Chapter 4

Evolution of Geomorphologic Hazards in Hindu Kush Himalaya

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Abstract Geomorphologic hazards in the Hindu Kush regions have been evolved due to the combined effect of tectonic settings, topographical variation, weak geological conditions, intense seasonal precipitation and the changes in climatic conditions. The underlying risk has been further intensified by human interference that arises either due to poverty, poor policy or weakness in implementing the policies. Tectonic setting of the Hindu Kush region has been originated due to the collision between southern Indian plate and northern Eurasian plate. The Himalayan Orogeny is thus developed and consequently earthquake hazard is evolved which is unavoidable. Weak geological conditions, diversified rock types, high degree of weathering in rocks and rock deformations all have contributed to most of the geomorphologic hazards. High gradient of rivers and extreme monsoon precipitation indicate that the upstream and downstream of major river basins are strongly interrelated and the risk of hazards like landslides, floods and debris flows in the upstream pose serious threat to the downstream flood as well. The impact of climate change, high rate of temperature rise and extreme rainfall events has exacerbated the landslide, flood, debris flow and Glacial Lake Outburst Flood (GLOF) hazards. At least one GLOF event was recorded in Himalayan region between every 3–10 years. All these hazards shape the landscape of the region and create severe problems on water resources as well as other development projects. These hazards have worst impact to people and livelihood by destroying their environment for living and production, thereby seriously affecting social and economic development. This chapter analyzes the major triggers of the geomorphologic hazards in HK regions with the scientific facts and figures.

Keywords Geomorphologic hazards • Earthquake • Floods • Landslides • Soil erosion

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H.K. Nibanupudi, R. Shaw (eds.), *Mountain Hazards and Disaster Risk Reduction*,
Disaster Risk Reduction, DOI 10.1007/978-4-431-55242-0_4

4.1 Introduction

Hindu Kush Himalaya (HKH) extends for about 3,500 km from Afghanistan in the west to Myanmar in the east covering an area of 4.19 million sq. km. The region covers mountain areas of eight countries namely Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal and Pakistan. Indus, Ganges, Brahmaputra, Mekong, Yangtze and Yellow are the major rivers that drain the HKH region. The landscape of the region is inherently fragile as a result of the combined effect of lithospheric plate dynamics, weak and deformed rock types, steep topography, intense seasonal precipitation and climate change impact. As a result, the region is exposed to multiple hazards like earthquake, landslide, flood, debris flow, soil erosion and glacial lake outburst flood (GLOF). The region has frequently witnessed many of these hazards converted to disaster. All these hazards and inherent processes have high capacity of altering the geomorphology of the region governed by geology, rivers and glaciers. In the Himalayan region, these hazards are controlled by geomorphology and topography as well. As for example: snow avalanche and GLOFs processes are common in higher Himalaya; landslides, soil erosion, debris flows and flash floods in the Lesser Himalaya and Siwaliks; and floods in the plain areas. Rock deformations and surface processes therefore interplay for the evolution of the present mountain landscapes. The occurrence of large landslides or slope failures, for example, may impact the geomorphic system at a wide range of spatial and temporal scales. Depending on their nature and volume, their impact may be local and short-lived in time, whereas the largest features may influence landscape morphology and evolution for thousands of years (Fort et al. 2009). These hazards create severe problems for water resources and other development projects and directly impact to people by destroying their environment for living and production, thereby seriously affecting social and economic development. This chapter provides detail analysis of the major triggers of geomorphologic hazards in the Hindu Kush Himalaya.

4.2 Analysis of Key Factors that Triggers Geomorphologic Hazards

Geomorphologic hazards are triggered by multiple factors in the HKH region. The kinematics and dynamics of continent-continent collision between southern Indian Plate and northern Eurasian Plate give rise to earthquake hazard; weak geological conditions, topographical variations and heavy monsoon precipitation contribute largely to the flood, debris flow and landslide hazard whereas global warming and high melting of glaciers contribute to the glacial lake outburst flood (GLOF). Climate change has intensified most of these hazards as well. Detail analysis of such triggers for different geomorphologic hazards is described in this section.

4.2.1 Collision Between Indian Plate and Eurassian Plate

The Himalayan mountain chain extends from east to west in an arc of about 2,500 km between the wide plains of the Indus and Bramhaputra in the south and the high Tibetan Plateau in the north (Dhakal 2012). The width of this mountain range is about 230–350 km (Thakur 2001). Constituting this Himalayan mountain chain and most unstable geological conditions; HKH region is most susceptible for earthquake as a consequence of collision between Indian plate and Eurassian plate (Dewey and Bird 1970; Powell and Conagan 1973; Searle et al. 1987; Dewey et al. 1989 among others). After this continent-continent collision, Indian plate is under-thrusted beneath the Eurasian plate resulting in over riding of later along the series of faults (Fig. 4.1). The movements along such faults generate earthquakes. Therefore, plate dynamics and Himalaya forming processes solely control the occurrence of earthquake and underlying geomorphologic processes in this region. Understanding the plate dynamics and Himalaya forming process is therefore imperative to understand the earthquake hazard in HKH region.

Himalayan range is formed by the collision of Indian plate with Eurasian plate which began about 55 million years ago and the process is still continuing. Therefore Himalaya is popularly known as the youngest mountain in the world. During the history of earth, the continents have moved constantly and changed their position, and continue to do so at present. Before the Himalaya was formed, there were two supercontinents in the earth namely Gondwanaland in the south and Laurasia in the north about 200 million years ago. India along with South America, Africa, Australia and Antarctica formed the Gondwanaland; whereas North America, Greenland, Europe and most of Asia formed the northern Laurasia. These two supercontinents were separated by a sea called Tethys. By about 100 million years ago, India was separated from other southern continents and started moving northwards at a rate of about 12 cm/year. Subsequently, the width of the Tethys sea started decreasing and eventually the sea vanished permitting the continent-continent collision between Indian landmass (Indian plate) and southern edge of Asia (Tibet) or the Eurasian plate about 55 million years ago. The dynamics of this collision in terms of cyclic process of storage and release of energy is the reason for high seismic activities and susceptibility of earthquake in this region.

