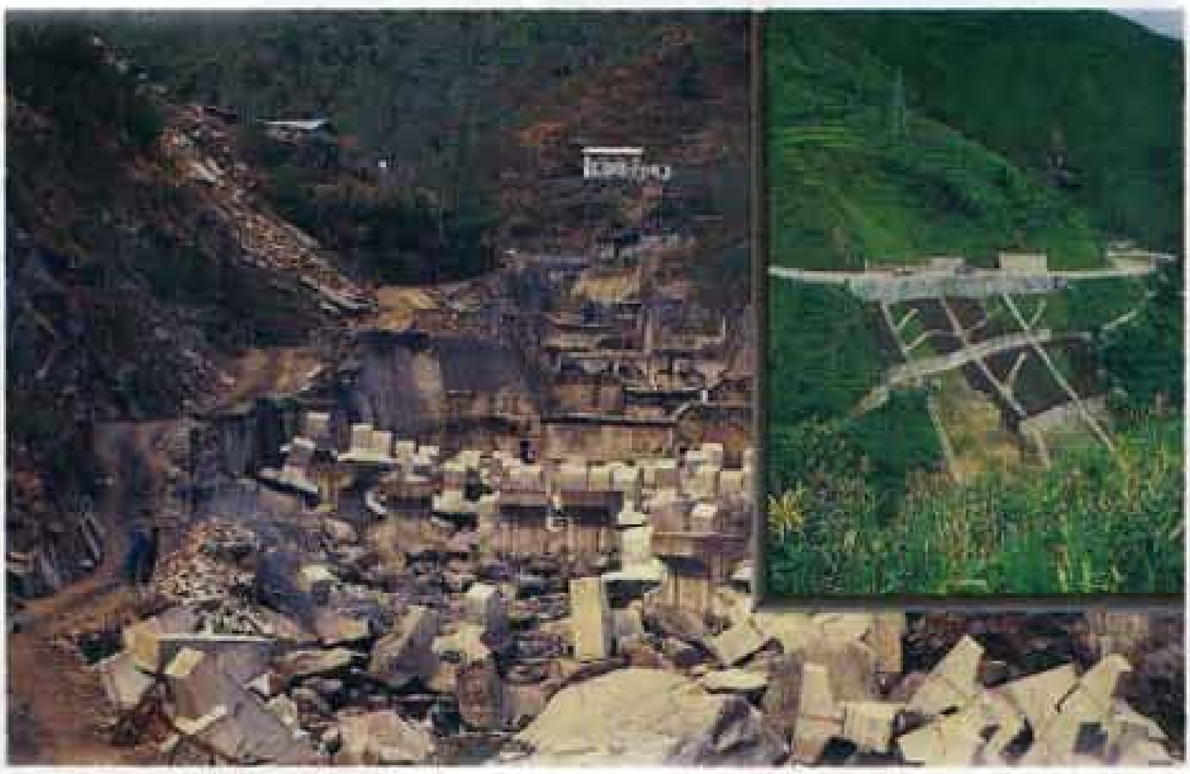
Landslide Studies and Management in Nepal



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International Centre for Integrated Mountain Development
Kathmandu, Nepal
1996

Cover Photograph: Gully erosion protection work in the Charnawati Valley.
Inset: Landslide stabilisation measures, Thankot-Naubise road, Central Nepal

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Preface

The inherently unstable nature of mountain areas of the Hindu Kush-Himalayas is well recognised. The steep slopes, unstable geology, and intense monsoon rains combine to make the Hindu Kush-Himalayas one of the most hazard-prone areas in the world. Although natural hazards of varying intensity have occurred frequently in the past in Hindu Kush-Himalayan countries, more recently there has been an increase in human settlement of hazard-prone areas as a result of population pressure, as well as improvements in accessibility by road and the onset of other infrastructural developments. Consequently, natural and man-made disasters are on the increase and each event affects an even greater number of people than before. Floods and landslides during the monsoon season are the most common natural disasters affecting this region, often resulting in substantial economic and environmental losses and causing great suffering to many people.

Despite all this the present levels of understanding and systematic analysis of these disastrous events are very poor and data bases are non-existent. No monitoring activities are carried out even in cases where such monitoring can be of direct benefit to project-related management activities. Investments in developing practical guidelines for managing such events as well as in forecasting them have been inadequate.

Since its inception, ICIMOD has been promoting the development of a better understanding of natural hazards. Various activities have been undertaken so far. These include several training programmes dealing with mountain risk engineering, focussing on improving road construction along unstable mountain slopes, a review of landslide hazard management activities in China, and field assessment of landslides and flood events in south central Nepal following the extreme climatic events that took place in July 1993.

One of the goals set by ICIMOD in its Mountain Natural Resources' programme is to "Improve the conditions of mountain resources and environments by halting and eventually reversing their degradation." Programme activities envisaged to achieve the above goal are directed to:

- identification of measures to mitigate different types of natural hazards which result in the loss of natural resources;
- promotion of skills and methodologies for natural hazard assessment; and
- improvement of public awareness for better disaster preparedness in mountain areas.

ICIMOD's programme on "Landslide Hazard Management and Control" focusses on these concerns to help protect valuable natural resources from different types of natural hazards. This programme is based on activities already introduced at ICIMOD in 1994 with support from the Government of Japan.

This programme is concerned not only with examining the types and extent of landslide events but also with measures for their mitigation and control; and in addition the skills and methodologies needed for natural hazard assessment.

To improve the knowledge base on Landslide Hazard Management and Control, state-of-the-art reviews were commissioned in four countries of the Hindu Kush-Himalayan Region. These countries are China, India, Nepal, and Pakistan.

Suresh Raj Chalise of the Mountain Natural Resources' programme at ICIMOD coordinated the work carried out on these reviews and the current document entitled "**Landslide Hazard Management and Control in Nepal**" was prepared by Dr. B.N. Upreti of the Department of Geology, Tri-Chandra Campus, Tribhuvan University, and Dr. M.R. Dhital of the Central Department of Geology, Tribhuvan University, Kathmandu, Nepal. Dr. Upreti and Dr. Dhital have produced a comprehensive document on a topic that is crucial to the development of mountain areas and the well-being of mountain inhabitants.

Abstract

The document covers the geographical make-up and geological framework of Nepal as an introduction to the topic. Specific topics such as erosion and sediment yield in the Himalayas are covered within these topic areas. Landslides are classified and factors causing them described, including the geological background to landslides. Climate and vegetation are among the factors covered along with hazards such as glacial lake outburst floods and earthquakes. The main part of the document focusses on landslides and their mitigation; the landslide sections are introduced by a short review of landslide studies in Nepal. The text is supplemented by an extensive bibliography and the curriculum for studies in engineering geology of Tribhuvan University, Kathmandu.

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Introduction

Background

Nepal is located in the very heart of the Himalayan arc and occupies nearly one third of the mountain range. About 83 per cent of the country is mountainous terrain, and the remaining 17 per cent in the south lies in the alluvial plains. Owing to the rugged mountain topography, complex and fragile nature of the geological structures, soft soil cover, high intensity rainfall in the monsoon season, and frequent earthquakes, the mountains are vulnerable to landslides, debris flows, soil erosion, and other mass wasting phenomena. The Himalayan rivers and streams, with their steep gradients and swift water flows, contribute significantly to the process of mass wasting.

