4 An Introduction to Climate, Hydrology, and Landslide Hazards in the Hindu Kush-Himalayan Region

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Extending some 3,500 km from Afghanistan to Myanmar, the Hindu Kush-Himalaya (HKH) is inherently fragile and susceptible to natural hazards as a result of its extremely weak geology, intense seasonal precipitation, and highly rugged topography. The climate at the macro scale is dominated by the summer monsoon. There is a general decrease in rainfall from east to west and south to north, with monsoon rains being less dominant in the west, and the Siwalik Zone (or Outer Himalaya) receiving more precipitation than the Trans Himalaya. The meso-scale climate is dominated by topography, with valleys being drier than the slopes and ridges, and southern slopes receiving more precipitation than northern ones. Microclimates are dominated by landforms, soil, vegetation, and other land-use practices, and are very complex and difficult to predict. Isolated heavy showers associated with afternoon convective heating, accompanied by lighting and intense precipitation, are characteristic of microclimatic effects in the region.

The HKH and the adjoining Tibetan Plateau together form the largest global storehouse of fresh water in the lower latitudes and are the source of several major rivers and their tributaries. The discharges of water and sediments in these rivers are determined by geology, topography, climate, and vegetation; they are dominated by monsoon characteristics, with high flows in summer and low flows in winter, and with the duration of the high-flow season increasing from west to the east. Suspended sediment discharge in these rivers is very high. The rivers of the Central Himalaya are of three distinct types: comparatively dry rivers originating from the Tibetan Plateau, perennial rivers originating from the Higher Himalaya, and rivers with flash flows originating from the Mahabharat and Siwalik (Churia) ranges. River flows are affected by many factors including extreme precipitation events, outbursts of glacial lakes, and development and failure of landslide-dams.

Inherent local factors, such as geology, topography, hydrology, land cover, and human activities relating to the use and management of land and water have triggered landslides, debris flows, and other forms of slope instability. Snow avalanches and glacial lake outburst floods predominate at very high elevations, debris flows and flash floods in the middle elevations, and floods in the plains. In the east, the likelihood of natural hazards of this type is highest in the summer because of the south-east monsoon, whereas in the west they are more frequent in winter.

Hundreds of lives and billions of dollars' worth of property and infrastructure are lost every year as a result of landslides, debris flows, and floods. A poor understanding of natural and man-made processes and a paucity of relevant hydrometeorological data have perpetuated uncertainties in dealing with natural hazards. It is necessary to fill these gaps and to develop appropriate methods and techniques to deal with mountain hazards within the overall context of integrated watershed management. Hazard control and management techniques should be simple and affordable. ICIMOD has accorded high priority to the problems of natural hazards in the HKH region, focusing on capacity building through training programmes and the dissemination of information.

Introduction to the HKH Region

General features

Extending about 3,500 km from Afghanistan in the west to Myanmar in the east, the Hindu Kush-Himalaya (HKH) is home to approximately 140 million people and influences the lives of more than three times as many living in the downstream basins and plains. As the largest global storehouse of fresh water in the lower latitudes, this greatest of mountain ranges, together with the associated Tibetan Plateau, is the source of such mighty rivers as the Indus, Ganges, Yarlung-Tsangpo, Brahmaputra, Nu-Salween, Mekong, Yangtze, and Yellow. The population of the HKH region, extending over an area of 3.4 million sq.km, is growing rapidly, with an estimated population of 140 million in 1993, expected to double by 2030 (Sharma 1993). The consequences of such population growth will be enormous.

The environment of the HKH is inherently fragile, and the land is highly susceptible to natural hazards due to a combination of weak geology, intense seasonal precipitation, and rugged topography. Hydrological factors further contribute to landslide hazards in the region, while the potential impacts of climate change, although largely unknown, are likely to further exacerbate such hazards.

Climatic features

The HKH acts as a physical and climatic barrier between regions to the north and south. The south-west monsoon, which is only 5,000m thick, cannot penetrate the much higher Himalaya, and must make a virtual U-turn toward the north-west from the Bay of Bengal (Boucher 1979). Similarly, the northern continental airmass cannot easily cross the range towards the south. Thus the HKH acts as an effective barrier between the lower- and middle-latitude climatic systems and can be looked upon as an 'air-shade' between the two.