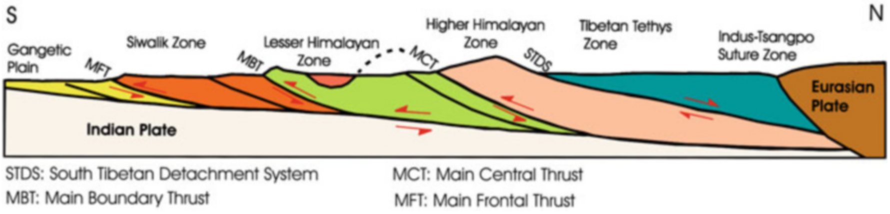


Fig. 4.1 Geological section of Himalaya (modified after Harris and Whalley 2001)

Indian plate continued moving northward against Asia even after the collision and its northern edge covered with predominantly marine sedimentary rock sequence got folded, faulted and uplifted to form the Himalayan mountain range; and due to the succeeding effect Tibetan Plateau is also created (Upreti and Yoshida 2005). After the disappearance of marine sediments, the continental crust of Indian plate could not sink and the resistance developed for the northward movement of Indian plate reducing its rate of movement. Today, India is still moving northward bulldozing through Asia at the rate of about 50 mm annually (Upreti and Yoshida 2005) and part of Indian crust is pushed underneath the Tibetan Plateau. The recent Global Positioning System (GPS) data in Nepal reveals that some parts of the Himalaya are rising at the rate as much as about 1 cm per year. The present boundary between the Indian and Eurasian plate lies in Tibet and is marked by the Indus-Tsangpo Suture Zone approximately running parallel to the Indus and Tsangpo rivers in an east–west direction. The rock assemblages found in this region represent Tethys oceanic crust.

Northern margin of Indian continent was sliced along a fault called Main Central Thrust (MCT) around 20–23 million years ago. The rock sequences above MCT were detached and moved towards south overriding the rocks of Lesser Himalaya giving rise to the rocks of Higher Himalaya in the north after bringing the deep seated metamorphic and granites to be exposed in the surface. The activity of the MCT is also regarded to be associated with the formation of the South Tibetan Detachment System (STDS) that reflects the gravitational slide normal fault, and it separates the northern Tibetan Tethys Himalaya with the Higher Himalaya. About 10 million years ago, a fault called Main Boundary Thrust (MBT) was developed in the south of the Lesser Himalaya after the slowdown of plate activities along the MCT; and it separates the Siwaliks from Lesser Himalaya. Subsequently, Main Frontal Thrust (MFT) was developed 0.5–0.2 million years ago that separates the southern Indo-Gangetic Plain with the Siwaliks. This gives a clear indication that the deformation activities of the Himalaya have shifted southwards as the thrusts are grown progressively younger from north to south. It is believed that series of thrust faults have accommodated about 500 km of crustal shortening after their formation generating metamorphism at mid crustal level of about 15–20 km depth (Thakur 2001).

Continent-continent collision, mountain building process (Himalayan Orogeny) and series of thrust faults control the seismicity of the Himalaya and contribute to the geomorphologic evolution. Continuous strain accumulations along the major active faults due to locking resulted in the high susceptibility of earthquake hazard in the region. The major great earthquakes in this region with magnitude greater than 8 in Richter Scale like Kangra Earthquake in 1905, Nepal-Bihar Earthquake in 1934 and Assam Earthquake in 1950 have occurred south of the Higher Himalaya. The region in between these earthquakes events show clear seismic gap without major earthquakes representing storage of energy in this region and potential of it hitting by big or great earthquake (Fig. 4.2) at any time in future. It should be noted that most of the earthquakes in this region are confined to shallow depths within a narrow zone of about 50–100 km between MBT and MCT and more than half of the

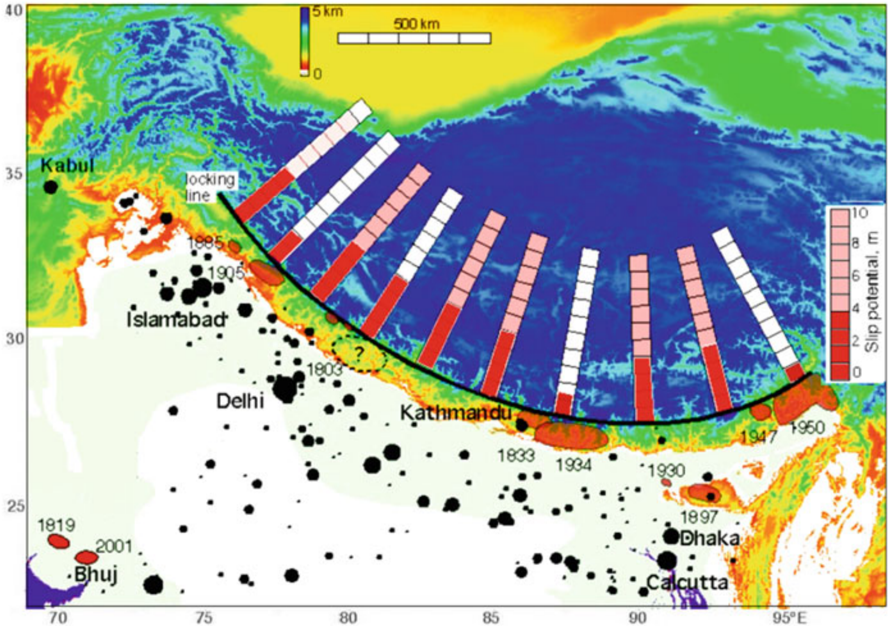


Fig. 4.2 Distribution of major earthquakes in Himalaya and seismic gap (modified version of Bilham et al. 2001). *Shaded areas* with dates next to them show epicenters and zones of rupture of major great. The *red portions of the bars* show the potential for slip based on how much strain has accumulated since the last great earth-quake. The *pink portions* show possible additional slip that could occur. The *bars* are not intended to indicate the locus of specific future great earthquakes but are simply spaced at equal 220-km intervals, the approximate rupture length of the 1934 and 1950 earthquakes. *Black circles* show population centers in the region. Detail descriptions are available at Bilham et al. 2001

Himalayan front is overdue for a great earthquake (Bilham et al. 2001). Details of major earthquakes in the Himalaya are listed in Table 4.1.