In the Himalayan region, the damage caused by landslides was estimated to cost more than US$ one billion in economic losses, causing more than 200 deaths every year, which is about 30 per cent of the total of such losses worldwide (Li 1990). Landslides are very common occurrences in Nepal and are also one of the main natural hazards. Every year, especially during the monsoon season, a lot of damage to life and property is caused by them. For example, in 1968, a large slide occurred in Labu Besi and blocked the entire Budhi Gandaki River. The breaching of the dam severely damaged the settlement and bridges downstream (Sharma 1981). In 1985, a landslide dam in the Trishuli River caused great damage to the hydroelectric project and the settlement downstream (Galay 1987). Not all landslides, especially large ones, occur during the monsoon season. For example, in September 1978, a large rockslide in the Tinau River destroyed a newly-built bridge over the river at Butwal.

Many hill villages in Nepal are situated on or adjacent to unstable slopes and old landslides which are reactivated from time to time (Plate 1). In 1988, a huge landslide in Darbang (approximately 200km WNW of Kathmandu) killed 109 people and temporarily dammed the Myagdi *Khola*. About 62 years before this incident, the same landslide buried Darbang *Bazaar* and killed about 500 people (Yagi et al. 1990). In 1980, an earthquake with a magnitude of 6.5 on the Richter scale rocked Bajhang District and the adjacent areas of Far-western Nepal. It triggered several landslides on the mountain slopes. More than 3,700 houses were damaged and 178 people lost their lives (Sharma 1981). Floods and landslides alone claimed more than 4,200 human lives during the period from 1984 to 1993 (MOH 1994).

The rapidly increasing construction of infrastructure, such as roads, irrigation canals, and dams, without due consideration given to natural hazards, is contributing considerably to triggering landslides. Such infrastructures are also often damaged by mass movements. For example, in 1964, the Chisang *Khola* Hydroelectric Scheme, which was in operation for a few decades, was severely affected by a sudden slide in the balancing reservoir and the canal. Since then, the powerhouse has not been in operation (Sharma 1981). In recent years, cases of infrastructural damage caused by floods and landslides have increased steadily. The cost of rehabilitation has escalated and the economy of the country will be seriously strained if extensive rehabilitation work has to be carried out almost every year. Road failures as a result of rains and floods alone have necessitated more than 2.5 billion rupees (approximately US$ 50 million) worth of rehabilitation work from 1979 to 1993 (Deoja 1994). Moreover, landslides also seriously degrade the natural environment of the mountains and add an enormous load to the streams and rivers.

A systematic study of landslides, including hazard mapping and risk assessment on a larger scale, has not been undertaken in Nepal. Most landslide studies are confined either to individual cases or the hazard-prone sectors of linear infrastructures. Landslide studies in Nepal are carried out by professionals from government departments, non-government and international organisations, and academic institutions. The area of investigation, methodology applied, and classification scheme followed by these investigators differ considerably. This paper summarises the status of landslide studies in Nepal and focusses on the geomorphological, geological, hydrological, seismic, and other factors causing landslides in the Nepal Himalayas. A few case studies on landslides involving landslide inventory studies, hazard mapping, and mitigation are also given.

Physiography of Nepal

Nepal covers an area of about 147,181sq.km. and is bounded by the northern latitudes 26.22' and 30.27' and the eastern longitudes 80.04' and 88.12'. Its length is about 885km from east to west and the width varies from 130 to 255km.

Hagen (1969) was among the earliest workers to propose the physiographic subdivision of Nepal. The subdivisions discussed below are based on his suggestions with some modifications (Fig. 1 and Table 1).

Table 1: Physiographic Subdivisions of the Nepal Himalayas

Physiographic Unit	Width km	Main Geologic Unit
Terai (Indo-Gangetic Plain)	10-50	Northern part of the Indo-Gangetic basin, comprised of Recent Alluvium
Churia (Siwalik) Hills and Dun Valleys	10-50	Sub-Himalayas (foreland basin), comprised of sedimentary rocks of the Siwalik or Churia Group; the Dun Valleys, comprised of Recent sediments
Mahabharat Range	30-40	Lesser Himalayan unit, comprised of sedimentary, metamorphic, and igneous rocks
Midlands	40-60	Lesser Himalayan units, comprised of sedimentary, metamorphic, and igneous rocks with thrust sheets
Fore-Himalayas	10-50	Lesser and Higher Himalayan units
Great Himalayas	10-60	Higher Himalayan unit, comprised of high grade metamorphic rocks
Trans-Himalayas		Tibetan or Tethys Himalayan unit, comprised of fossiliferous sedimentary rocks

Terai

The northern continuation of the Gangetic Plain in Nepal is called the *Terai* (Fig. 1). This zone lies south of the Churia Hills and ranges in elevation from 100 to 200masl. The width varies between 10-50km and forms a nearly continuous belt from east to west. The *Terai* is generally flat with minor relief caused by river channel shifting and downwarping of the basin.

The *Terai* is divided into three parts: the Bhabar zone, middle *terai*, and southern *terai* (Sharma 1990). The Bhabar zone is made up of alluvial fan deposits sloping to the south, with its southern margin marked by a spring line that gives rise to many streams. The middle *terai* is an undulating terrain with isolated pockets of waterlogged and marshy conditions towards the southern part of the Bhabar zone. The southern *terai* stretches along the Nepal-India border, with an altitude of less than 90m.

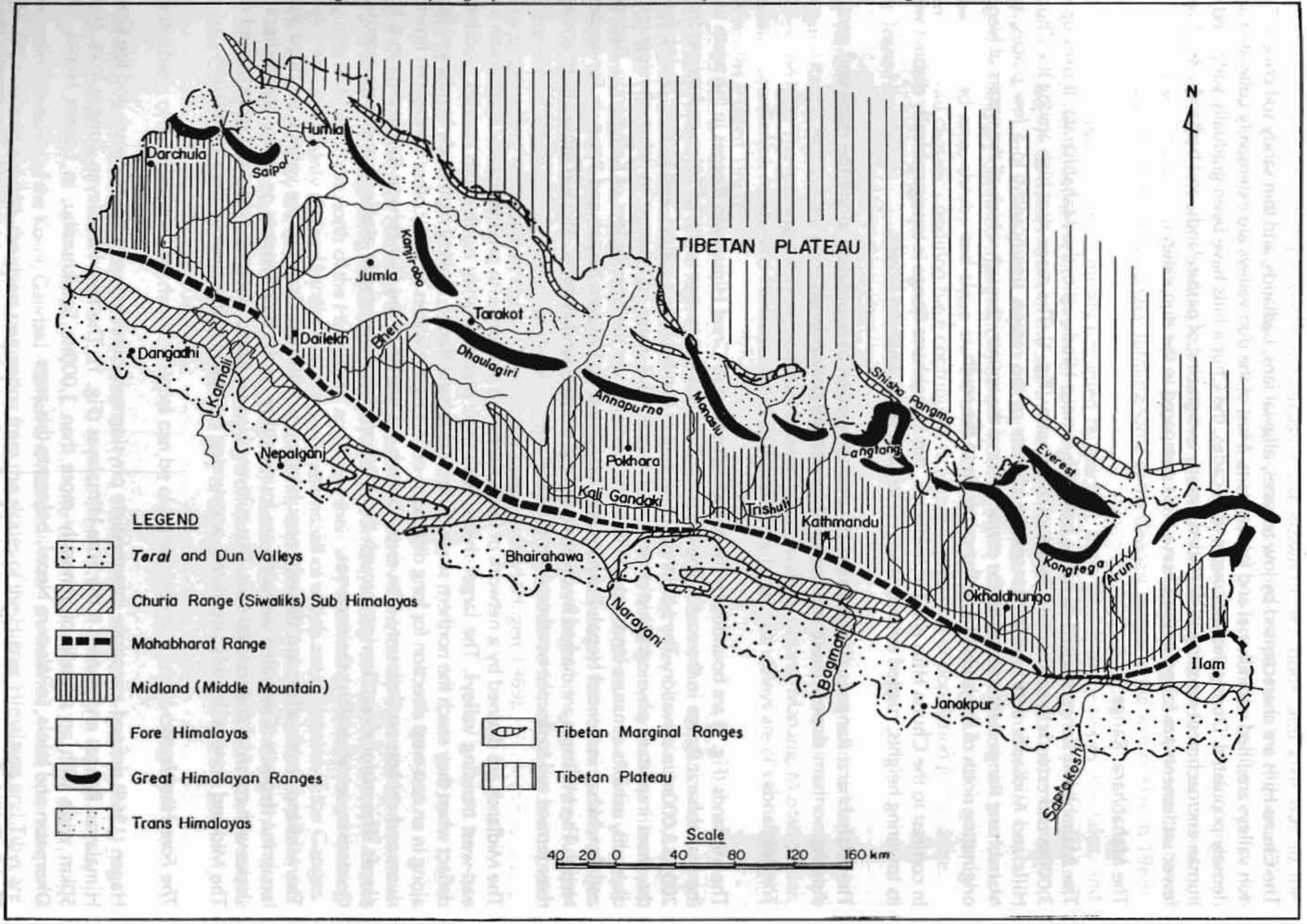
The land systems in the *Terai* can be divided into the flood plains of the rivers and recent and older river terraces. Generally, gravelly and bouldery soils prevail in the foothills, and sandy and/or silty soils are found in most of the remaining area. The region often suffers from devastating floods and droughts. The *Terai* has experienced massive deforestation since the control of malaria. Except for the 'protected forests', almost the entire *Terai* is cultivated.

