Rain and meltwater penetrate joints and produce hydrostatic stress in rocks. Rain increases the porewater pressure on soils and, consequently, decreases the shear resistance. Rainfall measurements have shown that recurrent slope movements occur during periods of exceptionally high rainfall (Záruba &Mencl 1982).

The relationship between the amount of rainfall and frequency of landslides has been studied by many authors. In Nepal, Karmacharya (1989) studied the relationship between total annual precipitation recorded in the *Gorkhapatra*, a daily newspaper, and the frequency of landslides during the period from 1971 to 1980 and found a strong correlation between them.

More detailed studies on the relationship between rainfall and landslide events are available on the Darjeeling Himalayas in India. The area lies close to Eastern Nepal. Froehlich et al. (1990) observed that short-distance overland flow and slope wash began in the tea plantation area when the rainfall exceeded 50mm with a 0.5mm/min intensity. Shallow slides or slumps on steep slope segments began to occur, mainly along undercut sections of roads or rivers, when 24-hour rainfall events exceeded 130-150mm, or on occasions of continuous rain over a three-day period in excess of 200-240mm.

Li (1990) studied the landslides induced by heavy rainstorms in the eastern part of the Sichuan Basin, about 240km NNW of Chengdu, China, in 1982. Three hundred and ten landslides in four different areas of the country, including 85 major landslides, were studied in detail. Li concluded that, if the cumulative precipitation of the area is 50 to 100mm in one day and daily precipitation more than 50mm, somewhat small-scale and shallow slides will occur. When cumulative precipitation within two days is from 150mm to 200mm and daily precipitation about 100mm, the number of landslides will increase with precipitation. And, when cumulative precipitation exceeds 250mm in two days, with an average intensity of more than 8mm/hour in one day, the number of large landslides increases abruptly (Li 1990, p27).

In Japan, rainfall of from 150 to 200mm, with an intensity exceeding 20 to 30mm/hour, is considered to be critical (Cotecchia 1978). In southern Italy, old landslides are immediately reactivated after every strong storm. In the Western Alps and their forehills, the most frequent critical rainfall is 100-200mm/day (Cotecchia 1978).

In the Higher Himalayan Zone, the water freezing in the fractures and discontinuities increases in volume and tends to widen them. As a result the rock becomes vulnerable to sliding.

Monsoon and Rainstorm (Cloudburst) Events in Nepal

The climate of Nepal is essentially controlled by monsoon winds and the physiography. The monsoon winds result from an inland low pressure that develops in summer, and they are accentuated by a northward migration of air from the southern hemisphere. These are south to southwesterly winds which carry moisture from the Indian Ocean to Nepal (Nelson et al. 1980). The wet season is from June to September. Generally, in Nepal, the precipitation decreases from east to west during the summer monsoon, whereas the winter monsoon shows the reverse trend. Approximately 80 per cent of the total annual rainfall occurs between June and September (Fig. 6), with relatively limited precipitation from November to February. Rains brought by these winds are characterised by strong seasonality, variation in the amount of precipitation, and high intensity at lower altitudes.

The regional climate (Fig. 7) is strongly influenced by the mountain ranges. A distinct rainshadow area is created by the Great Himalayan Range (Fig. 1). Generally, the Inner Himalayan valleys are very dry. The local climatic pattern is strongly controlled by the slope aspect. The south-facing slopes have a higher insolation rate, resulting in higher evaporation rates. This, in turn, is reflected in the greater sparsity of vegetation on the south-facing slopes than on the north-facing slopes (Nelson et al. 1980).

Measured values of mean annual precipitation in Nepal range from approximately 250mm in the stations north of the Great Himalayas to over 3,000mm in numerous other stations. The mean annual precipitation in the 114 stations considered was 1,627mm (Alford 1992). It is not uncommon for 10 per cent of the total annual precipitation to occur on a single day and for 50 per cent of the total to occur during 10 days of the rainy season (Alford 1992). Such uneven distribution plays an important role in triggering landslides.