After 1934 Bihar-Nepal Earthquake, several major earthquakes occurred in the region. For example, Nepal is hit by seven major earthquakes, the latest being the Sikkim/Nepal Earthquake of September 18, 2011. In this earthquake, 14,544 houses were damaged, 6 people were killed and 30 people were injured in Nepal only (Dahal and Bhandary 2013). Studies by Bilham and Wallace 2005 and Ader et al. 2012 have assumed that the largest earthquake in Himalaya can be as large as that of subduction zone mega earthquakes in the order of Mw 9.0 or more. Since many great and big earthquakes already occurred in the region, it has highly contributed to the evolution and alteration of the geomorphology. Beside surface rupture and subsidence, earthquake triggers landslides of various types and dimensions enhancing slope activities (Fig. 4.3). Further, there are evidences that some

Table 4.1 Major earthquakes in HKH region (modified after Joshi and Khan 2009)

Year, AD	Location	Magnitude	Deaths	Affected countries
819	Afghanistan	7.4	Heavy casualties	Afghanistan
1505	Afghanistan, Kabul	7.3	Heavy casualties	Afghanistan
16 June 1819	India, Kutch	8.0	1,543	India
22 Jan 1832	Afghanistan, Badakhshan	7.4	Thousands killed	Afghanistan
1833	Nepal	7.7	414	Nepal
12 June 1897	India, Assam	8.7	1,500	India
4 Apr 1905	India, Kangra	8.0	20,000	India, Pakistan, Nepal
15 Jan 1934	Nepal-India Border	8.3	10,653	India, Nepal
31 May 1935	Pakistan, Quetta	7.5	35,000	Pakistan
26 June 1941	India, Andman Islands	8.1	3,000 (Approx.)	India
1945	Pakistan, Makran	8.0	4,000	Pakistan, India
15 Aug 1950	India, Assam	8.6	1,526	India, Bangladesh
9 June 1956	Afghanistan, Kabul	7.6	400	Afghanistan
21 July 1956	India, Anjar	7.0	115	India
1974	Northern Pakistan	6.2	5,300	Pakistan
1980	Nepal	6.5	103	Nepal
20 Aug 1988	Nepal-India border	6.6	1,450	India and Nepal
20 Oct 1991	India, Uttarkashi	6.6	768	India
30 Sep 1993	India, Latur	6.4	10,000	India
22 May 1997	India, Jabalpur	6.0	60	India
4 Feb 1998	Afghanistan	6.1	2,500	Afghanistan
30 May 1998	Afghanistan-Tajikistan border	6.6	4,000	Afghanistan
29 Mar 1999	India, Chamoli	6.8	106	India
26 Jan 2001	India, Bhuj	6.9	13,845	India, Pakistan
3 Mar 2002	Hindukush	7.4	166	Afghanistan

(continued)

Table 4.1 (continued)

Year, AD	Location	Magnitude	Deaths	Affected countries
25 Mar 2002	Hindukush Region	6.1	1,000	Afghanistan
5 Apr 2004	Hindukush	6.6	3	Afghanistan
8 Oct 2005	Pakistan-India	7.6	74,500	Pakistan, India, Afghanistan
12 Dec 2005	Hindukush	6.5	5	Afghanistan
29 Oct 2008	Pakistan	6.4	163	Pakistan
17 Apr 2009	85 km ESE of Kabul	5.1	22	Afghanistan
2011	Sikkim/Nepal border	6.9	6	Nepal, India

Fig. 4.3 Photographs of earthquake triggered landslide in Bhedetar along Dharan-Dhankuta road in Nepal. This landslide was triggered by Sikkim-Nepal border earthquake of 2011 (Photo courtesy: R.K. Dahal)

great earthquakes in this region have dammed the Himalayan Rivers, however the dating of these events are yet not delineated. Breaching of such landslide dams should have brought flash floods in the downstream, which is quite possible in future earthquakes as well.

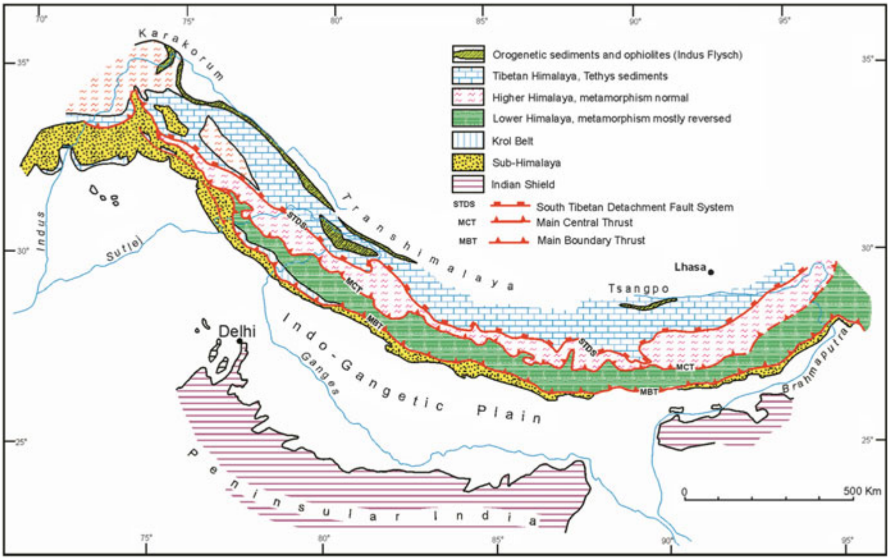


Fig. 4.4 Geological Map of Himalaya (*Source*: Upreti and Yoshida 2005)