The Churia (Siwalik) Hills and Dun Valleys

The Churia Hills or the Siwaliks (Fig. 1) are a unique topographic feature in the Himalayan region: the hills abruptly rise from the *Terai* and end with the beginning of the second topographic rise in the Mahabharat Range. They form the southernmost mountain range of the Himalayas.

The Churia Hills rise to altitudes of from 900 to 1,500m and show an arcuate face to the south. They form continuous east-west ranges all along the length of the country with steep escarpments towards the south. The Churia Hills have a young topography with numerous active gullies and escarpments.

Figure 1: Physiographic subdivisions of Nepal (modified after Hagen 1969)



There are several dun valleys within the Churia Hills. Some of the important ones are the Trijuga, East Rapti, Nawalpur, Deukhuri, Dang, and Surkhet valleys.

The Churia Hills are characterised by low terraces, alluvial fans, badlands, and thin sandy soil covers. The dun valleys are filled with alluvial and fan deposits. Most of the dun valleys are extensively cultivated and densely populated. During the last couple of decades, the Churia hills have been gradually subjected to human encroachment resulting in degraded forests, overgrazing of pasturelands, and badlands. Relatively fewer settlements are found in the Churia Hills compared to the dun valleys.

The Mahabharat Range

The Mahabharat Range derives its name from the famous Hindu epic, the *Mahabharata*. It rises up to 3,000m and extends throughout the length of the country (Fig. 1). The range rises high among the Churia Hills and Midlands and thus influences the climate of the region significantly. In a few places, the Mahabharat Range is intersected by the major rivers of the country through which all the waters of Nepal, originating north of the Mahabharat Range, drain to the south.

In contrast to the Churia Hills and the Midlands, the Mahabharat Range is topographically distinct with its towering heights, rugged terrain, sharp crests, and steep southern slopes.

The Mahabharat Range is characterised by a concentration of population along the ridge and gently-dipping northern slopes. There are degraded forests and pasturelands.

The Midlands

The Midlands (Fig. 1) are bounded by the towering snow-clad Great Himalayan Ranges in the north and the Mahabharat Range in the south. The Midland Zone has an average width of 60km and ranges from 200 to 3,000m in elevation. The Midlands, consisting of low hills, river valleys, and tectonic basins, form the most important physiographic province of Nepal. This zone, in contrast to other physiographic divisions, exhibits a mature landscape. Within the Midlands are the large valleys of Kathmandu, Banepa, and Panchkhal, in Central Nepal; Pokhara and Mariphant, in Western Nepal; and Patan, in Far-western Nepal. The Midlands are marked by diversity in land use and land systems. The soil ranges from ancient river terrace soil to deeply-weathered residual soil.

The Midlands are drained by a network of large rivers and streams with predominantly north-south and east-west trending valleys. The larger rivers, with their predominantly north-south courses, suddenly deflect when they reach the northern slope of the Mahabharat Range, making right angle bends, and flow along in an east-west direction for long distances, collecting the waters of many other north-south flowing rivers and streams on their way. The rivers breach the barrier of the Mahabharat Range only in a few places. The major rivers flowing through the Midlands have very gentle gradients and form extensive Quaternary terraces along their courses.

The Midland river valleys are densely populated and cultivated. Some of the valleys are filled with lacustrine deposits. Cultivated wetlands are found either on the river terraces or on the gently-dipping slopes with colluvial and residual soils. Dry cultivated land is found along the ridges and spurs of the hills. The Midland Zone is densely populated, accounting for nearly half of the country's population.

The Fore-Himalayas

Hagen (1969) defined a separate intermediate physiographic unit between the Midlands and the Great Himalayan Ranges and named it the Fore-Himalayas (Fig. 1). The Fore-Himalayan Zone is from 10 to 50km wide with an altitude of generally more than 3,000m. Solukhumbu, in Eastern Nepal, and Dhorpatan and Jumla, in Western Nepal, belong to this zone.

The Fore-Himalayas are generally covered by forests and are sparsely populated. The population is concentrated in river valleys.

The Great Himalayas

The hills of the Midland Zone and Fore-Himalayas rise slowly to the north and give way to the snowcapped ranges of the Great (or Higher) Himalayas. Not only does Nepal have the highest peak in the world, Mount Everest (Sagarmatha 8,848m), but it also has the greatest number of high peaks in the world. Unlike the other physiographic units, the Great Himalayas are not comprised of a single range but of several discontinuous and overlapping parallel ranges (Fig. 1). The trend of these ranges varies from E-W and NW-SE to NE-SW. The main north-south flowing rivers, originating from beyond the Great Himalayas, have dissected these ranges, forming some of the deepest gorges in the world (Hagen 1969).

The Great Himalayan Zone is mostly occupied by glaciers, snow peaks, rocky slopes and talus, and colluvial deposits. Topographically, this mountain range has an extremely rugged terrain with very steep slopes and deeply-cut valleys. Most of the soil in this zone is made up of landslide or talus material and glacial till with some fluvio-glacial deposits along the river banks. In the Great Himalayan Zone, taller species of plants are confined to elevations below 4,000m, while above 4,000m, below the permanent snow-covered area, shrubs and algae are the only vegetation. Lack of good agricultural land and an extremely cold climatic condition have contributed to a very low density of population in this zone.

