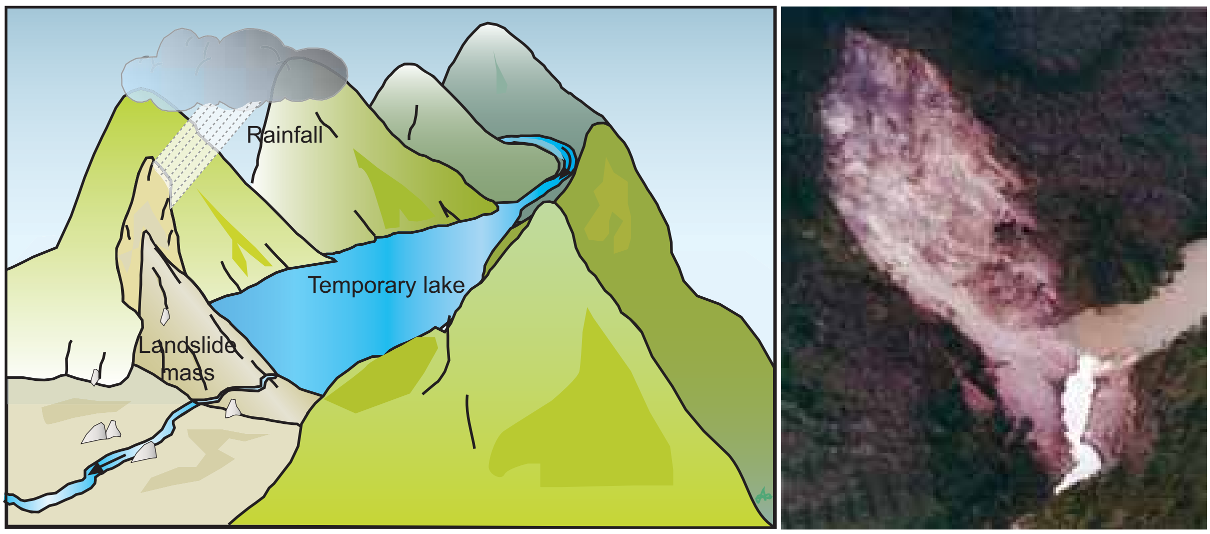


Photo source: WECS 1987

Figure 11: Formation of a natural dam (left) and photograph (right) of river damming due to a landslide

In general, high landslide dams form in steep-walled, narrow valleys because there is little area for the landslide mass to spread out (Costa and Schuster 1988). Commonly, large landslide dams are caused by complex landslides that start as slumps or slides and transform into rock or debris avalanches. The most important processes in initiating dam-forming landslides are excessive precipitation and earthquakes. Volcanic eruptions can also cause landslide dams, although there are no examples of such dams in the HKH region. Other mechanisms include stream under-cutting and entrenchment.

Landslide dams can be classified geomorphologically with respect to their relation to the valley floor (Swanson et al. 1986, in Costa and Schuster 1988). Landslide dams may form due to various causes and can vary according to the location of the dam (Table 1 and Figure 12).

In 1883, a landslide dam 350m high was created in a tributary of the Alaknanda River of the Garwal Hills, India and a 50m high flood was created when the dam broke. Nepal has also experienced several landslide dam outburst floods. The Budigandaki River has been dammed at least twice, and the Tinau River was dammed in 1978 due to a landslide after 125 mm of rainfall in the catchments. The subsequent outburst caused heavy damage to property and loss of several lives in Butwal.