The range's abrupt rise from the plains further complicates the climate of the region (see, for example, Figure 4.1). It is therefore not possible to speak of a single HKH climate. Although there is a broad monsoonal influence over the southern slopes, a great number of meso and micro climates exist influenced by topographical variations. The different Himalayan climates can be broadly classified as follows.

Macro scale: dominated by the monsoon

The climate of the HKH is, like other parts of South Asia, dominated by the monsoon; but the monsoon is generally weaker here than in the plains as it is further from its source of moisture. Rainfall from the south-west monsoon, which originates in the Bay of Bengal, generally decreases from east to west. Thus while the 'summer' rainy season in the Eastern Himalaya (Assam) lasts about eight months (March-October), it only lasts four months (June-September) in the Central Himalaya (Sikkim, Nepal, and Kumaon) and two months(July-August) in the Western Himalaya of Kashmir. In the Western Himalaya, summer monsoon rains are no longer the most dominant feature, while orography (the terrestrial relief form) becomes extremely important for rainfall (Domroes 1979).

Table 4.1 shows the variation of rainfall patterns from east to west as well as between the Trans Himalayan and Siwalik (Outer Himalaya) Zones. Rainfall in eastern locations such as Pasighat (Assam) and Darjeeling is not only higher but also highly concentrated in the summer months; summer rainfall gradually drops off, and winter precipitation becomes relatively more important, as