The Trans-Himalayas

The Trans-Himalayas (Fig. 1) are situated to the north of the Great Himalayas and south of the Tibetan Marginal Range. Beyond the marginal range lies the Tibetan Plateau. It includes several Inner Himalayan valleys and hills. The important valleys, from east to west, are Rolwaling, Kutang, Manang, Mustang (Thak *Khola*), Dolpa (Sanju), Mugu, and Humla, some of which are very large. The valleys are of various lengths and widths (Hagen 1969).

As the Trans-Himalayas lie in the high altitude region and rain shadow zone, they are generally covered by talus and colluvial deposits, bare rocky slopes, snow, and ice. Though they lie within the Himalayan Zone, their climatic conditions and geomorphic features are quite different from those of the Himalayas and resemble those of the Tibetan Plateau. However, unlike the cold desert climate of the Tibetan Plateau, the Inner Himalayan valleys receive some rain (below 250mm on an average). Rain-bearing clouds enter these valleys through the deep gorges between the Higher Himalayan Ranges bringing rain that sustains the coniferous forests and agriculture in these valleys. In this zone, human settlements have been found up to an altitude of 4,300m (i.e., Phopa *Gaun* in the Langu Valley) (Hagen 1969).

Rivers of Nepal

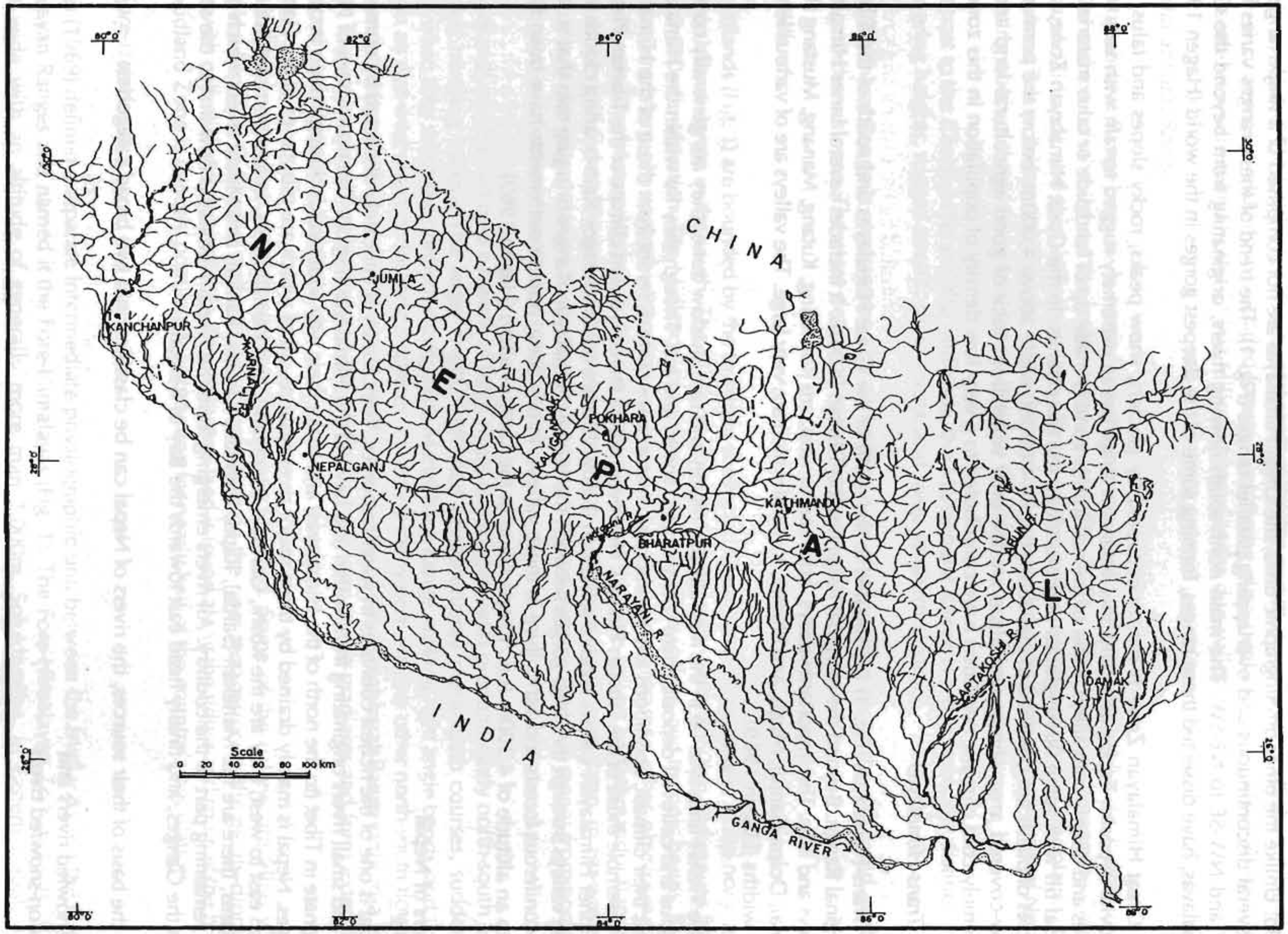
Nepal is one of the richest countries in water resources. The country is intricately dissected by numerous big and small rivers originating from within and beyond the Himalayas (Fig. 2). The main rivers of Nepal originate in Tibet (to the north of the Himalayas) and make their way southwards through deep incutting gorges. Nepal is mainly drained by three major river systems, all of which are tributaries of the Ganges. From east to west, they are the Koshi, Gandaki (Narayani), and Karnali rivers. In addition to these river systems, there are the Mahakali (Sarda), Rapti, Bagmati, Kamala, Kankai, and Mechi rivers which drain the remaining part of the country. All rivers emerging from the Nepal Himalayas flow first to the south, join the Ganges, and finally head east towards the Bay of Bengal.

On the basis of their sources, the rivers of Nepal can be classified into two broad categories:

a) snowfed rivers and
b) non-snowfed rivers

The main tributaries of the Koshi, Gandaki, Karnali and Mahakali rivers are snowfed, while others are non-snowfed rivers. In general, the rivers originating from the slopes of the Higher Himalayas and Tibet are snowfed, whereas those originating from the Midlands and the Churia Hills are non-snowfed. The river profiles of the main rivers show typically high elevations in the north and sudden drops while entering

Figure 2: Rivers of Nepal (modified after DPTC 1994)



the Midlands. In the Midlands, the rivers have moderate to low gradients, and they become steeper while crossing the Mahabharat and Churia Ranges.

Geological Framework of Nepal

Like the other parts of the 2,400km long Himalayan Range, the Nepal Himalayas are also geologically divided into the following five tectonic zones, from south to north respectively (Gansser 1964, Hagen 1969; Fig. 3).

Terai Zone
Sub-Himalayan Zone
Lesser Himalayan Zone
Higher Himalayan Zone
Tibetan-Tethys Zone

These east-west extending zones, which run almost parallel to each other, differ in their lithology, structure, and geological history. The Himalayan Ranges are tectonically very active and susceptible to frequent earthquakes. Generally, instabilities in the Himalayas are controlled by the textural and structural characteristics of the rocks and soils within the zone. There are also several active faults along which large landslides are often aligned.