Table 1: **Types of landslide dams**

Type	Cause	Effect
I	Falls, slumps	Dams are small with respect to the width of valley floor and do not reach from one side to the other
II	Avalanches, slumps/slides	Dams are larger and span the entire valley floor
III	Flows, avalanches	Dams fill the valley from side to side and considerable distances upstream and downstream
IV	Falls, slumps/slides, avalanches	Dams formed by contemporaneous failure of materials from both sides of a valley
V	Falls, avalanches, slumps/ slides	Dams formed when the same landslide has multiple lobes of debris that extend across a valley floor at two or more locations
VI	Slumps/slides	Dams created by one or more surface failures that extend under the stream or river valley and emerge on the opposite valley

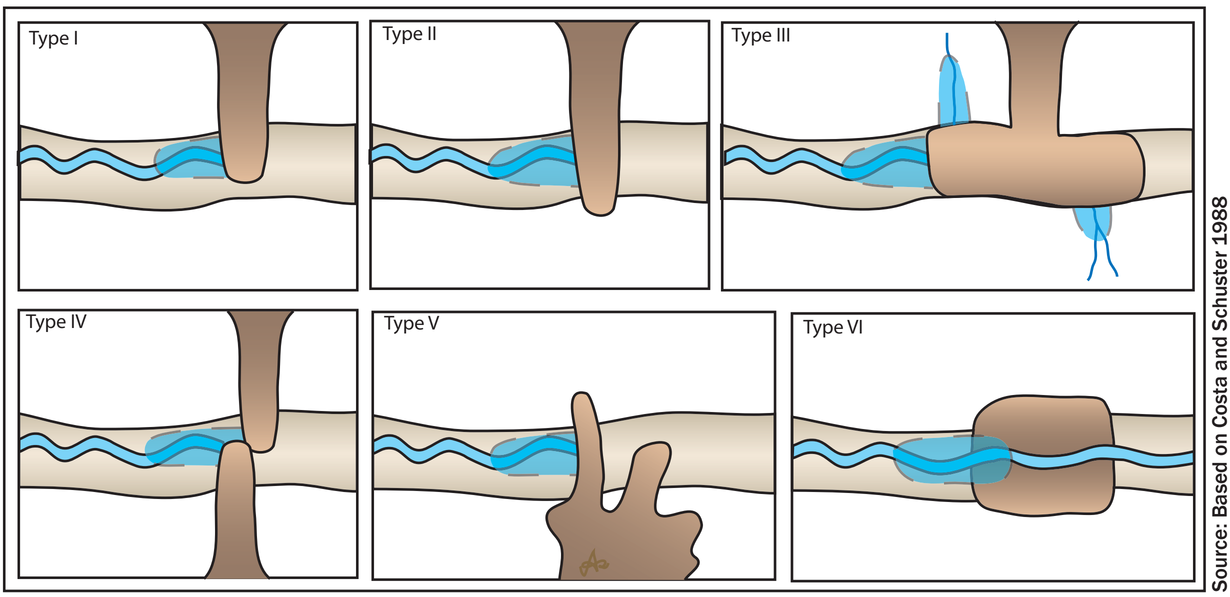


Figure 12: Types of river-damming landslides

Four case studies

Case 1: Yigong landslide dam outburst flood

One of the most striking examples of a LDOF is that of the Yigong River in eastern Tibet. As a result of sudden temperature increase, a huge amount of snow and ice melted in the region, and a massive, complex landslide occurred on 9 April 2000 in the upper part of the Zhamulongba watershed on the Yigong River, a tributary of the Yarlung Zangbo River. About 300 million cubic metres of displaced debris, soil, and ice dammed the Yigong River (Figure 13). In eight minutes a 100m high, 1.5 km wide (along the river), and 2.6 km long (across the river) landslide dam was created. The Type III landslide dam had a volume of 300 million m^3 (Shang et al. 2003). The dam blocked the Yigong River, and, due to an inflow of about 100 m^3/s from Yigong River, the lake level rose by about one metre per day. An attempt was made to dig a large trench and release the water from the lake, but it failed to avert the outburst. The outburst occurred on 10 June 2000 and created a huge flash flood downstream. The maximum depth of the flood was 57m, the maximum velocity was 11.0 m/s, and the flood was 1.26×10^5 m^3/s. The peak flood was 36 times greater than the normal flood. Tongmai Bridge, the highway between Yigong Tea Farming Base and Pailong County, and two suspension bridges in Medong County were all destroyed by the flood, but no injuries or deaths occurred on Chinese territory (Figure 14). On the Indian side of the border, however, damage from the flash flood from the dam failure was of a scale seldom seen before and resulted in the death of 30 people, with more than 100 people missing. The flood in the Brahmaputra River as it entered India was 1.35×10^5 m^3/s (Zhu and Li 2000; Zhu et al. 2003). More than 50,000 people in five districts of Arunachal Pradesh, India, were rendered homeless by the flash flood, and more than 20 large bridges, lifelines for the people, were washed away. The total economic loss was estimated at more than one billion rupees (22.9 million US dollars).