Figure 6: The distribution of active faults in Nepal (Dixit et al. 1993)

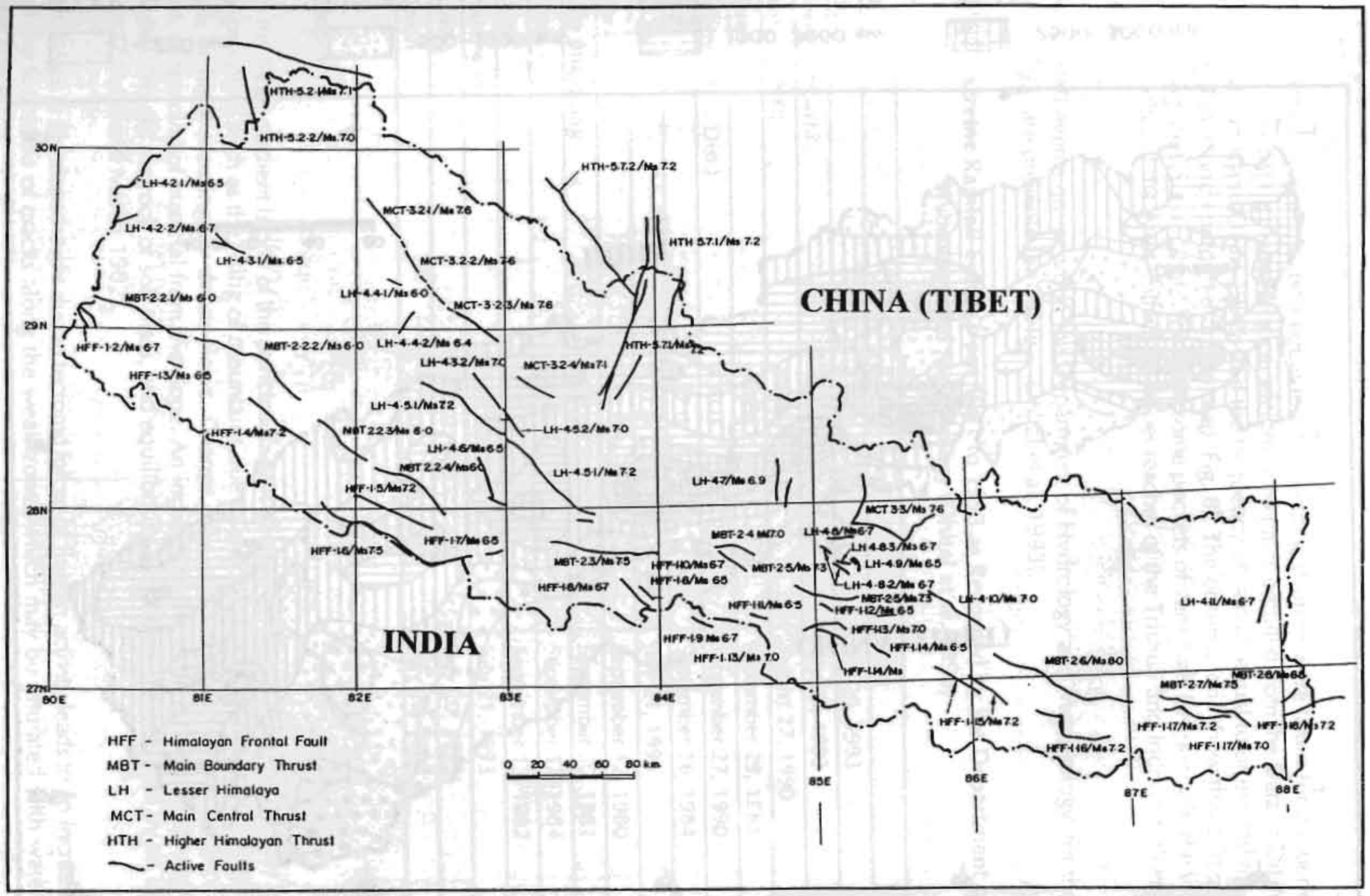
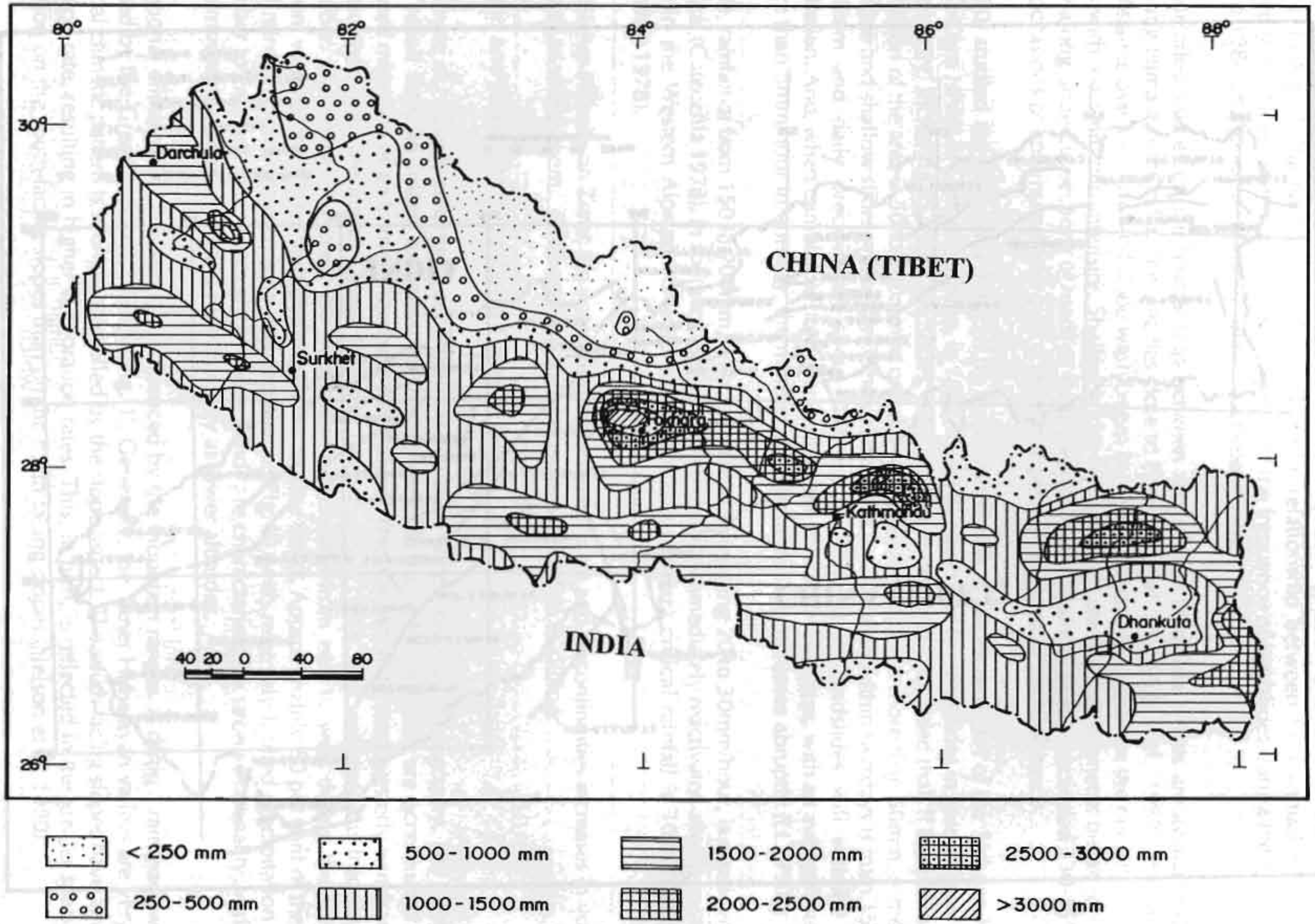