4.2.2 Weak Geological Conditions

The geology of the Himalayan region is quite fragile since the rocks are highly jointed and deformed because of the tectonic activities and Himalaya forming process. Further, the rock types are highly diversified in north south direction within a narrow width of less than 350 km. Typical rock types found in the Himalaya vary from weak and fragile mudstone and sandstone; other sedimentary rocks like limestone, dolomite; meta-sedimentary rocks like slate, phyllite, schist; and metamorphic crystallines like gneiss, marble, quartzite etc. Such a diversified rock types within very small width of the Himalaya, together with high topographical variations, contribute to the diversified geological, hydro-geological and geomorphologic processes in the region. Such a geologic conditions together with heavy monsoon precipitation, diverse climatic conditions and extreme climate change impact are responsible for intense erosion, sedimentation, landslide and flood hazard in HKH region. Detail geology of the region is described in this section.

Overall geology of HKH can be described by dividing the area into four major geological zones (Figs. 4.1 and 4.4) that vary according to morphology and tectonics as well. Each of these zones is separated by distinct geological structures known as fault or thrust. From south to north, the four geological zones are Sub Himalayan zone or Siwaliks, Lesser Himalayan zone, Higher Himalayan zone and Tibetan Tethys zone. The Himalaya is boardered in the south by Indo-Gangetic Plain; which is separated from northern Siwaliks by a thrust fault called Himalayan

Frontal Thrust (HFT) or Main Frontal Thrust (MFT). Siwaliks is separated from Lesser Himalayan zone by Main Boundary Thrust (MBT); and Lesser Himalaya is separated from Higher Himalayan zone by Main Central Thrust (MCT). Higher Himalaya and Tibetan Tethys zone are separated by a normal fault called South Tibetan Detachment System (STDS). The lithology and structures in each morpho-tectonic zone from south to north are described here briefly.

4.2.2.1 The Indo-Gangetic Plain

It lies in the south of the mountain front (also called the foothills of the Himalaya or the Siwalik Range) and represents the plain formed by the great Himalayan river systems, viz, the Ganges and the Indus. It has formed a very extensive modern-day sedimentary basin, geologically also known as the foreland basin (Upreti and Yoshida 2005). It represents great alluvial tract of the Himalayan Rivers and consists of recent to Pleistocene deposits of boulder, gravel, sand, clay and remains of animals and plants. It is bounded by the Main Frontal Thrust (MFT) or Himalayan Frontal Thrust (HFT) in the north. The Siwalik Zone has been thrusted over the young alluvial deposits of Gangetic Plain along the MFT. The floor of the basin is quite uneven and therefore, the thickness of the sediments varies from 500 m to as much as 2.5 km.

4.2.2.2 The Sub-Himalayan Zone (Siwaliks/Churia)

This zone forms the southernmost mountain range of the Himalaya and is bounded by MFT in the south and Main Boundary Thrust (MBT) in the north. This zone is also called Churia in Nepal. The Lesser Himalayan rocks thrust southward over the Siwalik rocks along the MBT and a large part of the Siwalik Group has been buried beneath the overthrusted Lesser Himalayan rocks. This zone consists of fluvial sedimentary rocks of Neogene to Quaternary period (14–1 million years old) that are soft, loose and easily erodible; and are represented by sandstone, siltstone, mudstone and conglomerate. Siwaliks is divided into three stratigraphic formations from bottom to top; namely Lower Siwaliks, Middle Siwaliks and Upper Siwaliks.

In general, Lower Siwaliks zone comprises of fine grained red, ash grey, grey and reddish brown sandstone interbedded with purple, grey and green shales. Some vertebrate fossils are also noted in this part. Middle Siwaliks consists of relatively coarse grey sandstones with small portions of green, grey shales and clays. Thick bedded salt pepper sandstones are typical of middle siwalik and are cross laminated as well. Occasionally, conglomerates are seen in middle and upper part. Fossils of gastropoda and coalified plants are also present in this zone. Upper Siwaliks is characterized by coarse conglomerates, sands, grits and clays. Pebble, boulder and cobbles of gneisses, schists, granites and quartzites of Higher Himalaya as well as limestones, phyllites, slates and sandstones of Lesser Himalaya is common in this zone. Side cutting action of river is very fast in this zone, and recently due to the deforestation and concentrated precipitation in this zone, Siwaliks is highly degraded; and is susceptible to high grade of weathering and landslides which are source of sediment deposition in the southern Gangetic Plain.

4.2.2.3 Lesser Himalayan Zone

Lesser Himalayan Zone is bounded by MBT in the south and Main Central Thrust (MCT) in the north. At many places, high grade metamorphic rocks that have travelled from northern Higher Himalayan zone along MCT overlie the low grade metasedimentary rocks showing reverse metamorphism. Recumbent folding and faulting are prominent geological structures found within this zone. Lesser Himalaya is divided into two; namely Lesser Himalayan Meta-sediments and Lesser Himalayan Crystallines. Lesser Himalayan meta-sediments consist of low grade metamorphic rocks and unfossiliferous sedimentary rocks. Lesser Himalayan crystallines consist of metamorphosed rock sequence somewhere overlies by fossiliferous sedimentary cover. Typical rock types are schists, phyllites, quartzites as well as argillo-arenaceous and argillo-calcareous rocks with horizons of marble beds. This zone is intruded by granite rocks and gnessified. The age of this group of rocks is Precambrian to Proterozoic.