The Terai Zone

This zone represents the northern edge of the Indo-Gangetic alluvial plain and is the southernmost tectonic division of Nepal (Fig. 3). Though physiographically this zone does not belong to the main part of the Himalayas, it is a foreland basin and owes its origin to the rise of the Himalayas; it is thus genetically related. To the north, this zone is often delineated by an active fault, the Main Frontal Thrust (MFT). Churia rocks are found to rest over the sediments of the *Terai* in many places along this thrust,

The *Terai* is covered by Pleistocene to Recent alluvium. The average thickness of the alluvium is about 1,500m. The basement topography of the *Terai* is not uniform. There appear to be a number of transverse ridges and valleys below the alluvium. The alluvial sediments were deposited over the Siwaliks, which in turn rest over Precambrians and Gondwanas or Eocene-Oligocene rocks (Tater et al. 1989, Sharma 1990).

The Sub-Himalayan Zone (Siwaliks)

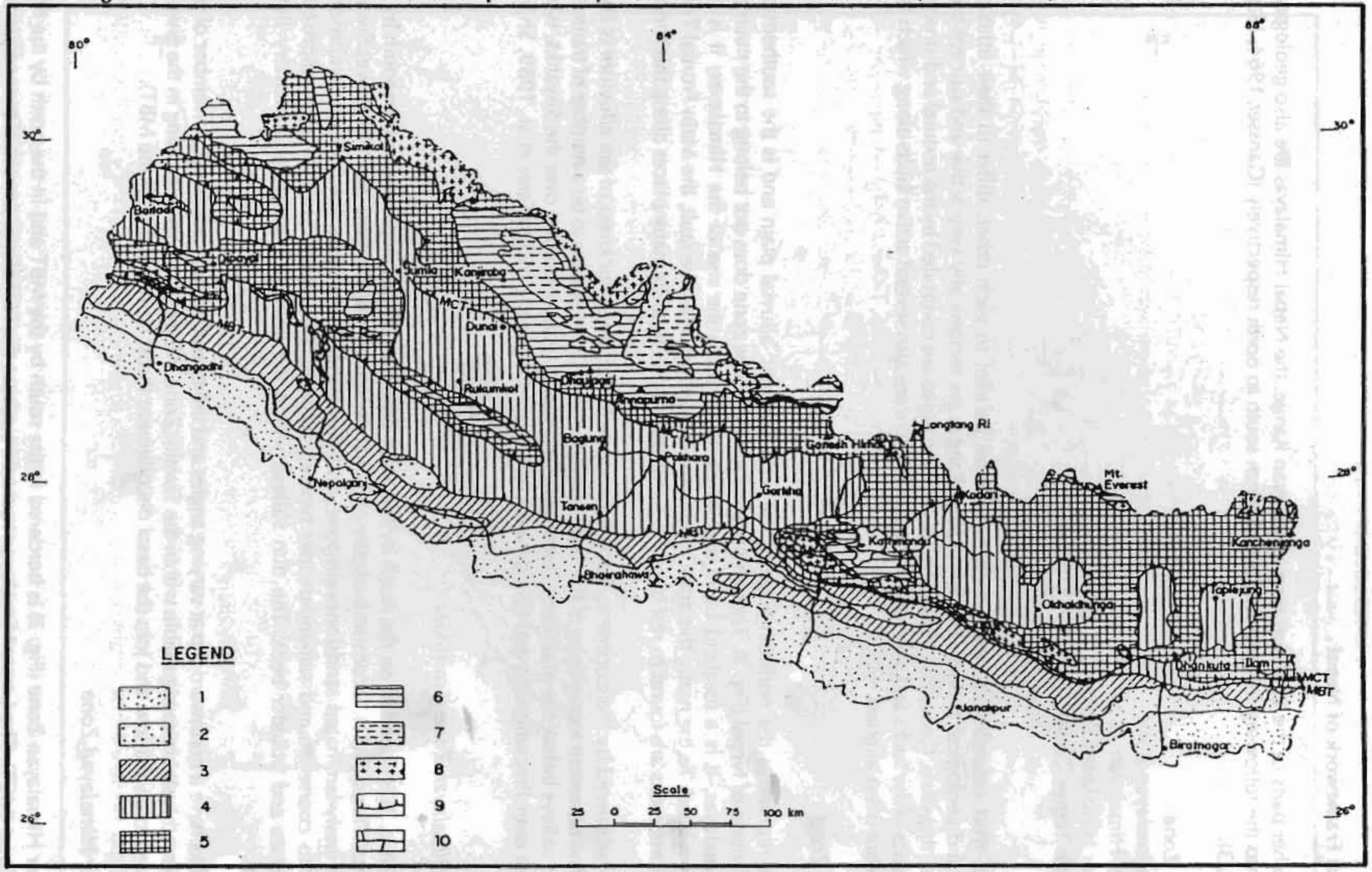
This zone (Fig. 3) is bounded on the north by the Main Boundary Thrust (MBT) and on the south by the Main Frontal Thrust (MFT). It consists basically of fluvial deposits of the Neogene age. The Lower Siwaliks consist of finely-laminated sandstone, siltstone, and mudstone. The Middle Siwaliks are comprised of medium- to coarse-grained salt-and-pepper type sandstones. The Upper Siwaliks are comprised of conglomerate and boulder beds. The dun valleys within the Siwaliks consist of Quaternary fluvial sediments.

The Siwaliks have a northward dip at varying angles and the overall strike is east-west. A number of east-west running thrusts are recognisable within the Siwalik Zone. All these thrusts originating in the Siwaliks are believed to be shallow and join the basal decollement thrust (continuation of the MBT).

The Lesser Himalayan Zone

The Lesser Himalayan Zone (Fig. 3) is bordered in the south by the MBT and in the north by the Main Central Thrust (MCT). The Lesser Himalayan rocks throughout the Himalayas consist of two sequences: allochthonous and autochthonous. The MBT itself is a fault zone that has brought older Lesser Himalayan rocks over the Siwaliks.

Figure 3: Tectonic subdivisions of the Nepal Himalayas (modified after Stocklin 1980, Kizaki 1988, and ESCAP/DMG 1993)



1. *Terai* Zone, 2. Sub-Himalayan Zone (Dun Valleys), 3. Sub-Himalayan Zone, 4. Lesser Himalayan Zone, 5. Higher Himalayan Zone and the Lesser himalayan Crystalline Rocks, 6. Tibetan Tethys Zone (Paleozoic Rocks), 7. Tibetan Tethys Zone (Mesozoic Rocks), 8. Granites, 9. Thrusts, 10. Roads

The Lesser Himalayas are mostly comprised of unfossiliferous, sedimentary, and metasedimentary rocks such as slate, phyllite, schist, quartzite, limestone, dolomite, etc, ranging in age from Precambrian to Eocene. There are also some granitic intrusions in this zone.

From east to west, the Lesser Himalayas of Nepal vary in stratigraphy, structures, and magmatism. Eastern Nepal is characterised by the development of extensive thrust sheets of crystalline rocks (gneiss and schist) that have travelled southwards. There are large tectonic windows which expose the low-grade metamorphic rocks below the cover of the crystalline thrust sheets. They are the Taplejung, Arun, and Chautara-Okhaldhunga windows. In Central Nepal, a large thrust sheet called the Kathmandu Nappe covers a wide area around the Kathmandu region. West of Kathmandu, between the Budhi Gandaki and Bheri rivers, crystalline rocks are restricted to the north of the MCT. West of the Bheri River, up to the western border of Nepal, crystalline nappes reappear and cover much of the terrain (Fig. 3).