Figure 7: Mean annual precipitation (mm) in Nepal between 1971 and 1985 (DHM 1988)



The bulk of the precipitation data from the Nepalese hills is from the valley stations and may not represent the precipitation records of the adjacent slopes and ridges. In the Khumbu Basin of Eastern Nepal, Yasunari and Inoue (1976) as well as DIHM (1976) reported that, during the monsoon period, the precipitation values of the adjacent ridges and glaciers were four to five times those of the valley floors. On the other hand, the available hydrometeorological data are often inadequate and discontinuous (Chalise et al. 1993).

The 24-hour maxima with precipitation equal to or exceeding 100mm were taken for the period from 1981 to 1990 from the existing meteorological stations of Nepal (Compiled from the Data of DIHM 1984, DIHM 1986, DHM 1988, and DHM 1992), and the frequency of rainfall equal to or exceeding 100mm in 24 hours were plotted and contoured on the map (Fig. 8). The observations show that a frequency of 10 to 20 exists along the Churia Range. There are some pockets of very high frequency in the vicinity of Ilam, the upper reaches of the Arun Valley, the upper reaches of the Trishuli and Indrawati rivers, and in Pokhara (Fig. 8).

The extreme rainfall events on record in the Department of Hydrology and Meteorology, for the period from 1981 to 1993, are presented in Table 7 (Dhital et al. 1993).

Table 7: Extreme Rainfall Events from 1981 to 1993 as Recorded by the Department of Hydrology and Meteorology (Dhital et al. 1993)

Station	Rainfall (mm)	Date
Tistung	539.5	July 20, 1993
Hariharpur Garhi	482.5	July 20, 1993
Hetaunda (NFI)	453.2	August 27, 1990
Baluwa	446.0	September 29, 1981
Hetaunda (Ind. Dist.)	438.0	September 27, 1990
Kankai	437.0	September 16, 1984
Patharkot	437.0	July 21, 1993
Bajura	431.0	September 12, 1980
Mane Bhanjyang	420.0	September 30, 1981
Tribeni	403.0	September 17, 1984
Semari	401.0	September 13, 1982
Amlekhganj	399.0	July 21, 1993
Markhu	385.0	July 20, 1993
Daman	375.0	July 20, 1993