Source: Zhu et al. 2003

Figure 13: The Zhamulongba landslide that blocked the Yigongzanghu River (left) and the landslide dammed lake across the Yigongzanghu River (right)

Source: G. McCue

Figure 14: The Palung Zambo River, a tributary of the Yigongzanghu River, before (top) and after (bottom) the Zhamulongba landslide dam outburst of 10 June 2000

Case 2: Tsatichhu landslide dam outburst flood

Another example of a LDOF in the HKH region is the Tsatichhu LDOF in Bhutan. On 10 September 2003, material with an estimated volume of 7-12x10^6 m^3 failed on the wall of a valley and slid into the narrow Tsatichhu River valley. The ground shaking felt at Ladrong village, 2.5 km away, suggests that the main slide occurred over a period of 30 minutes. The slide formed a river-blocking dam 110m high. The deposited material had an estimated volume of 10-15x10^6 m^3. The dam crest extended approximately 580m across the valley (Dunning et al. 2006), and the deposited material spread a distance of 200m upstream and 700m downstream. The event caused winds strong enough to fell trees and strip vegetation.

The landslide dammed the Tsatichhu River and formed a lake referred to as Tsatichhu Lake (Figure 15). The lake extended 1 km up-valley, and had an estimated volume of 4-7x10^6 m^3 at its full level. A small surface outflow occurred in December 2003, but did not cause failure of the dam. There was also significant seepage through the dam, which together with the surface outflow maintained equilibrium with the river inflow of 0.53 m^3/s.

The dam survived for 10 months. From 15 to 21 May 2004, heavy rainfall caused some material from the downstream face of the dam to fail, but did not cause a major failure. On 10 July 2004, a major failure of the dam occurred after a period of prolonged intense rainfall. The exact process of the failure is unknown although it is suggested that a combination of downstream slope failure and overtopping was the cause. The failure caused an enormous flood downstream. The mass of debris blocked the Kurichu River for 45 minutes. After 80 minutes the flood arrived at Kurichu Hydropower Plant 35 km downstream, where the peak discharge was 5900 m^3/s. Later calculations estimated the peak discharge at the outflow at 7700 m^3/s. The flood wave was up to 20m high. Due to the 10 months' gap between the formation and failure of the dam, the Department of Energy had sufficient time to put an early warning system into place, which resulted in timely warning to the hydropower plant. Pre-lowering of the water level enabled the reservoir to cater to the flood with only minor damage to the infrastructure. This flash flood did not result in any human casualties, although loss of agricultural land was significant (Xu et al. 2006). A significant section of road into the Autosho village at the confluence of Tsatichhu/Wabrangchhu and Kurichhu was completely destroyed.