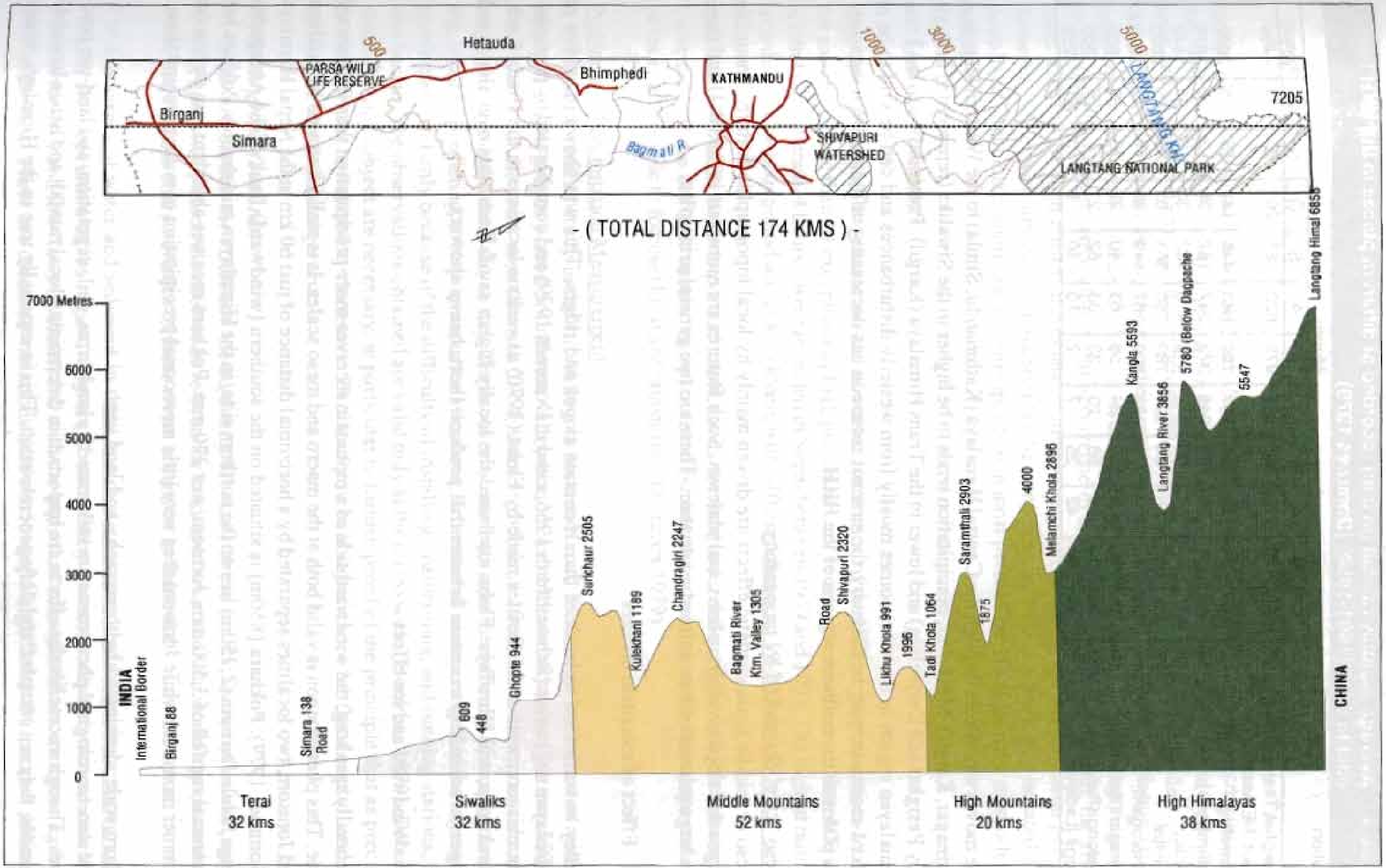

Figure 4.1: **Cross-section of central Nepal (Chalise 1994)**

Table 4.1: Average monthly rainfall (in mm) recorded at different places in the HKH from east to west (1901-1950) (Domroes 1979)

Station	Month												
	J	F	M	A	M	J	J	A	S	O	N	D	Annual
Pasighat/Tirap Frontier Tract, NE Assam	55	97	138	273	466	967	975	622	585	261	33	24	4494
Darjeeling	11	32	54	113	231	597	792	643	446	142	25	6	3092
Kathmandu	10	42	15	26	129	246	373	347	182	36	2	8	1416
Simla	65	70	64	46	60	149	416	419	182	33	10	28	1542
Nainital	70	73	53	38	84	391	769	750	363	61	13	25	2690
Pithoragarh	44	56	40	28	73	183	300	287	149	33	7	22	1223
Srinagar (Kashmir)	70	74	94	90	60	34	56	63	40	28	13	37	659
Kyelong (Punjab)	59	64	102	79	56	23	33	33	52	21	7	26	555
Kargil (Ladakh)	37	38	60	42	25	7	7	10	10	6	3	21	265

one moves westwards through the Central Himalaya (Kathmandu, Simla) to the Western Himalaya (Srinagar, Kargil). Moreover, precipitation tends to be higher in the Siwaliks (represented in Table 1 by Pasighat and Darjeeling) and lower in the Trans Himalaya (Kargil). Precipitation in the Trans Himalayan region in the west comes mostly from westerly disturbances and can be said to be of mixed-monsoon type. In summary, the summer monsoon has decreasing influence from the southern plains to the northern regions of the HKH.

<u>Meso scale: dominated by topography</u>

Meso or middle scale climatic effects are driven mainly by local topographic features: mountain ridges and slopes, valleys, plains, and plateaux. Such features are numerous in the HKH and there is a large amount of meso-climatic variation. There are two general principles.

- Effect of mountain breezes

Valley bottoms tend to be drier than mountain slopes and ridges. This was shown in studies of Himalayan vegetation (Schweinfurth 1956, cited in Domroes 1979) and corroborated by precipitation measurements and estimates made by Flohn (1970) at various locations in the Hindu Kush, Karakoram, and Himalaya. Flohn attributed the locally higher rainfall amounts over slopes and ridges to ascending mountain breezes that produce short, heavy showers.