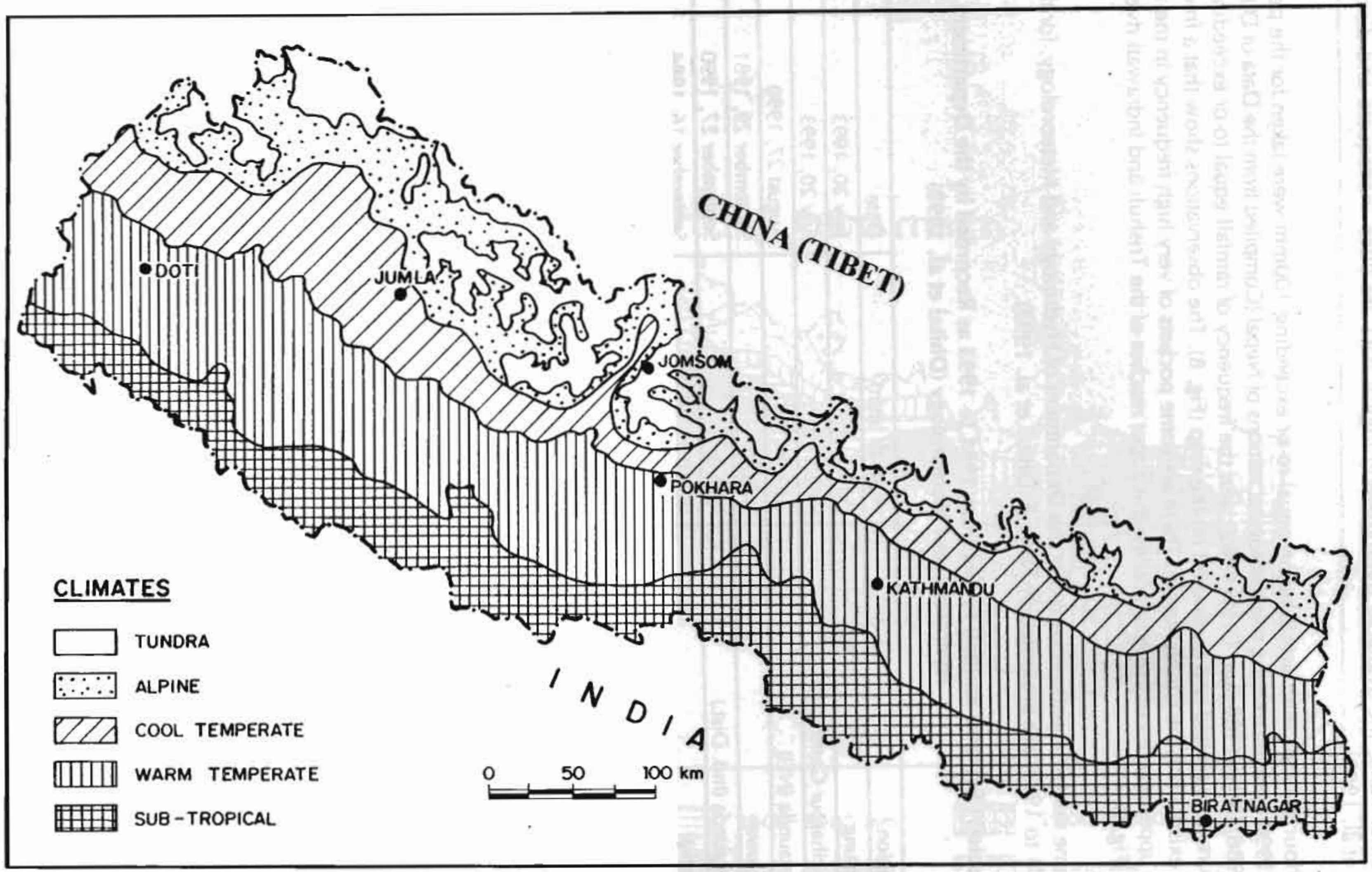
Natural Slopes

Change in the slope gradient is one of the principal factors causing landslides. The change may be caused by natural processes such as the rising of mountains due to tectonic forces, river undercutting of the toe of a slope, or bank scouring by debris flows. Change may also be caused by excavation, blasting, cultivation, or removal of material from the slope. An increase in the slope gradient produces a change in the internal stress of the rock or soil mass, and equilibrium conditions are disturbed by an increase in shear stress (Záruba and Mencl 1982).

Similarly, change in the slope height due to tectonic forces or human activity leads to an increase in shear stress and the formation of cracks along the weak zones which may be saturated with water, thereby causing the failure.

Generally, in the Nepal Himalayas, slope gradients between 30 and 40 degrees are most critical for failure (Dixit 1994 a,b; Deoja et al. 1991; DPTC/TU 1994 a,b). However, landslides occur on gentler as well as on steeper slopes.

Figure 8: Types of climate in Nepal (Shrestha et al. 1984, redrawn)



Vegetation

Vegetation plays a vital role in slope stability and the soil erosion process. Rainfall erosivity increases during the monsoon, as does the ability of vegetation to protect the topsoil, consequently reducing the surface erosion rate as the monsoon progresses. However, mass wasting probability increases during the monsoon because the subsoil becomes saturated with moisture (Galay 1987). Generally, the vegetation cover increases the shear strength of the soil with its root network and protects the slope from landslides. The roots of the trees maintain the stability of slopes through their mechanical and biological effects and help to dry the slopes by absorbing some of the groundwater. However, if the landslide is deeper than the penetration depth of the roots, the vegetation cannot stabilise the slope.

Greenway (1987) classified the mechanism by which vegetation influences slopes into hydrological factors and mechanical factors. A short description of these is presented in Table 8.