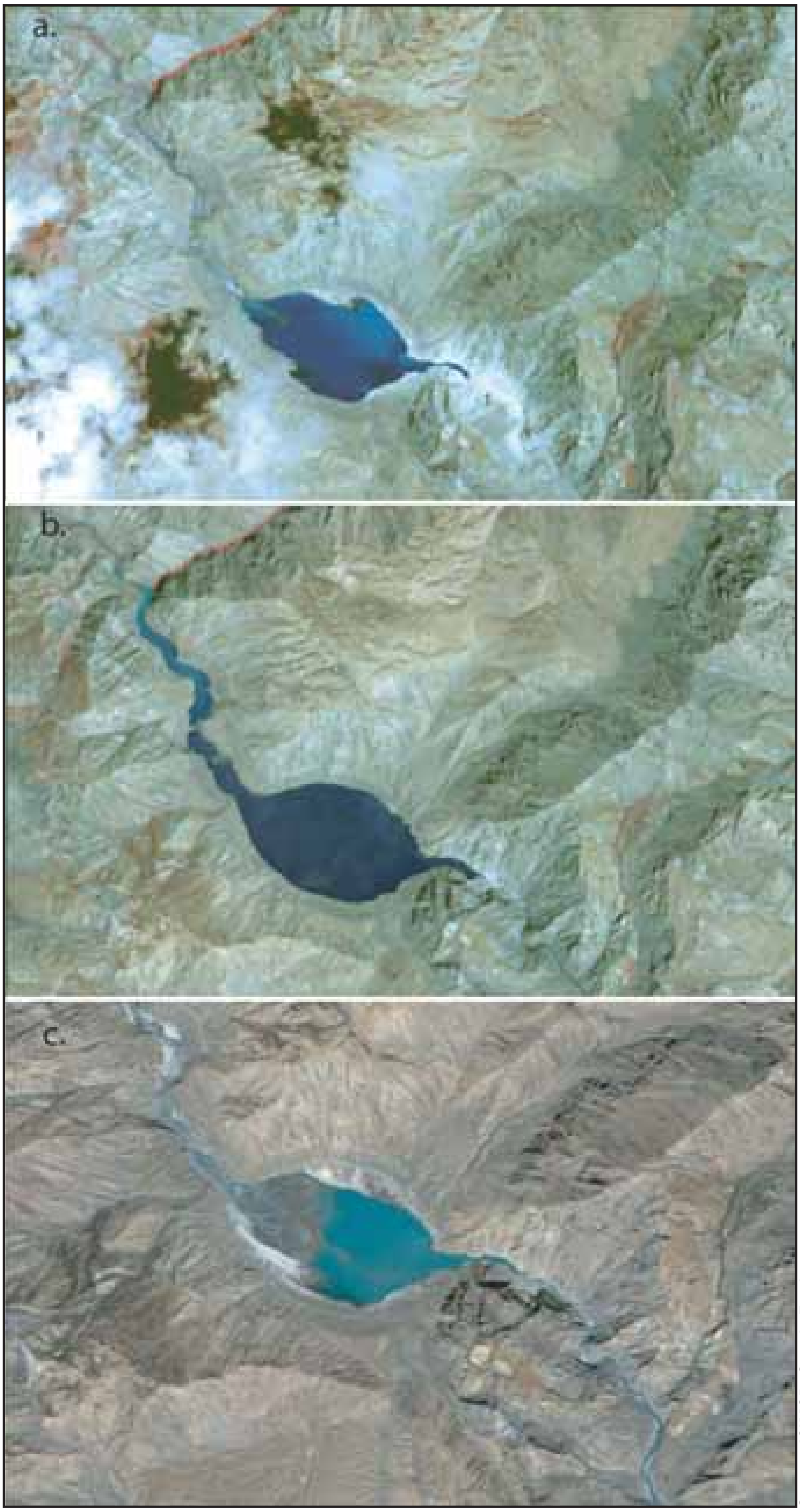
Case 3: Pareechu landslide dam outburst flood