- Windward and lee effect

Generally speaking, the windward side of a mountain receives more precipitation than the leeward side. This phenomenon is valid both at the macro and meso scales. It is well illustrated by Pokhara and Jomsom, two localities separated by a horizontal distance of just 60 km in the Nepal Himalaya (Domroes 1979). Pokhara (850m) is situated on the southern (windward) flank of the Annapurna range, while Jomsom (2,750m) lies on the northern side, in the Himalayan rain shadow. Pokhara has an annual rainfall of 3,500 mm; Jomsom, just 270 mm. Pokhara receives abundant rain during the summer monsoon, while Jomsom sees very little monsoonal precipitation or winter precipitation.

<u>Micro scale: dominated by topography and land use</u>

Micrometeorological phenomena are influenced by landforms, soil, vegetation, and land-use practices. Though microclimatic effects are important in determining local rainfall and hence landslide hazards, they are complex and defy generalisation. This is especially true in the Himalaya, where extreme topographical variations occur within a short distance. In terms of rainfall, two microclimatic features are of special significance.

- Diurnal variation of rainfall

Studies of diurnal rainfall in Nepal (Dhar 1960) and India (Prasad 1970) have shown conclusively that diurnal variations in rainfall is small in places where precipitation is mainly caused by depressions and cyclonic storms, as these phenomena act irrespective of the time of the day. Diurnal variation can, however, be significant where precipitation is caused by strong insolation (solar radiation per unit area), with heating up and evaporation of moisture during the morning, followed by the creation of convective clouds and occurrence of isolated heavy showers during the afternoon. This can be seen outside the monsoon months, especially during the pre-monsoon period. However, while such diurnal cloudbursts may be very intense, they are generally isolated and short-lived, and hence contribute less precipitation in most parts of the HKH than the macro-level monsoon.

- Intensity of rainfall

High-intensity rainfall is a characteristic microclimatic feature of the HKH region (Domroes 1979). For example, more than 19 exceptionally high precipitation events – those with more than 400 mm of rain falling within 24 hours – were recorded in Nepal between 1959 and 1993. The highest rainfall recorded in a 24-hour period was at Kulekhani, with 540 mm of rain on 19-20 July 1993.

Such heavy rainfalls have important implications for landslide, debris flow, and flood hazards. Unfortunately, the difficult terrain, complex features, and sheer heights of the Himalaya make it virtually impossible to forecast localised rainstorms (Domroes 1979).

Problems of Precipitation Measurement

A micro-scale rainfall study in the Jiri Valley, in eastern Nepal, found wide variations in rainfall among five rain gauges placed at different valley-bottom and hillside locations (Dittman 1970). Other studies in the same area (Boesch 1964; Boesch and Groh 1966) have shown considerable irregularity in rainfall from day to day. These observations highlight the difficulty of simply recording, let alone predicting, precipitation in the Himalaya. True rainfall measurements in the region are problematic, not only because of the difficulty of installing, maintaining, and running stations, but also because the observations obtained are valid only at the micro scale (Domroes 1979). Detailed studies on this subject are necessary, in particular to furnish proof of the principle that as precipitation increases its variability decreases. This is of practical significance for flood control and for agriculture and soil management.

Hydrological features

As mentioned earlier, the HKH and the adjoining Tibetan Plateau are the source of several major rivers (Figure 4.2) , which themselves have been the cradles of several of the world's great civilisations. Some of the characteristics of these rivers are given in Table 4.2.

The discharges of water and sediment in these rivers are governed by the geology, topography, climate, and vegetation of the region; they are dominated by monsoon characteristics, with high flows in summer and low flows in winter, and with the high-flow season's duration increasing from west to the east. There are dramatic variations between low and high flows. Suspended sediment