Table 8: Effects of Vegetation on Slope Stability (Greenway 1987)

Hydrological Mechanism		Influence
1.	Foliage intercepts rainfall, causing absorptive and evaporative losses that reduce rainfall available for infiltration.	B
2.	Roots and stems increase the roughness of the ground surface and the permeability of the soil, leading to increased infiltration capacity.	A
3.	Roots extract moisture from the soil which is lost to the atmosphere via transpiration, leading to lower porewater pressure.	B
4.	Depletion of soil moisture may accentuate desiccation cracks in the soil, resulting in a higher infiltration capacity.	A
Mechanical Mechanisms		
5.	Roots reinforce the soil, increasing soil shear strength.	B
6.	Tree roots may anchor into firm strata, providing support to the upslope soil mantle through buttressing and arching.	B
7.	Weight of the trees surcharges the slope, increasing normal and downhill force components.	A/B
8.	Vegetation exposed to the wind transmits dynamic forces into the slope.	A
9.	Roots bind soil particles in the surface of the ground, reducing their susceptibility to erosion.	B

A - Adverse to stability
B - Beneficial to stability

Glacial Lake Outburst Floods

A glacial lake originates from a glacier and is usually formed at the end (terminus) of it. Almost all the glacial lakes in the Himalayas are surrounded by lateral and end moraines deposited during glacial activity in the Little Ice Age between the 15th and 19th centuries (Yamada 1993). Glacial ice tends to melt in the lower part of the glacier when it is retreating, and the meltwater is often surrounded by lateral and end moraines. As a result, a glacial lake is formed. As the morainic material (till) is generally unconsolidated and unsorted, a slight disturbance or overtopping of the lake by meltwater may lead to a catastrophic flood. A Glacial Lake Outburst Flood (GLOF), or *jokulhloup*, is a catastrophic surge of water and debris caused by the sudden outburst of glacial lakes. It creates serious problems for cultivated land, infrastructure, and settlements downstream.

Glacial lakes in the Himalayas of Nepal can be classified into moraine-dammed lakes, glacier ice-dammed lakes, and ice core-moraine-dammed lakes. The transportation of sediments during a GLOF is exceptionally great and material is eroded from river banks, terraces, and slopes. As a result, several slope instabilities are triggered.

The most active glaciers in Nepal and the adjoining region of Tibet in China are located in the eastern part of the region. The frequency and extent of GLOFs in the Himalayas are not yet adequately documented.

Most of the known cases have occurred in the major rivers of the Koshi Basin (Nepal) and the Pumpu Basin (China). Some of the well-recorded events are the GLOFs along the Bhote Koshi-Sunkoshi (Zhangzangbo) in 1964 and 1981; and the GLOFs along the Arun River (1964) and the Tamur River (1980) (Mool 1995). On August 4, 1985, the Dig Tsho moraine-dammed lake in front of the Langmoche Glacier overtopped and burst its dam. It destroyed the nearly-completed Namche Small Hydel Project (cost estimated at US$ 1.5 million) and numerous footbridges and trails; many lives were lost (Ives 1986, Mool 1995).

Earthquakes

Ground shaking, caused by earthquakes, large-scale explosions, vibration of the trees by strong wind, and mechanical vibrations affect slope equilibrium on account of the temporary changes of stress caused by oscillations of different frequencies. In water-saturated fine sand and sensitive clays, the displacement and rotation of grains can result in sudden liquefaction of the soil.

During earthquakes with intensities higher than VIII on the Modified Mercalli Scale (of a magnitude over 6.5 on the Richter Scale), particularly those occurring in the mountain regions, the greatest damage to property and lives is caused by seismo-gravitational phenomena. Movement of the earth's crust is accompanied by major deformations of the ground surface and destruction of mountain slopes (Záruba and Mencl 1982).

Seismicity in Nepal

The continued northward movement of the Indian Plate against Asia keeps the Himalayan region constantly seismically active. Numerous active faults, within Nepal and the adjacent regions (Fig. 9), are the potential sources of earthquakes, along with the moderate to deep focus earthquakes that develop along the main decollement plane beneath the Himalayas.

Nepal has experienced numerous earthquakes in the past. Some of the earliest recorded earthquakes date back to 1255, when an earthquake occurred around Kathmandu Valley with an estimated magnitude of 7.7 on the Richter scale. Earthquakes of similar magnitude rocked Kathmandu in 1408, 1681, 1833, and 1869 (MHP 1993). Bajhang District, in Western Nepal, experienced strong earthquakes in 1916 (7.7M) and 1980 (6.5M). The famous 1934 Bihar-Nepal earthquake, with an estimated magnitude of about 8.4, caused great losses of life and property. In 1988, an earthquake with a magnitude of 6.6, with its epicentre near Udayapur in Eastern Nepal, destroyed 65,000 houses and caused 700 people to lose their lives (Dixit et al. 1993).