On 22 June 2004, a landslide blocked the Pareechu River, which is the upper reaches of Sutlej River in Tibet. The mass of earth and rock created a natural dam, forming a water body with a volume of about 6x10^6 m^3. At 5:00am on 5 July, after holding water for 15 days, the landslide block collapsed. On 8 July, another major landslide occurred and blocked the river about 30 km from the China-India boundary, forming a new natural dam about 35m high. Due to continuous heavy rainfall, the water body within the dam grew to 1500m wide, 6000m long, and 19m deep by 4 August. The total volume of the lake was about 79x10^6 m^3 (Figure 16). As estimated by the water resources department in Tibetan Autonomous Region, about 40 m^3/s of water flowed into the dam; the water level rose at a rate of 0.48m per day; and the outflow from the dam was about 7.3 m^3/s. Chinese authorities communicated the formation and growth of the lake and eminent danger of flooding to their Indian counterparts. On 9 August armed forces and paramilitary forces were put on red alert in Himachal Pradesh, India as the artificial lake had started spilling over and could burst at any time. Chinese authorities informed the Government of India that a breach had started appearing in the lake that could give way at any time. On 13 August several Tibetan villages downstream of the lake were evacuated. The state government of Himachal Pradesh identified 56 villages along the Sutlej from Kinnaur to Bilaspurthat that could be affected (Dams, Rivers & People 2004). The dam burst on 25 June 2005. The flood damaged 200km of roads, houses, bridges, hydroelectric stations, and so on in Indian territory. The direct cost of the flood damage was estimated at US $200 million (Xu et al. 2006). Fortunately, due to good communication between China and India, no human causalities occurred.

Landslide damming is widespread in the HKH region, although many of these events are not recorded due to remoteness of the location. Li (1994) reports more than 12 well-documented landslide dams in China, of which nine have failed and caused flash floods. Shrestha and Shrestha (2005) report 18 cases of landslide dams in Nepal. There have been several such events in the India Himalaya and Bhutan.

Source: Dunning et al. 2006

Figure 15: Tsatichhu landslide dam: a. the source area of the landslide; b. detailed view of the dam; c. Tsatichhu lake



Source: ICIMOD; Google Earth

Figure 16: Satellite image of the Pareechu River: a. about one month after the landslide damming (15 July 2004); b. about 2.5 months after damming (1 September 2004); and c. after the outburst

Case 4: Budhi Gandaki and Larcha Khola in Nepal

The Budhi Gandaki River in Nepal was twice dammed near Lukubesi. In 1967, the river was dammed for three days after the failure of Tarebhir. Another landslide in 1968 dammed the river again with a huge amount of displaced material. The river's water level dropped from a normal level of 4m on 1 August to 0.9m on 2 August. After the breaching of the landslide dam, the water level rose to 14.61m. The peak flow was estimated to be 5210 m^3/s, which was significantly greater than the mean annual instantaneous flood (2380 m^3/s). One bridge and 24 houses at Arughat Bazaar, about 22 km downstream from the damming site, were swept away after the breach .

Bhairabkunda Khola was dammed in 1996. The landslide dam outburst flood destroyed 22 houses and killed 54 people in Larcha village. The highway bridge was swept away by the flash flood (Figure 17).

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Figure 17: a. Bhairabkunda Khola a few days after the LDOF; b. debris deposited by the LDOF; c. large boulders trapped at the highway bridge; and d. Larcha village destroyed by the flash flood

3.3 Glacial Lake Outburst Flood

Flash floods resulting from the outburst of lakes of glacial origin are called glacial lake outburst floods or GLOFs. GLOF is one of the important mechanisms that cause flash floods in the Himalayas. They are a common phenomenon in Iceland, where the outburst is generally triggered by volcanic action and the phenomenon is known as jokulhaup. Many of the early studies on GLOFs were based in Iceland. Although GLOFs are not a recent phenomenon in the Himalayas, they were only given attention recently, probably because several high-magnitude events caused substantial damage in different parts of the region.