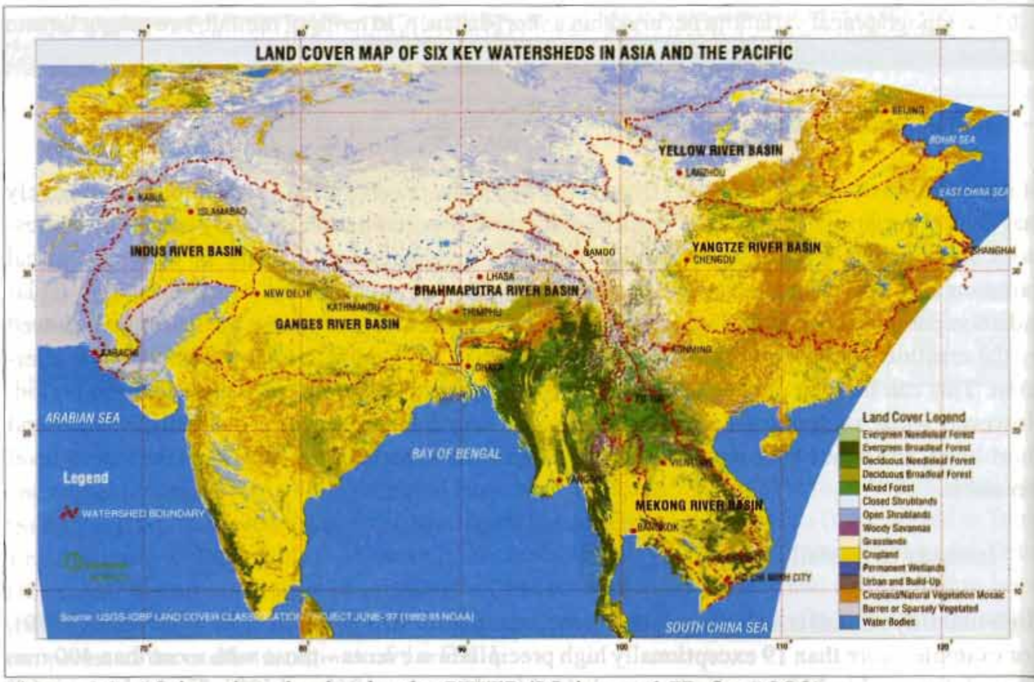

Figure 4.2: Major river basins in the HKH (Myint and Hofer 1998)

Table 4.2: **Major rivers draining the HKH region (Myint and Hofer 1998; Alford 1992)**

River	Indus	Ganges	Brahmaputra	Mekong	Yangtze	Yellow
Basin area (sq. km.)	945,000	1,050,000	580,000	795,000	1,808,500	752,443
Length (km)	3,200	2,950	2,880	4,800	6,290	5,464
Average annual discharge (million cumec)	115,000 (upstream from Tarbela)	460,000	600,000 (at Bahadurbad)	NA	NA	NA
Total suspended sediment (million tons per year)	250	520	540	150	480	1100
Suspended sediment load (world rank)	9	5	4	12	7	2

Note: NA = data not available; cumec= cubic metres per second

discharge in these rivers is very high. Discharge in the Indus river in the west is highest in summer as a result of increased ice melt, almost all its tributaries are fed by glaciers. In the central area the contribution of glacier melt is less significant. In the east, the Brahmaputra's seasonal variation in discharge correlates with the temporary storage of early precipitation as snow and subsequent melting.

The rivers of the Central Himalaya are of three distinct types: comparatively dry rivers originating from the Tibetan Plateau, perennial rivers originating from the Higher Himalaya, and flashy rivers (i.e., rivers with flash flows) originating from the Mahabharat and Siwalik ranges.

From time to time river flows may be affected by mud flows or landslide blockages. Flood waves as high as 9m have been attributed to glacial lake outburst floods and the failure of landslide-dams (Alford 1992). The bedloads (the solid material like sand, gravel, and sometimes boulders pushed down by rivers rather than being carried in suspension) in these rivers at the time of the failure is extremely high but difficult to measure.

The region's rivers have witnessed major climate-induced disasters in recent years such as the consecutive catastrophic monsoon floods in Bangladesh during 1987 and 1988 (Rogers et al. 1989), the Indus Basin floods in Pakistan in September 1992, and floods and debris flows in south-central Nepal in July 1993 (Dhital et al. 1993).