4.2.2.4 The Higher Himalayan Zone

This zone is sometimes also known as Greater Himalayan Zone. It is bounded by MCT in the south and South Tibetan Detachment System (STDS) in the north. This zone is characterized by the presence of high grade metamorphic rocks; mostly gneisses of various types. The lower succession consists of Kyanite-Silliminite gneisses and some quartzites. The middle part consists of calcareous gneisses interbedded with argillites. The top most part comprises of augen gneisses, granitic gneisses and migmatites. It can be the product of volcanism. Acid magmatism is the major part of top sequence consisting of layers of leuco-granites, granitic gneisses and pegmatites as documented in Nepal Himalaya.

4.2.2.5 Tibetan Tethys Zone

It is the northern most zones of the Himalaya and is bounded by a normal fault called STDS in the south and the Indus–Tsangpo Suture Zone (ITSZ) in the north which is exposed beyond the Nepal border in Tibetan Plateau. The ITSZ marks the boundary between southern Indian Plate and northern Eurasian Plate. It consists of sedimentary sequence known as Tibetan-Tethys Sedimentary Series that comprises of shale, sandstone, siltstone and conglomerate with competent limestone and quartzite beds ranging in age from Cambrian to upper Cretaceous (Colchen et al. 1986). The rocks are somewhere folded and faulted.

4.2.2.6 Hazards Triggered by Geology

Weak and adverse geological conditions in the HKH regions in combination with hydro-meteorological conditions have triggered hazards like landslides, sediment production and floods. Each of the geological and physiographic zones is susceptible for different hazards. As discussed already, the Sub-Himalayan regions consist of fragile sandstone and mudstones which are highly susceptible to weathering that converts rock into soil. The rocks loose shear strength after the weathering enhancing the potentiality of landslides and slope failures. Further increase in pore water pressure through available joints and fractures increases the pore water pressure that increases the driving force in the rock forming slopes and triggers slope failure. Increase in deforestation, construction of infrastructures and intensity of extreme rainfall in this region further accelerates this process (Fig. 4.5). Landslides, slope failures and erosion of this type shape the landscape of this zone and accelerate sedimentation and flooding in the southern Gangetic Plain. It is found that land degradation of this type in the Siwaliks provided enough load to the high gradient seasonal rivers that originate from the Siwaliks; and ultimately large amount of sediments are deposited in the southern Gangetic Plain. This is the reason why many communities in Gangetic Plain are well below the river beds and every monsoon season brings loss of lives and properties due to flooding and inundation.

Highly jointed meta-sedimentary rocks along with numerous folds and faults in Lesser Himalaya accelerates the landslides and slope failure. Further, intense precipitation and high gradient of rivers in this zone accelerates the debris flow. The scale of devastation brought by such debris flow in this region is huge, as for example single event of the central Nepal cloudburst in 1993 collapsed several highway bridges along the Prithvi Highway of Nepal (Fig. 4.6). The Higher

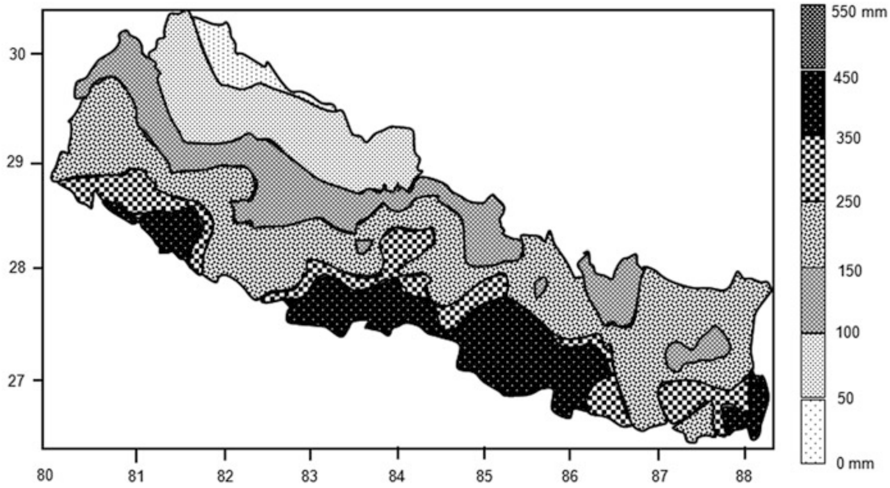


Fig. 4.5 Extreme rainfall map of Nepal, *bar in the right* is rainfall in mm (reproduced after Practical Action 2009)

Fig. 4.6 Collapse of bridge over Malekhu River in central Nepal by the impact of huge amount of debris brought by 1993 central Nepal cloudburst

Himalayan rocks have also gone severe weathering and deformation providing potentiality of big landslides. In many locations, landslides have dammed the deeply incised rivers contributing to Landslide Dammed Outburst flood (LDOF), which is, for example, common in Kaligandaki valley of Nepal. Higher Himalaya along with Tibetan Tethys zone has many glaciers which are retreating very fast contributing to the formation of glacial lakes and their breaching potential is also controlled by geology posing serious threat to GLOF hazard. Occurrence of snow avalanche is also very frequent in this zone. Tibetan Tethys zone is characterized by intense river bank erosion in the alluvial and glacial moraine deposits contributing to bank failure. Debris flow is common in snow fed rivers in this zone.

4.2.3 High Topographical Variation and River Gradient

Topographical variation is quite high in the HKH region that ranges from less than 100 m to more than 8,000 m within a narrow width of few hundred kilometers. Such a high relief together with weak geology and intense precipitation has contributed to the landslide, flood, erosion and sedimentation. The resisting force diminishes in the steep slopes and safety factor becomes critical increasing the probability of landslides and other mass movement activities. The driving force further increases after intense rainfall as a result of increased pore water pressure in the slope; and many landslides got newly generated or reactivated.