Glacial lakes are directly related to the glacier fluctuation process, which in turn is attributed to climate variability. The glaciers in the region have been in general retreat since the end of the Little Ice Age of the mid-19th Century. However, the retreat has accelerated in recent decades, most probably due to anthropogenic climate change, which is highly pronounced in the region. The retreat of glaciers leaves behind large voids to be filled by meltwater, thus forming moraine-dammed glacial lakes. These natural moraine dams are composed of unconsolidated moraines of boulders, gravel, sand, and silt. The dams are structurally weak and unstable, and undergo constant changes due to slope failures, slumping, and similiar effects and are in danger of catastrophic failure, causing glacial lake outburst floods. Moraine dams may break by the action of some external trigger or by self-destruction (Table 2). A huge displacement wave generated by a rockslide or snow/ice avalanche from the glacier terminus into the lake may cause the water to overtop the moraine, create a large breach, and eventually cause dam failure (Ives 1986). Earthquakes may also trigger dam breaks depending upon magnitude, location, and characteristics. Self-destruction is caused by the failure of the dam slope and seepage from the natural drainage network of the dam.

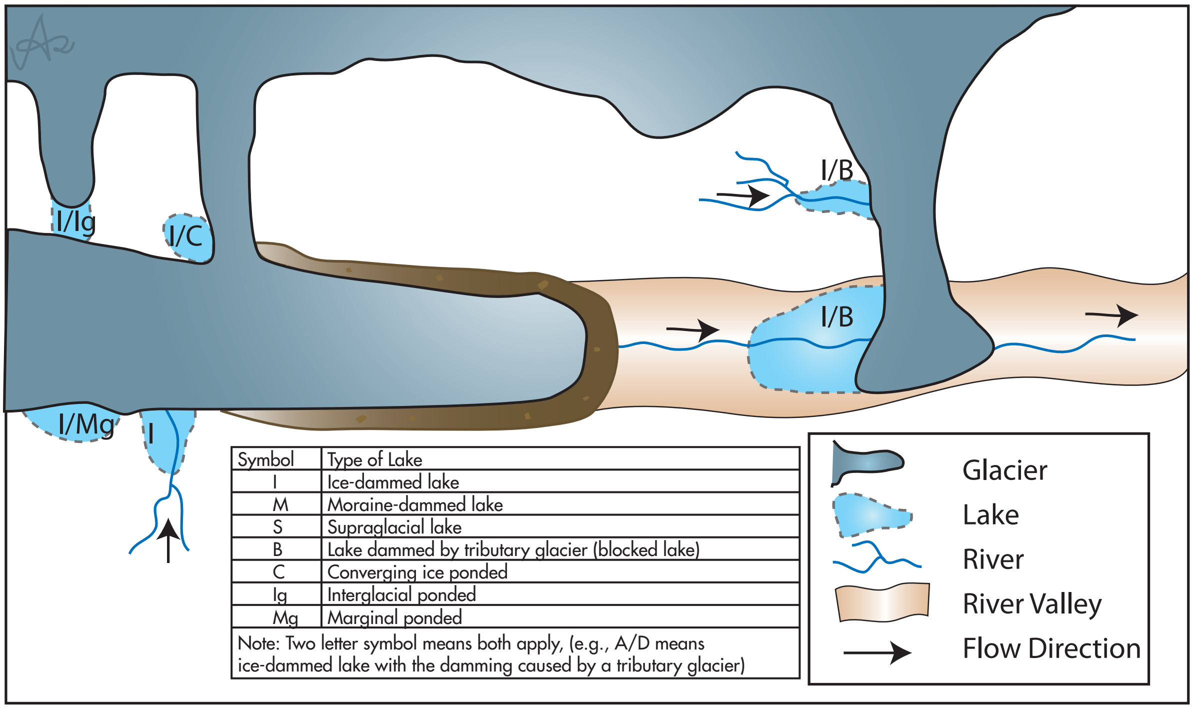
Table 2: **GLOF triggering mechanisms**

Internal	External
Hydrostatic pressure (increase in water level)	Overtopping of moraine dam due to rock, ice, snow avalanche into the lake
Seepage	Earthquake
Destruction of conduits within ice core	

3.4 Types of Glacial Lakes

Glacial lakes formed as a result of damming material are widely divided into two categories: ice-dammed lakes and moraine-dammed lakes. Ice-dammed lakes are created when a stream is intercepted by a glacier, often during the advance stage, while moraine-dammed lakes are confined by moraines left by retreat of the parent glacier. Ice-dammed lake failure is a complicated process and the resulting flood discharge is less ‘spiky’, whereas moraine-dammed lake outbursts cause sharp rises and falls in flood discharge.