Landslide Hazards in the HKH

Terminology

The term **landslide** is commonly used to denote the downward and outward movements of slope-forming materials along surfaces of separation by falling, sliding, or flowing at a faster rate. **Falls** are abrupt movements of materials that become detached from steep slopes or cliffs and drop down by free fall or a series of leaps and bounds. **Slides** (often called landslides) refer to mass movements with a distinct surface of rupture separating the slide material from more stable underlying material (**slope failure**). The downward sliding material is usually relatively dry. A **debris slide** is a slide of coarse-grained soil usually containing angular rock fragments, typically made up of debris from glaciers or from colluvium resulting from the disintegration of rocks in situ. A **debris flow** is a rapid mass movement of loose soil, rocks, and organic material along with entrained air and water to form a slurry that flows downslope. A **debris avalanche** is a very to extremely rapid debris flow. An **earth flow** has a characteristic bowl-like depression at the head where the slope material becomes liquefied and flows out; the flow is usually channelised on the slope and spreads out at the toe. The flow generally occurs in fine-grained materials or clayey rocks under saturated conditions. A **mud flow** is a type of earth flow containing about 50% of sand, silt, and clay-sized particles that are well saturated and flow rapidly. (Deoja et al. 1991)

A **landslide-dam** is a natural river dam formed by the rock, earth, debris, and or mud transported by a landslide. They are easily formed in the steep, narrow valleys of high rugged mountains, and can fail catastrophically, causing major downstream flooding and loss of life. A **glacial lake outburst flood (GLOF)** is a debris torrent resulting from the sudden and catastrophic release of water from a lake of glacial origin. Such lakes are usually impounded by glacial ice or a moraine. (Deoja et al. 1991)

Factors affecting landslide hazards

Mountain slopes are only conditionally stable, as they are continually subject to the downward pull of gravity. There is therefore a general tendency for mountain slopes to slide down, making them inherently hazardous. The causative and triggering factors for landslide hazards and slope instability are briefly discussed here in the context of the HKH.

<u>Natural factors</u>

These include inherent local factors such as:

- geology (including tectonics, seismicity, and soil type);
- topography (slope inclination, elevation, relief, and aspect);
- hydrology (including groundwater);
- vegetation cover;
- climate[1] (radiation, temperature, precipitation).

[1]Although climate is generally considered to be an external factor, it determines the characteristics of local ecosystems and hence can be considered as an inherently local factor too.

In addition, there are external (uncertain) factors such as:
- abnormal/extreme weather events;
- impacts of climate change (at present essentially unknown).

Human factors
These include:
- changes in (or inappropriate) land use and poor watershed management practices (deforestation, extension of agriculture on steep slopes, unplanned settlement, rural and urban growth);
- intensive agriculture/unsuitable crops;
- poor water management.

Principal triggering factors
The principal triggering factors for landslides, debris flows, slope failures, and other associated natural hazards in the HKH are:
- intense precipitation;
- earthquakes.

As it is difficult to predict or control earthquakes, disasters triggered by them cannot be avoided (although their potential effects can be mitigated by appropriate planning and construction). However, landslides, debris flows, and slope failures triggered by intense precipitation can be predicted, controlled, mitigated, and to a large extent managed.

Natural hazards in different elevation zones

The HKH is tectonically very active and hence inherently vulnerable to hazards. In addition, these mountains – particularly in their eastern parts – are exposed to intense seasonal precipitation during the summer monsoon. This acts as a trigger for various types of natural hazards in different elevation zones. Snow avalanches and glacial lake outburst floods predominate at high elevations (above 3,500m), while landslides, debris flows, and flash floods are common in the middle elevations (500-3,500m). Floods are the principal hazard in the lower valleys and plains. Figure 4.3 shows a generalised view of natural hazards at different altitudes; the relative seasonal susceptibility to hazards from west to east is schematically represented in Figure 4.4.