Additionally, high topographical variation provides high gradient to the rivers that originate and flow through this region. The rivers are characterized by very high sediment loads and high bed loads resulting from intense channel erosion, bank erosion, landslides and debris flows. This process triggers the flood and inundation problem in the downstream plain area where the river gradient decreases forcing the rivers to lay down the load. As a result there is annual increase in the river bed in the southern edge of the Himalaya generally known as Indo Gangetic Plain. However, there is a challenge of precise data availability on the sediment loads, bed loads and sedimentation in the rivers of the HKH region. Studies show that 600–1,200 mm of rainfall within 3 days in Darjeeling activated many landslides transforming about 20–25 % surface area under cultivation and about 20 mm of soil was removed across the region (Agarwal and Chak 1991). Materials as thick as 10 m were deposited in the river bed due to this single event. The scale of sedimentation in the major river basins within HKH region is very high. As for example, Yellow river is ranked 2nd, Brahmaputra is ranked 4th and Ganges is ranked 5th in terms of the total suspended load they deposit (Chalise 2001; Myint and Hofer 1998; Alford 1992). Studies reported that these rivers deposited 1,100, 540 and 520 million tons of sediment load per year respectively.

4.2.4 Intense Monsoon Precipitation

High intensity rainfall is a characteristic climatic feature of the HKH region which has important implications for landslide, debris flow, bank erosion and flood hazards. For example, during the years 1976–2005, the mean annual rainfall of Nepal was found to be 1,857.6 mm out of which monsoon season that elapses from June to September alone received an average of 79.58% of the total annual rain (Practical Action 2009), which is evident from Fig. 4.7.

In Nepal, flood is the most significant hazard type and landslide is also another hazard that brings big economic loss (Fig. 4.8) and these two hazards affect the lives and properties during the monsoon season from June to September. Floods and landslides are frequent and repetitive, and affect the most populated areas. These two hazards are concentrated in the monsoon season. Correlation between the seasonality of hazard events and that of the affected population reveals that most people are affected in the month of July (Table 4.2), which is the peak monsoon month in Nepal; and most of the flood and landslide events occurred in this month.

Large amount of rainfall within a short period, generally known as extreme rainfall, causes flash floods, massive landslides, soil erosion and sedimentation in hilly and mountainous regions and contribute to inundation in the plain areas. Study

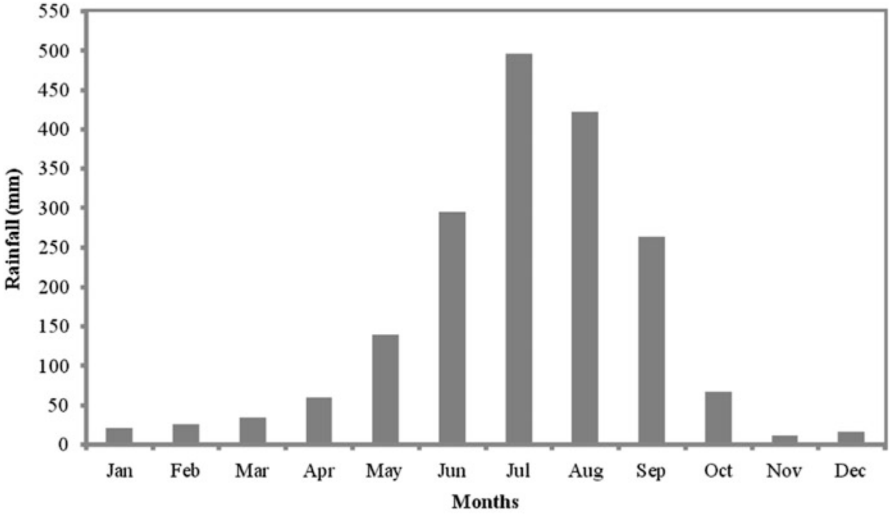
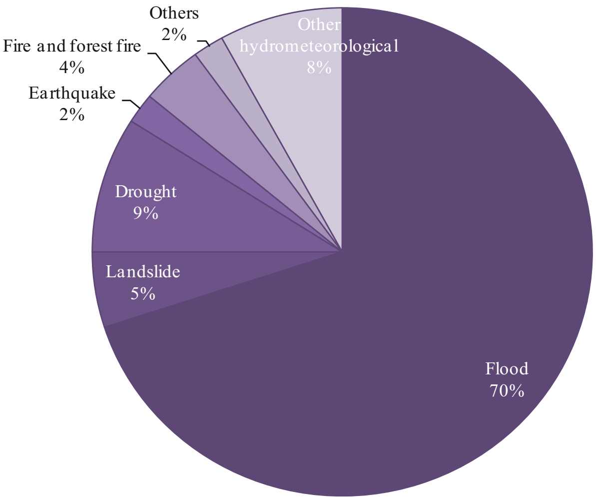


Fig. 4.7 Monthly rainfall distribution in Nepal, average of 1976–2005 (reproduced from Practical Action 2009)

Fig. 4.8 Proportion of economic losses due to different hazards in Nepal during 1971–2010 (reproduced from MoHA 2011)



in Nepal Himalaya indicates that maximum 24 h extreme rainfall reaches up to 482.2 mm (see Fig. 4.5) and such a high 24 h precipitation is concentrated in the foothills of Siwalik which comprises of weak sedimentary rocks that are vulnerable for weathering and erosion. This process contributes to massive landslides and land degradation. Seasonal rivers that originate from the Siwalik region therefore carry lots of sediment and deposit them in the southern plain areas. As a result, in many places the river beds in the highly populated plain areas in the southernmost part of the Himalaya are well above the settlements. Such a high sedimentation and

Table 4.2 Seasonality of affected people in Nepal by months during 1971–2007 (*Source*: UNDP 2009)

Month	Number of affected people
January	25,345
February	8,884
March	282,298
April	163,229
May	61,747
June	79,746
July	3,062,008
August	800,964
September	336,868
October	42,165
November	5,131
December	58,177
Total	4,926,562

increasing level of river bed has intensified the flood events by inundating the villages and ruining the crops. Dahal and Hasegawa (2008) established relationships between landslide occurrence and rainfall characteristics in the form of empirical equations. These empirical relationships of rainfall with landslide occurrence described a threshold rainfall necessary for triggering landslides in Nepal. According to this threshold relation, for rainfall events of shorter duration, such as below 10 h, a rainfall intensity of 12.0 mm/h is necessary to trigger landslides, while an average precipitation of less than 2 mm/h appears sufficient to cause landslide if continued for more than 100 h. Similarly, if 24-h rainfall exceeds 144 mm, there is always risk of landslides in Nepal Himalaya. Comparison between the rainfall data and this threshold relation indicate that there is lot of potential of landslides in this region that are initiated by rainfall. Therefore intense monsoon precipitation and extreme rainfall events can be considered as the major triggers of the geomorphologic hazard in this region.