Depending on the juxtaposition of the lake with respect to the glacier, the lakes can be supraglacial, englacial, or marginal. Figures 18 and 19 show schematic and real representations of typical locations of ice-dammed and moraine-dammed lakes.



Symbol	Type of Lake
I	Ice-dammed lake
M	Moraine-dammed lake
S	Supraglacial lake
B	Lake dammed by tributary glacier (blocked lake)
C	Converging ice ponded
Ig	Interglacial ponded
Mg	Marginal ponded

Note: Two letter symbol means both apply, (e.g., A/D means ice-dammed lake with the damming caused by a tributary glacier)

Figure 18: Types of glacial lakes

Source: Yamada 1998

Figure 19: Typical ice-dammed (left) and moraine-dammed (right) lakes

3.5 Glacial Lake Outburst Flood in the HKH Region

There have been at least 35 recorded GLOF events in the HKH region: 16 in China, 15 in Nepal, and four in Bhutan. There have been some reports of floods of glacial origin in India and Pakistan, but details of the sources and mechanisms are not available. Many of the GLOFs in China occurred in the southern part of the Tibetan Plateau, where rivers drain into Nepal. Ten of these events led to transboundary damage and many caused major damage in Nepal. One of the most remarkable in this context is the Zhangzanbo lake GLOF of 11 July 1981. The lake burst due to a sudden ice avalanche. A breach 50m deep and 40-60m wide formed at the moraine. The peak discharge of the burst at the outlet was about 16,000 m^3/s. The main flood lasted for an hour, during which time an estimated 19 million m^3 of lake water drained. This GLOF created a great change in the landform downstream due to 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 (Figure 20). The flood caused heavy damage to the diversion weir of Sunkoshi hydropower station.

Source: Mool et al. 2001

Figure 20: Remnants of a bridge pier (left) on the Arniko Highway and a section of the highway destroyed by the 1981 Zhanzangbo GLOF

One of the region's best-documented GLOF events is the Dig Tsho GLOF of 4 August 1985. Dig Tsho lake is located at the headwaters of the Bhotekoshi, a tributary of the Dudhkoshi River. The lake is in contact with Langmoche, a steep glacier. The GLOF destroyed the nearly complete Namche hydropower project. In addition, the GLOF destroyed 14 bridges, trails, and cultivated land, and caused the loss of many lives. The total damage was estimated at US $1.5 million. Figure 21 shows the Dig Tsho Lake before and after the burst.