The Higher Himalayan Zone

Ever since Heim and Gansser (1939) identified and described the 'Central Crystalline Zone' in the Kumaon Himalayas, this zone has been mapped and traced along the entire Himalayan region and has been given different names in different places. Geologically, the Higher Himalayas include the rocks lying north of the MCT and below the fossiliferous Tibetan-Tethys Zone.

The northern or upper limit of this zone is generally marked by normal faults. This zone consists of an approximately 10km-thick succession of crystalline rocks, also known as the Tibetan Slab (Le Fort 1975). The crystalline unit of the Higher Himalayas extends continuously along the entire length of the country, and its width varies from place to place. The high-grade, kyanite-sillimanite-bearing gneisses, schists, and marbles of the zone form the basement of the Tibetan-Tethys zones. Granites are found in the upper part of the unit (Fig. 3).

The Tibetan-Tethys Zone

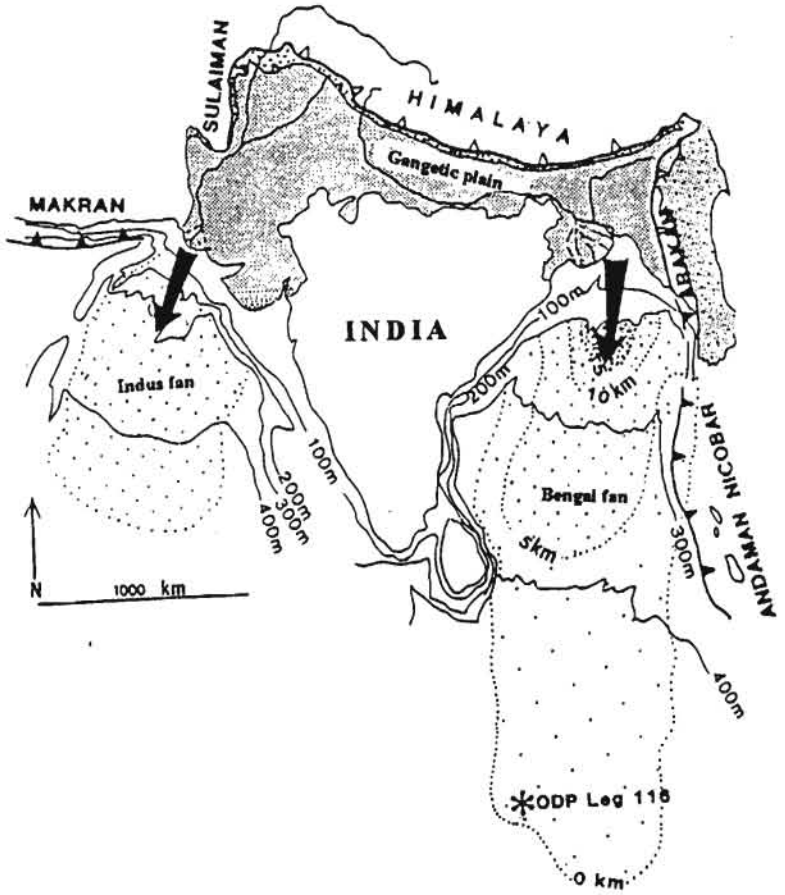
The Tibetan-Tethys Zone begins at the top of the Higher Himalayan Zone and extends to the north in Tibet. In Nepal, the fossiliferous rocks of the Tibetan-Tethys Zone are well-developed in Thak *Khola* (Mustang), Manang, and Dolpa. Most of the Great Himalayan peaks of Nepal, including Mt Everest, Manaslu, Annapurna, and Dhaulagiri, belong to the Tibetan-Tethys Zone (Fig. 3). This zone is composed of sedimentary rocks, such as shale, limestone, and sandstone, ranging in age from Lower Palaeozoic to Palaeogene.

Erosion and Sediment Yield in the Himalayas

The erosional history of the Himalayas can be deciphered by studying the submarine fan in the Bay of Bengal. The Bengal Fan (Fig. 4) came into existence through the accumulation of sediments from the rising Himalayas. It is the world's largest submarine fan, extending to about 3,000km south from Bangladesh into the Indian Ocean (France-Lanord et al. 1993). The sediments constituting the fan have a maximum thickness of approximately 22km, and the mass of the sediments derived from the collision of India and Asia is about 22.9×10^{16} tonnes (Curry 1991). The Bengal Fan is fed by the Ganges and the Brahmaputra rivers, which currently drain both the northern and southern slopes of the Himalayas (Figs. 2 and 4). The high relief, intense precipitation during the monsoon season, and extensive glaciation are responsible for the world's highest erosion rates. The Ganges-Brahmaputra River system (with approximately 1.4 million square kilometres of watershed area) produces 12 per cent of the river particulate flux in the world's oceans, while providing less than three per cent of the water flux (Milliman and Meade 1983).

The isotopic study of the sediments from the Bengal Fan indicates that the Higher Himalayan Crystallines (HHC) have been the predominant source of sediment supply to the Bengal Fan at least since the last 17Ma (France-Lanord et al. 1993). This situation has still not changed significantly. The presence of a large volume of the sediment derived from the HHC has significant implications for the tectonic history

Figure 4: Sketch map of Bengal and Indus fans (France-Lanord et al. 1993)



of the Himalayas. It implies that the Himalayan Range had already achieved an elevation of the same order as the present day by 17Ma (France-Lanord et al. 1993).

Today, the Ganges and Brahmaputra rivers are the second and third largest sediment carriers in the world (Fig. 5), and the average annual suspended load carried by them to the Bay of Bengal is more than $1.6x10^9$ tonnes and $0.8x10^9$ tonnes respectively (Holeman 1968). If we calculate the average rate of sedimentation in the Bengal Fan from the total post-collisional sediment deposits in the fan for 17Ma, it is about $2.9x10^{10}$ tonnes per year.

Studies on the annual sediment load of the Koshi River (one of the tributaries of the Ganges), from 1948 to 1981, have shown that the total average annual sediment load at Barahakshetra is $94.95x10^6m^3$ (about 190 million tonnes per year) (RONAST/CWRC 1994). The same river further downstream at Baltara, India, has only $57.35x10^6m^3$ (about 115 million tonnes) of sediment load. The measurements of annual sediment load at Barahakshetra and Baltara are shown in Table 2, and the monthly sediment load in the Koshi River at Barahakshetra is given in Table 3.