4.2.5 Climate Change Impact

The Hindu Kush–Himalayan (HKH) region is believed to be a hotspot of climate change (IPCC 2007), as the rates of warming in this region are significantly higher than the global average of 0.74 °C over the past 100 years (IPCC 2007). Study showed that a major part of the HKH region is undergoing warming at rates higher than 0.01 °C per year. Warming rate of 0.01–0.03 °C per year is observed in the western Himalayas, Eastern Himalayas, and the plains of the Ganges basin. Greater warming rates (0.03–0.07 °C per year) are observed in the central Himalayas and the whole of the Tibetan Plateau. However, the change is heterogeneous with respect to the elevation. The area averaged trends of three elevation zones

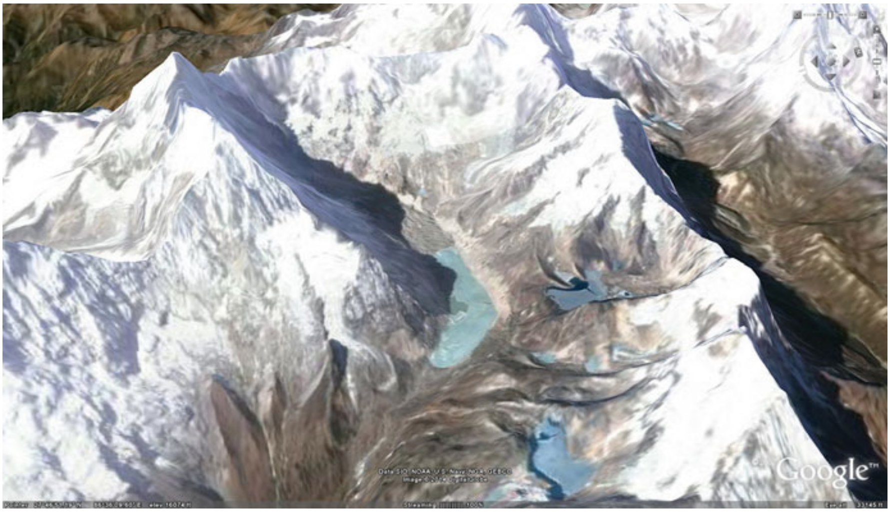


Fig. 4.9 Google image of Lumding Tsho Glacial Lake in Dudh Koshi basin Nepal which is growing very fast, other two lakes can also be seen to the right side of the Lumding Tsho

(<1,000 msl, 1,000–4,000 msl and >4,000 msl) in this region over the past one and a half decades depict that the trend is greater at higher elevations (in the >4,000 msl zone) compared to the other two elevation zones (Shrestha and Aryal 2011). This significant temperature rise in higher elevation zone implies that the glaciers present in this zone are subjected to melt at higher rate resulting in the retreat of glaciers, formation of new glacial lakes or expansion of previously formed lakes. This process ultimately triggers the Glacial Lake Outburst Flood (GLOF) hazard. It is important to note that temperatures are predicted to increase with altitude and are expected to be greater during winter than during summer that can enhance GLOF hazard. Recent simulations by the Indian Network for Climate Change Assessment 2010 to the 2030s indicate an all-round warming over the Indian subcontinent associated with the increasing concentration of greenhouse gases. The annual mean surface air temperature for India is projected to rise by 1.7–2.0 °C in the 2030s (INCCA 2010). At the end of the century the annual average temperature is projected to be warmer by 4–5 °C for western, central and eastern Himalaya and rainfall may increase by 20–40 % over the entire HKH region (Singh et al. 2011).

A number of glacial lakes have developed in the Hindu Kush Himalaya (HKH) during the last half century as a result of the retreat and melting of glaciers (Fig. 4.9). The glaciers are melting rapidly, leading to the formation of new glacial lakes and the expansion of existing moraine-dammed lakes. Mitigation and prevention of GLOF hazards are urgent issues, which need to be addressed in regards to water resource development and conservation in the Himalayas.

Differences in many influencing factors such as climatic variability, local topographic effects, and thickness and spatial distribution of debris cover leads to differences in size, numbers, distribution and types of glacial lakes, as well as rate of retreat or even the existence of advancing glaciers. It should be known that at least one GLOF event was recorded in Himalayan region between every 3–10 years (Bajracharya et al. 2008). These GLOF events have resulted in loss of many lives, as well as the destruction of houses, bridges, fields, forests and roads. The hazardous lakes, however, are situated in remote areas. Study by International Center for Integrated Mountain Development (ICIMOD) in Bhutan, Nepal, India, Pakistan, and China during 1999–2004 revealed that there are 8,790 numbers of glacial lakes in the Himalaya out of which 204 glacial lakes are potentially danger (Bajracharya et al. 2008). Within the HKH region, the eastern part contains the highest number of glacial lakes which are larger in size with the majority being pro-glacial type in nature, while in the western part, most lakes are supra-glacial, less numerous and smaller. Richardson and Reynolds (2000) reported that ice avalanches triggered more than half of all the recorded GLOFs in the Himalayas.