Singh (1985) studied the earthquake of July 29 1980 in Far-western Nepal and prepared intensity maps. Dikshit (1991) studied the geological effects and intensity distribution of the Udayapur (Nepal) earthquake of August 20 1988. He also prepared an intensity map of the earthquake. Pandey and Molnar (1988) reassessed the distribution of intensity of the Bihar-Nepal earthquake of January 15 1934 and concluded that the rupture zone of the earthquake lay beneath the Lesser Himalayas and not beneath the plains of North India. Pande and Nicolas (1991) assessed the aftershock sequence of the Udayapur earthquake of August 20 1988; the preliminary fault plane solution for the main shock shows a 135°N thrust faulting with dextral strike-slip component.

There are few data available on the nature and extent of seismically-induced landslides in Nepal. Historical records on large earthquakes do not mention landslides induced by earthquakes. Dikshit (1991) has reported numerous landslides induced by the 1988 earthquake in Eastern Nepal.

Bajracharya (1994) made an epicentre distribution map of past earthquakes (M>4) in Nepal (Fig. 10). He also prepared a simplified seismic risk map of Nepal based on the historic seismic data from 1911 to 1993. The map shows three prominent high seismic risk zones in Far-western, Western, and Eastern Nepal (Fig. 11).

Figure 9: The frequency of precipitation equal to or exceeding 100mm in 24 hours, total of 1981-1990 (Compiled from the Data of DIHM 1984, DIHM 1986, DHM 1988, and DHM 1992)