Table 2: Annual Sediment Load at Barahakshetra and Baltara (RONAST/CWRS 1994)

Location	Annual Sediment Load in million m^3			
	Coarse	Medium	Fine	Total
Barahakshetra	17.978	23.858	53.114	94.95
Baltara	4.70	11.36	41.29	57.35

Figure 5: The sediment load of selected South Asian rivers compared to the world average (Ferguson 1984)

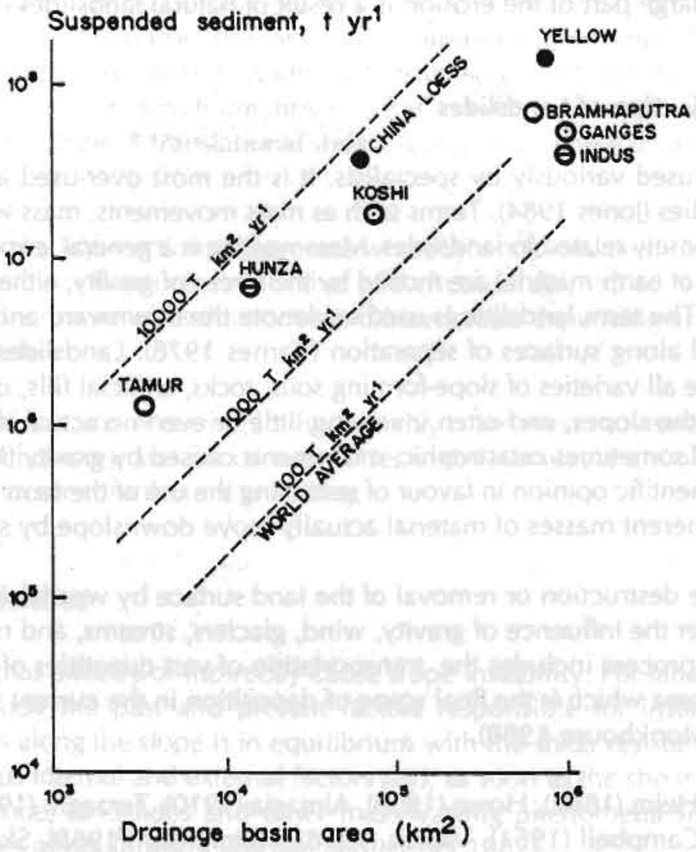


Table 3: Monthly Sediment Load in the Koshi River at Barahakshetra (RONAST/CWRS 1994)

Month	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Total
Sediment Load (x106m^3)	0.099	0.074	0.12	0.44	2.82	14.02	26.90	29.01	15.13	5.82	0.71	0.20	94.99
Total between July and October													90.88

The annual sediment load and sediment yield per km^2 of the tributaries of the Koshi River are presented in Table 4 (RONAST/CWRC 1994).

Table 4: The Annual Sediment Load and Sediment Yield of the Tributaries of the Koshi River (RONAST/CWRC 1994)

Tributary	Annual Sediment Load (given in x10^{6}m^3)	Annual Sediment yield (given in m^3/km^2)
Sunkoshi	54.2	2818
Arun	34.6	947
Tamur	29.6	5016
Total	118.4	8781

The sediment load of the Karnali River has been estimated at between 93.5 and 170 million tonnes per year. Similarly, the sediment load of the Narayani River at Bhainsalotan is estimated at 170 million tonnes per year (Sharma 1988). From Nepal's 147,181sq.km. of land, about 240 million cubic metres of eroded per year (Sharma 1988). From Nepal's 147,181sq.km. of land, about 240 million cubic metres of eroded soil is transported each year by the country's four major rivers and over 6,000 tributaries (DSWC 1977). It is estimated that the soil loss range is between 20-50tonnes/ha/year and may increase locally to 200-500tonnes/ha/year. A large part of the erosion is a result of natural landslides (DSWC 1977).

Definition and Classification of Landslides

The term landslide is used variously by specialists. It is the most over-used and loosely-defined term employed in slope studies (Jones 1984). Terms such as mass movements, mass wasting, slope movement, slope failure, etc, are closely related to landslides. Mass wasting is a general term for a variety of processes by which large masses of earth material are moved by the forces of gravity, either slowly or quickly, from one place to another. The term landslide is used to denote the downward and outward movements of slope-forming material along surfaces of separation (Varnes 1978). Landslides are quick mass-wasting processes. They include all varieties of slope-forming soils, rocks, artificial fills, or combinations of these, moving out and down the slopes; and often involving little or even no actual sliding over a long period of time, or sudden, and sometimes catastrophic, movements caused by gravity (Monkhouse 1988). There is a growing body of scientific opinion in favour of restricting the use of the term 'landslide' to cover those situations in which coherent masses of material actually move downslope by sliding (Jones 1984).

On the other hand, the destruction or removal of the land surface by weathering, corrasion, corrosion, and transportation under the influence of gravity, wind, glaciers, streams, and running water are termed 'erosion'. The erosion process includes the transportation of vast quantities of weathered rock, usually downhill, towards the area which is the final scene of deposition in the current sequence; transportation is an essential phase (Monkhouse 1988).

Many authors, such as Heim (1882), Howe (1909), Almagia (1910), Terzaghi (1925), Ladd (1935), Sharpe (1938), Ward (1945), Campbell (1951), Varnes (1958), Hutchinson (1968), Skempton and Hutchinson (1969), Záruba and Mencl (1969), Crozier (1973), and Varnes (1978) have tried to classify landslides. Here, the classification by Varnes (1978) is followed. The International Association of Engineering Geology (IAEG) has also suggested the same nomenclature (IAEG 1990).

Varnes classified landslides on the basis of the types of movement and material. Movement types are divided into five main groups: falls, topples, slides, spreads, and flows. A sixth group, complex slope movements, includes combinations of two or more of the other types of movement (Table 5). Similarly, materials are divided into two classes: rocks and engineering soil. Soil is further subdivided into debris and earth, based on the grain size (Varnes 1978). A short description of the various landslide types is given below (Varnes 1978).

Table 5: Classification of Landslides (Varnes 1978)

Type of Movement			Type of Material		
			Bedrock	Engineering Soil	
				Predominantly coarse	Predominantly fine
Falls			Rockfall	Debris Fall	Earth Fall
Topples			Rock Topples	Debris Topples	Earth Topples
Slides	Rotation	Few units	Rock Slump	Debris Slump	Earth Slump
	Translation	Many units	Rock Block Slide Rockslide	Debris Block Slide Debris Slide	Earth Block Slide Earth Slide
Lateral Spread			Rock Spread	Debris Spread	Earth Spread
Flows			Rock Flow (Deep Creep)	Debris Flow	Earth Flow
				(Soil Creep)	
Complex			Combination of two or more principal types of movement		

Falls are masses of rock and/or soil that move downslope by falling or bouncing through the air. They are most common on steep road cuttings.

A Topple denotes the overturning or tilting of a block of rock on a pivot or hinge. Finally, it separates from the main mass resulting in a fall or slide.

The term **slide** is applied to a mass movement process in which a distinct surface of rupture or zone of weakness separates the slide material from the more stable, underlying material. The slide materials can be broken up and deformed or they can remain fairly cohesive and intact. A cohesive landslide is called a **slump.** A **rotational slide** is one in which the movement is more or less rotational about an axis that is parallel to the contour of the slope. A **translational slide** is a mass movement on an approximately planar surface.

Spreads are failures caused by liquefaction: the process whereby water-saturated sediments transform into a liquid state. The movement of **flows** resembles that of a viscous fluid; slip surfaces are almost absent. Flow can take place as one or more lobes that move at different rates depending upon the viscosity of the material and the slope angle.

The most common natural hazards occurring in the Himalayas are mass movements (landslides, debris flows, and mud flows), earthquakes, and floods. Landslides in the Himalayas are often complex, as there is usually more than one factor contributing to sliding.

Factors Causing Landslides

There are several factors that directly or indirectly cause slope instability. For landslide assessment, it is necessary to carefully study the past and present factors responsible for instability. Under normal conditions, the shear stress along the slope is in equilibrium with the shear resistance of the slope. But it is often modified by various internal and external factors and, as soon as the shear stress along the slope exceeds the shear resistance, landslides and other mass-wasting phenomena set in and the slope is modified to the new values of equilibrium (Záruba and Mencl 1982).