Conclusions

The landscape of the Hindu Kush Himalaya is inherently fragile as a result of the combined effect of lithospheric plate dynamics, weak and deformed rock types, steep topography, intense seasonal precipitation and climate change impact. The region is therefore exposed to multiple geomorphologic and geological hazards like earthquake, landslide, flood, debris flow, soil erosion and glacial lake outburst flood. Each of these hazards and inherent contributing factors are summarized in Fig. 4.10.

Continent-continent collision between southern Indian Plate and northern Eurasian Plate, mountain building process (Himalayan Orogeny) and series of thrust faults control the seismicity of the Himalaya and contribute to the geomorphologic evolution. Continuous strain accumulations along the major active faults due to locking resulted in the high susceptibility of earthquake hazard in the region. The major great earthquakes in this region like Kangra Earthquake in 1905, Nepal-Bihar Earthquake in 1934 and Assam Earthquake in 1950 have occurred south of the Higher Himalaya. The region in between these earthquake events show clear seismic gap without occurrence of major earthquakes representing storage of energy in this region and potential of it hitting by big or great earthquake at any time in future.

Weak geological conditions, topographical variations and heavy monsoon precipitation contribute largely for the flood, debris flow and landslide hazard. Impact of climate change has triggered most of these hazards in recent years. The geology of the Himalayan region is quite fragile since the rocks are highly jointed and deformed because of the tectonic activities and Himalaya forming processes. Further, the rock types are highly diversified in north south direction within a narrow width of few hundred kilometers. Overall geology of HKH can be described by dividing the area into four geological zones that also correspond to definite morphology and tectonics. From south

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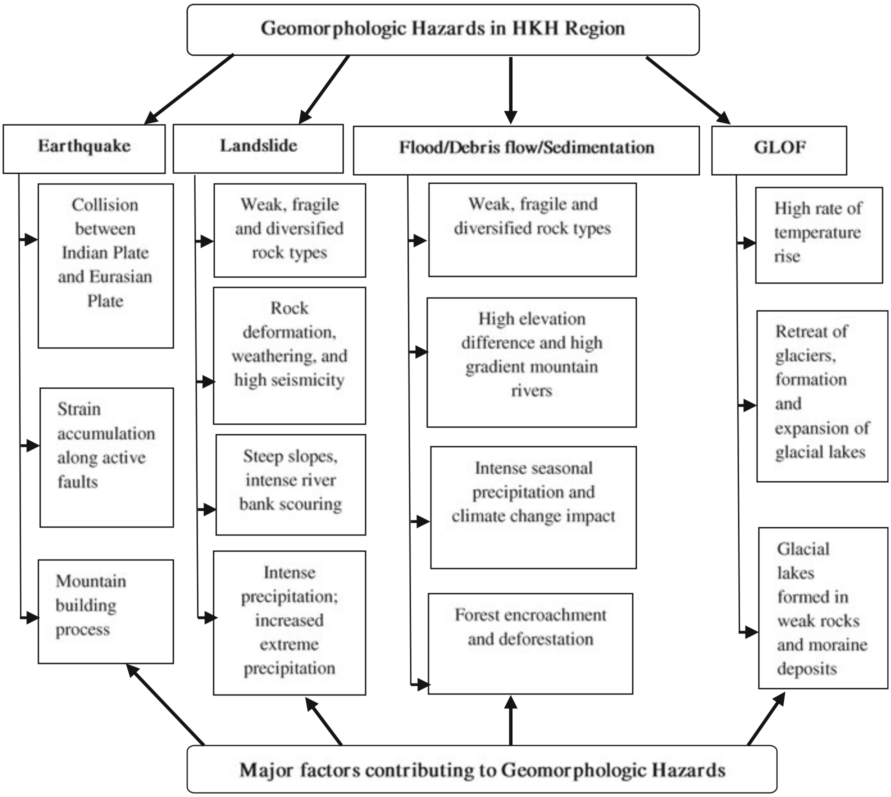

Fig. 4.10 Diagram showing geomorphologic hazards in the HKH region and their contributing factors

(continued)

to north, the four geological and morpho-tectonic zones are Sub Himalayan zone or Siwaliks, Lesser Himalayan zone, Higher Himalayan zone and Tibetan Tethys zone. The Himalaya is bordered in the south by Indo-Gangetic Plain that constitutes recent to Pleistocene deposits of boulder, gravel, sand, clay and remains of animals and plants. Siwalik zone consists of fluvial sedimentary rocks of Neogene to Quaternary period that are soft, loose and easily erodible; and are represented by sandstone, siltstone, mudstone and conglomerate. Landslides, slope failures and erosion shape the landscape of this zone and accelerate sedimentation and flooding in the southern Gangetic Plain. Typical rock types in the Lesser Himalaya are schists, phyllites, quartzites as well as argillo-arenaceous and argillo-calcareous rocks with horizons of marble beds. Highly jointed meta-sedimentary rocks along with

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numerous folds and faults in Lesser Himalaya accelerates the landslides and slope failure. Further, intense precipitation and high gradient of rivers in this zone accelerates the debris flow.

High relief together with weak geology and intense precipitation has contributed to the landslide, flood, erosion and sedimentation. High topographical variation provides high gradient to the rivers that originate and flow through this region. The rivers are characterized by very high sediment loads and high bed loads resulting from intense channel erosion, bank erosion, landslides and debris flows. This process together with extreme monsoon precipitation triggers the flood and inundation problem in the downstream plain area where the river gradient decreases forcing the rivers to lay down the load. These hazards are further intensified by the climate change impact such as high rate of temperature rise and high intensity of extreme precipitation. The Hindu Kush–Himalayan (HKH) region is believed to be a hotspot of climate change as the rates of warming in this region are significantly higher than the global average of 0.74 °C over the past 100 years. Significant temperature rise in higher elevation zone of HKH implies that the glaciers present in this zone are subjected to melt at higher rate resulting in the retreat of glaciers, formation of new glacial lakes or expansion of previously formed lakes. This process has triggered the Glacial Lake Outburst Flood (GLOF) hazard.

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