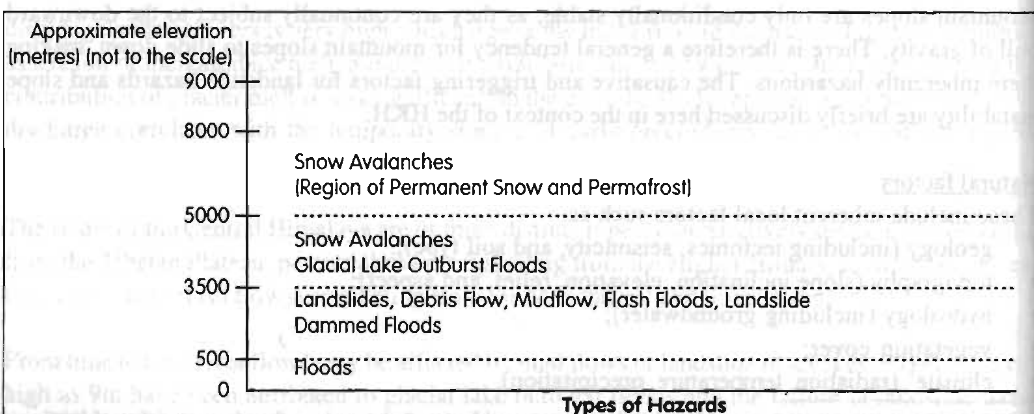

Figure 4.3: Types of natural hazard in different elevation zones of the HKH

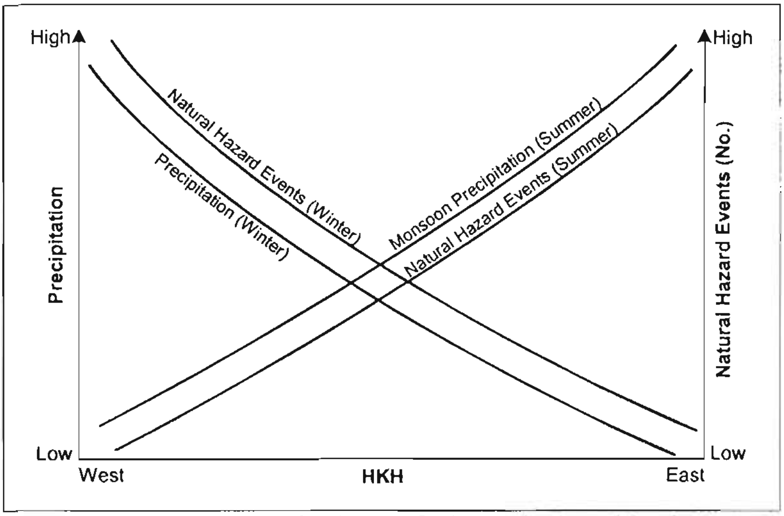

Figure 4.4: **Generalised view of the relationship between precipitation, natural hazards, and seasonality across the HKH**

Loss and damage from natural hazards

The consequences of extreme weather events are grave. Hundreds of lives and billion of dollars' worth of property and infrastructure are lost in the region every year as a result of landslides, debris flows, and floods, along with the permanent or temporary destruction of scarce agricultural lands. In China, for example, landslides alone are estimated to cost US$15 billion and cause 150 deaths annually (Li 1996). In the Indian Himalaya, average annual economic losses resulting from landslides are estimated to be about US$60 million (Thakur 1996). In Nepal, landslides and floods take approximately 400 lives and cause nearly US$ 20 million worth of infrastructure damage annually (Khanal 1996). Across the globe, the total loss of life and property resulting from landslides is far greater than that resulting from any other potentially predictable geological hazard (Leighton 1976).

Natural hazards: lack of information and understanding

Much of the discussion about environmental degradation in the HKH that started in the mid-1970s (Eckholm 1975 and 1976) focused on ecological concerns, particularly on deforestation caused by a fast-growing human and animal population and its impact on erosion and sedimentation. Since then the bulk of research work has attempted to quantify the relative roles, impacts, and contributions of human and natural processes in the region's environmental degradation. A recent study has shown that human processes are more influential in the degradation of micro-basins (the area drained by a stream or small river) whereas natural processes predominate in macro-basins (the area drained by a river and all its tributaries) (Grosjean et al. 1995).

The continued preoccupation with differentiating the roles of humankind and/or nature has somewhat overshadowed the fact that the HKH environment is not only inherently fragile but also subject to two powerful triggering factors: earthquakes and climate. Earthquakes are occasional occurrences; although their effects can be devastating they are difficult if not impossible to predict. In contrast, climate affects the environment regularly, and overall there is a better chance of predicting and avoiding climate-caused hazards. The effects are more intense during extreme weather events — which have occurred with increasing frequency in recent years (Chalise and Khanal this volume).