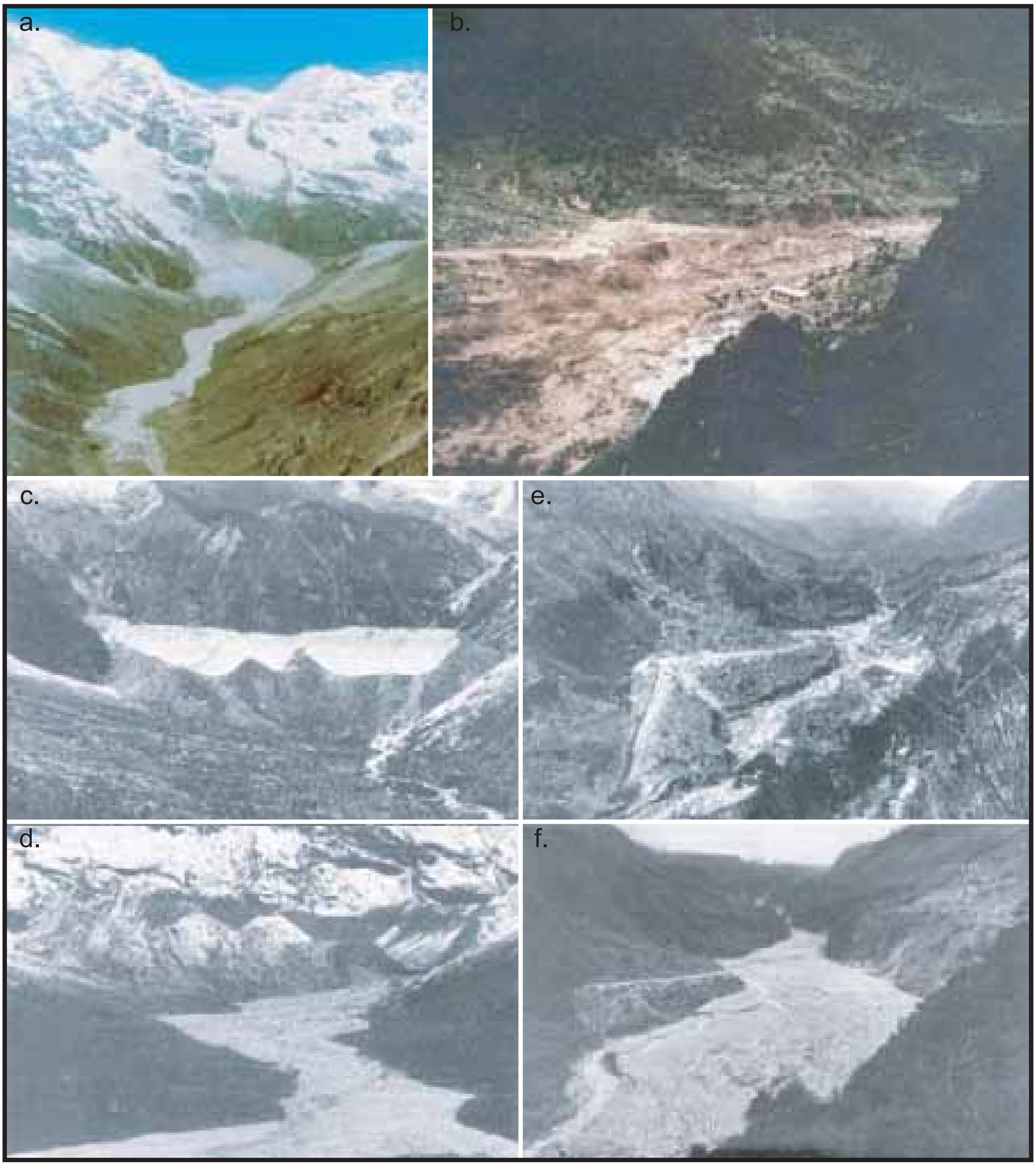


Figure 21: a. Dig Tsho lake after the GLOF outburst in 1985; b. the flash flood caused by the Dig Tsho outburst; c. the end moraine of Dig Tsho before the breach; and d. after the breach; e. the Namche hydropower station site before; and f. after the outburst

How do humans contribute to flooding?

Floods are a naturally occurring hazard that become disasters when they affect human settlements. The magnitude and frequency of floods is often increased as a result of the following human actions.

Settlement on floodplains contributes to flooding disasters by endangering humans and their assets. However, the economic benefits of living on a floodplain outweigh the dangers for some communities. Pressures from population growth and shortages of land also promote settlement on floodplains. Floodplain development can also alter water channels, which if not well planned can contribute to floods.

Urbanisation contributes to urban flooding in four major ways. Roads and buildings cover the land, preventing infiltration so that runoff forms artificial streams. The network of drains in urban areas may deliver water and fill natural channels more rapidly than naturally occurring drainage, or may be insufficient and overflow. Natural or artificial channels may become constricted due to debris, or obstructed by river facilities, impeding drainage and overflowing the catchment areas.

Deforestation and removal of root systems increases runoff. Subsequent erosion causes sedimentation in river channels, which decreases their capacity.

Failure to maintain or manage drainage systems, dams, and levee bank protection in vulnerable areas also contributes to flooding.