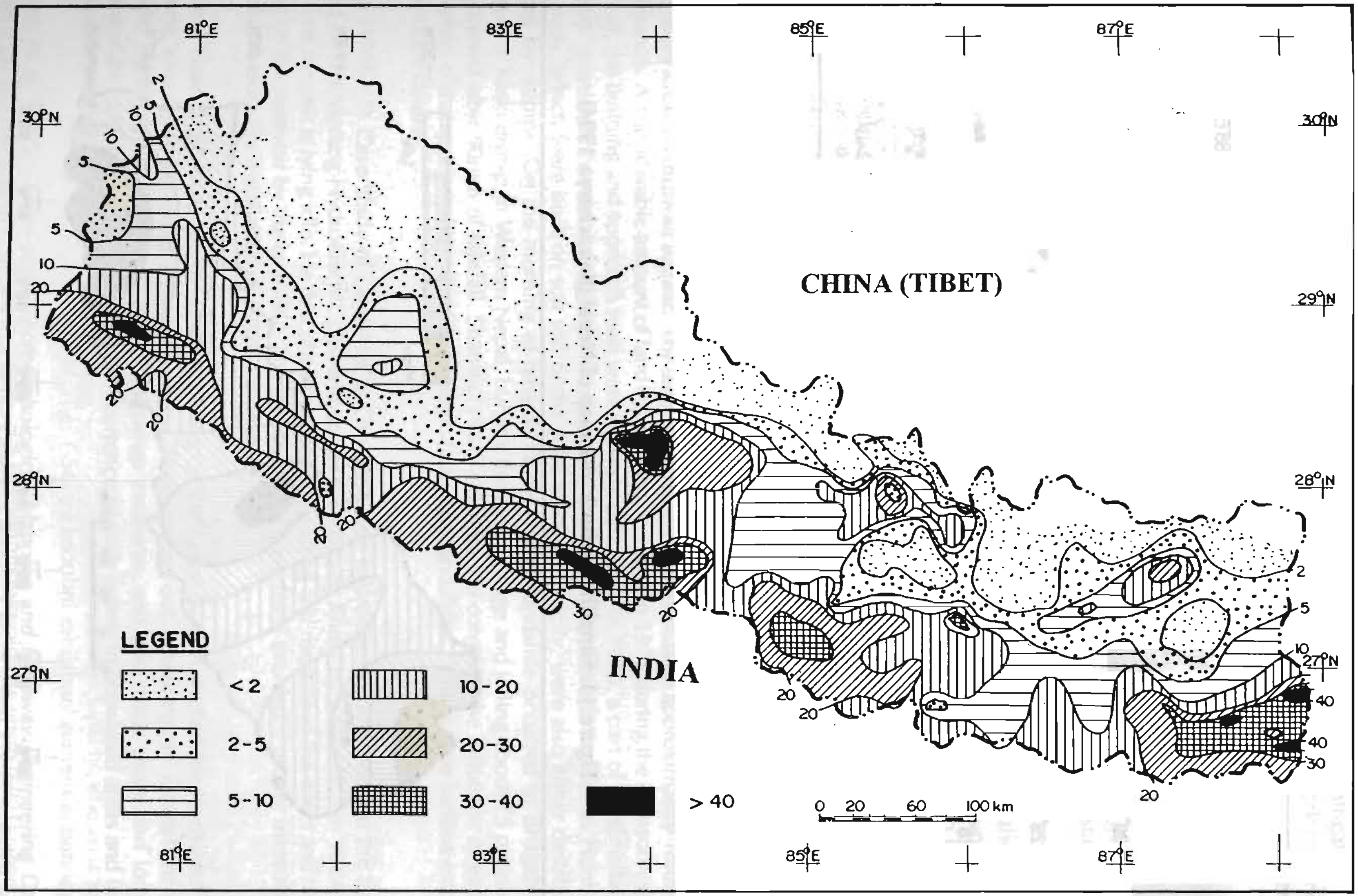


Figure 10: The epicentre distribution of the past earthquakes (M < 4) in Nepal (data between 1911-1993, 830 earthquakes) (Bajracharya 1994)

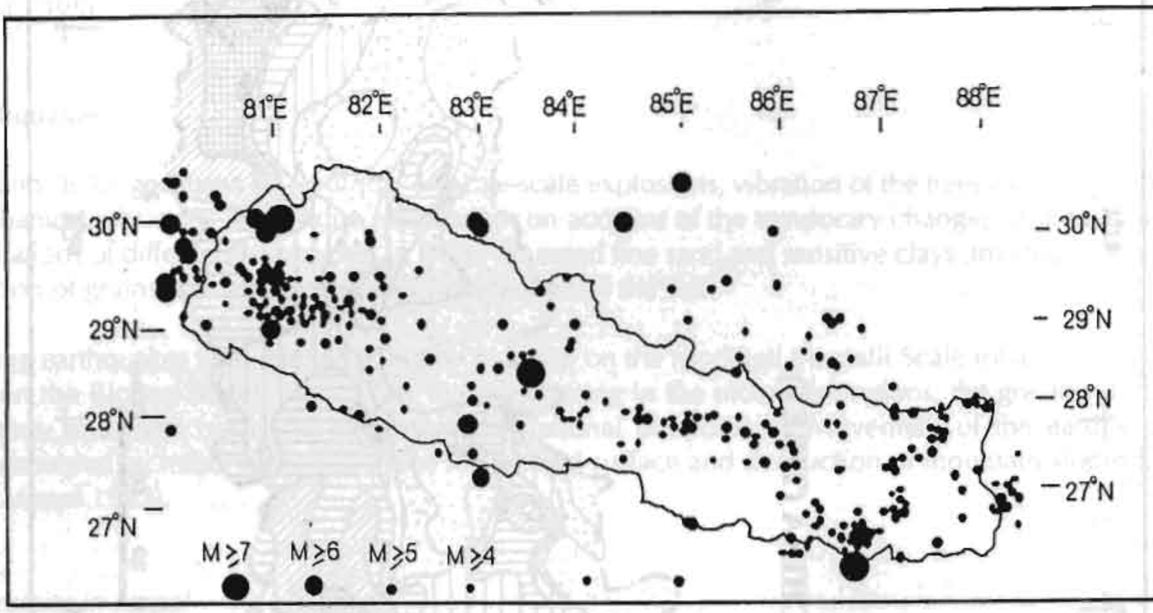


Figure 11: Simplified seismic risk map of Nepal (Bajracharya 1994)