Though still uncertain, the effects of climate change on the HKH region could include increased monsoon rainfall, enhanced precipitation outside the monsoon period, and shrinking of areas under snow and permafrost (Chalise 1994). These carry the risk of an increase in hazardous events associated with water flows, since both accumulation and melting of snow occur primarily in the summer in most parts of the HKH, and could increase the summer discharge and thus the risk of floods.

There has been insufficient research into climate and hydrology in the HKH. This is primarily because it is difficult and expensive to establish reliable monitoring systems. In addition, hydrometeorological services and research have a short history in many countries of the region. Although hydrological and climatic data for operational and forecasting purposes are regularly collected in many countries, the data are rarely shared. These difficulties are serious stumbling blocks for dealing with known or new uncertainties.

More attention should be focused on understanding, predicting and avoiding climate-based hazards so that increased loss of life, property, and infrastructure can be avoided.

Control and Management of Slope Instability

Although much progress has been made, new methods and techniques are still needed to deal with the problems of slope instability and associated hazards. The concerns of mountain people about slope instability or landslides on their own farmlands are no less important than those associated with infrastructural development. This aspect tends to be neglected, however, and priority is normally given to devising new methods and techniques to stabilise slopes or control landslides in areas of major infrastructural development projects. It is extremely important to consider the problems of slope instability within the overall context of integrated watershed management, including local communities perceptions of hazards, and their socioeconomic imperatives and cultural practices. It is equally important that any new method should not only be well tested for its suitability but should also be

- simple – easily understood, assimilated, and adopted by the community, and
- affordable – within the means of the community.

If they are not simple and affordable, new methods and techniques, however technically sound, are unlikely to be used widely.

Another important consideration in the development of methods to control and manage slope instability and landslides is the chronic lack of data for the HKH, and the continuing difficulty in obtaining them, in particular:

- long-term climatological, hydrological, ecological, and spatial data;
- short-term data for parameters such as precipitation intensity and infiltration;
- detailed information on local geology, land use; and land cover; and
- critical threshold values of rainfall for slope stability.

Considering these limitations, both simple methods such as direct measurements of rainfall and runoff, and innovative approaches such as remote sensing (RS) data and geographic information systems (GIS), will need to be used in developing measures to stabilise slopes and landslides and for the mitigation of natural hazards in the HKH.

It is equally important to remember that a unique combination of 'extremes' (high population pressure, active geology, high elevations, very steep slopes, and intense seasonal rainfall) makes the HKH extremely vulnerable to natural hazards. Methods should be devised that help to mitigate and avoid disasters through better preparedness. An improved understanding of natural processes, their impacts on natural hazards, and their interrelationships with human processes on mountain slopes are the important elements to be considered while devising methods for the control and management of mass movements and slope instability in the HKH watersheds. It should also be remembered that although individual slopes can be stabilised in isolation, it is best to look at slope instability within the context of a watershed.

ICIMOD's Programme Activities in the Management of Natural Hazards

ICIMOD has accorded high priority to the problems of natural hazards, including slope instability, in the HKH within the overall context of its concern for sustainable development and improved living conditions for the region's inhabitants. From ICIMOD's very inception, its programme activities have focused on the problems of environmental degradation due to both natural and human processes. Programme activities relating to the management and control of natural hazards and slope instability are essentially geared towards building regional countries' capacities to deal with these problems. They are implemented in partnership with national institutions (GOs, NGOs, and academic bodies) and are developed through regional consultation and the integration of available knowledge, methods, and skills with new and sophisticated technologies and analytical systems. These programmes are mainly focused on training at various levels and raising awareness to create better preparedness for, and avoidance and mitigation of, disasters. Considering the challenges of natural hazards in the region and the lack of pertinent data, much work still needs to be done. However, the training organised by ICIMOD under its various programmes is expected to contribute significantly to enhancing human capacity to deal with these problems in the HKH countries at all levels.

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