Factors that are more or less long-lasting and inherent in the constituent rock and soil can be called the primary causes of failure. The basic factor is the force of gravity. There are also many other factors. Some of the important ones are: rock and soil type and strength, rock structure (folding, faulting, jointing, foliation, bedding (Hoek and Bray 1981), soil depth, porosity, and permeability.

The factors that are either variable or very short-lived can be called the secondary causes or triggers. They are seismicity, intensity of precipitation, land use, natural slope conditions, rock and soil weathering conditions; presence or absence of gullies, streams, and rivers; and groundwater conditions.

A short description of the important landslide-causing factors common in the Nepal Himalayas is presented below.

Geology

Lithology

Lithology is one of the primary factors causing landslides. The rocks in the Himalayas range from granite, gneiss, and schist in the Higher and Lesser Himalayas to soft sandstone, mudstone, and conglomerate in the Siwaliks. The most common types of mass rock movement in the Himalayas are rockslides, rockfalls, rock toppling, and wedge failure. Short descriptions of the common rocks are given below (Dhital 1991).

Fractured Slate: This type is found in a large portion of the Midlands and breaks easily into long pencil-shaped or small flat polygonal chips which cleave off the bed even in the dry season. Slate is susceptible to wedge failure, gully erosion, and toppling.

Interbedded Quartzite/Sandstone and Shale: These types of rock are found north of the MBT as well as in the inner part of the Lesser Himalayas. The anisotropy inherent in the interbedding of resistant quartzite or sandstone with weak slate or mudstone contributes significantly to mass movement. Huge rockslides and smaller wedge failures are common.

Interbedded Limestone/Dolomite and Slate: The most common types of mass movements on these rocks are rockslides parallel to the bedding/joint planes and wedge failures. Thick beds of dolomite fail along the discontinuity planes. On the other hand, rockfall is likely if the slope is steep.

Massive Limestone, Dolomite, Marble, or Quartzite: Under normal conditions, these rocks are quite stable, but, when strongly jointed, wedge failure or rockfall is possible.

Interbedded Soft Sandstone and Mudstone: This type of rock is found in the Siwalik Zone. Occasionally, it forms high cliffs. Large-scale wedge failures and plane rockslides often occur in the wet areas and areas with deep gully erosion.

Massive Granite, Gneiss, and Crystalline Rocks: These rocks are found in the Lesser and Higher Himalayan zones. Generally, these rocks are quite stable. They form steep cliffs and narrow gorges. Rockfalls, rock avalanches, boulder gliding, talus cones, and wedge failures are seen at higher altitudes and along fault zones.

Phyllite and Quartzite Alternation: Generally, a thick succession of the phyllite and quartzite alternation is found in the Midlands. Large anticlines and synclines with numerous small-scale folds also occur in this rock unit. The main mass movements associated with this rock unit are debris slides, wedge failures, and gully erosion. Large-scale rotational slides may occur in the weathered or crushed zones.

Deeply Weathered Residual or Colluvial Soils: After rock weathering and disintegration, various kinds of soils are formed on slopes. Generally, translational and rotational slides are common on these soils. If the slope is gentle (less than 25 degrees), it may be quite stable. However, depending upon the intensity of precipitation, gully erosion may occur and badlands may develop.

Alluvial Soil: Alluvial soil is found along the river banks and in the proximal areas. It is of two types: the old consolidated (cemented) river terrace type and the recent terrace type with loose gravel and fines. Often, in the old terraces, vertical joints develop which may fail by toppling and fall. On both types of terraces, deep gully erosion and rotational and translational slides also occur.

Rock Structure

The geological structure of the Himalayas is such that there are several roughly east-west trending major thrusts and faults with several weak and crushed zones (Plate 2). In such areas, numerous small and big landslides occur along these linear structures. On the other hand, the orientation of folds, bedding, foliation, and joints in the rock also play a vital role in landsliding (Plate 3). Active faults are common in the Nepal Himalayas. The MFT, MBT, and other active faults (Fig. 3) are characterised by the parallel alignment of many small and large landslides.

Weathering

Mechanical and chemical weathering change the strength parameters of the rock and soil considerably. In many landslide events, chemical alterations, such as hydration and ion exchange in clay, are thought to have contributed to triggering off landslides (Záruba and Mencl 1982). Chemical weathering in rocks along the discontinuities may reach tens of metres below the surface and thus weaken the rocks considerably. Himalayan rocks, especially in the warm-temperate and subtropical climatic zones, are usually deeply weathered The weathering grades of rocks applicable for engineering practices are presented in Table 6.

Table 6: Weathering Grades of Rocks

Grade	Degree of Weathering	Description
VI	Residual Soil	The rock is discoloured and completely changed to a soil in which original rock fabric is destroyed. There is a large change in volume.
V	Completely Weathered	The rock is discoloured and changed to a soil but original fabric is mainly preserved. There may be occasional small core stones. The properties of the soil depend in part on the nature of the parent rock.
IV	Highly Weathered	The rock is discoloured. Discontinuities may be open, discoloured surface, and original fabric of discontinuities may be altered. Alteration penetrates deeply but core stones are present.
III	Moderately Weathered	The rock is discoloured, discontinuities may be open and show discoloured surfaces with alteration starting to penetrate inwards. Intact rock is noticeably weaker, as determined in the field, than the fresh rock.
II	Slightly Weathered	The rock may be slightly discoloured, particularly adjacent to discontinuities, which may be open and will have slightly discoloured surfaces. The intact rock is noticeably weaker than the fresh rock.
I	Fresh	The parent rock is not discoloured and there is no loss of strength or any other weathering.

Geotechnical Properties of Soil

The geotechnical properties of soil are the main factors contributing to soil slope failures. Soil composition, depth, shear strength (which depends on density, cohesion, plasticity, dilatancy, and angle of internal friction), porosity, permeability, grading, packing, moisture content, and organic material content are some of the important geotechnical parameters for soil study. The Unified Soil Classification System (USCS) is often applied in soil classification and studies in engineering practices.

Genetically, the soils on the hillslopes of the Himalayas can be classified as colluvium and as residual soils, in addition to the alluviums found along the river and stream banks in the form of terraces. Along many of the major river valleys, alluvial soils are present on the hill slopes - much higher than the present river levels due to the upliftment of the Himalayas. All these types of soils are often silty gravel and occasionally clayey silt. Debris slides are observed in coarse-grained soils with steeper (35-45 degrees) slopes and rotational slides are characteristic of fine-grained and thick soils with gentler slopes (less than 35 degrees).

Groundwater

Flowing groundwater exerts pressure on soil particles thus impairing slope stability. Abrupt changes in the water level, as might occur in reservoirs, cause the porewater pressure on slopes to increase and this, in turn, may lead to the liquefaction of sandy soils. Groundwater can wash out soluble cementing substances and thus weaken the intergranular bonds and reduce the mechanical strength of the ground. Flowing groundwater flushes out fine particles in fine sand and silt and the strength of the slope is reduced by the cavities formed in the process (Záruba and Mencl 1982).

Perched groundwater exerts upthrust on overlying beds. The most important aspect of porewater pressure on rock and soil is that it reduces the normal stress but does not affect the shear stress of the material.

Precipitation

Rainfall is one of the main factors controlling the frequency of landslides. The magnitude of the influence depends upon climatic conditions, the topography of the area, the geological characteristics of the slope, and the porosity and permeability of rocks and soils. The variation in the soil depth and the nature and frequency of discontinuities on the rock may also play their roles.

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)

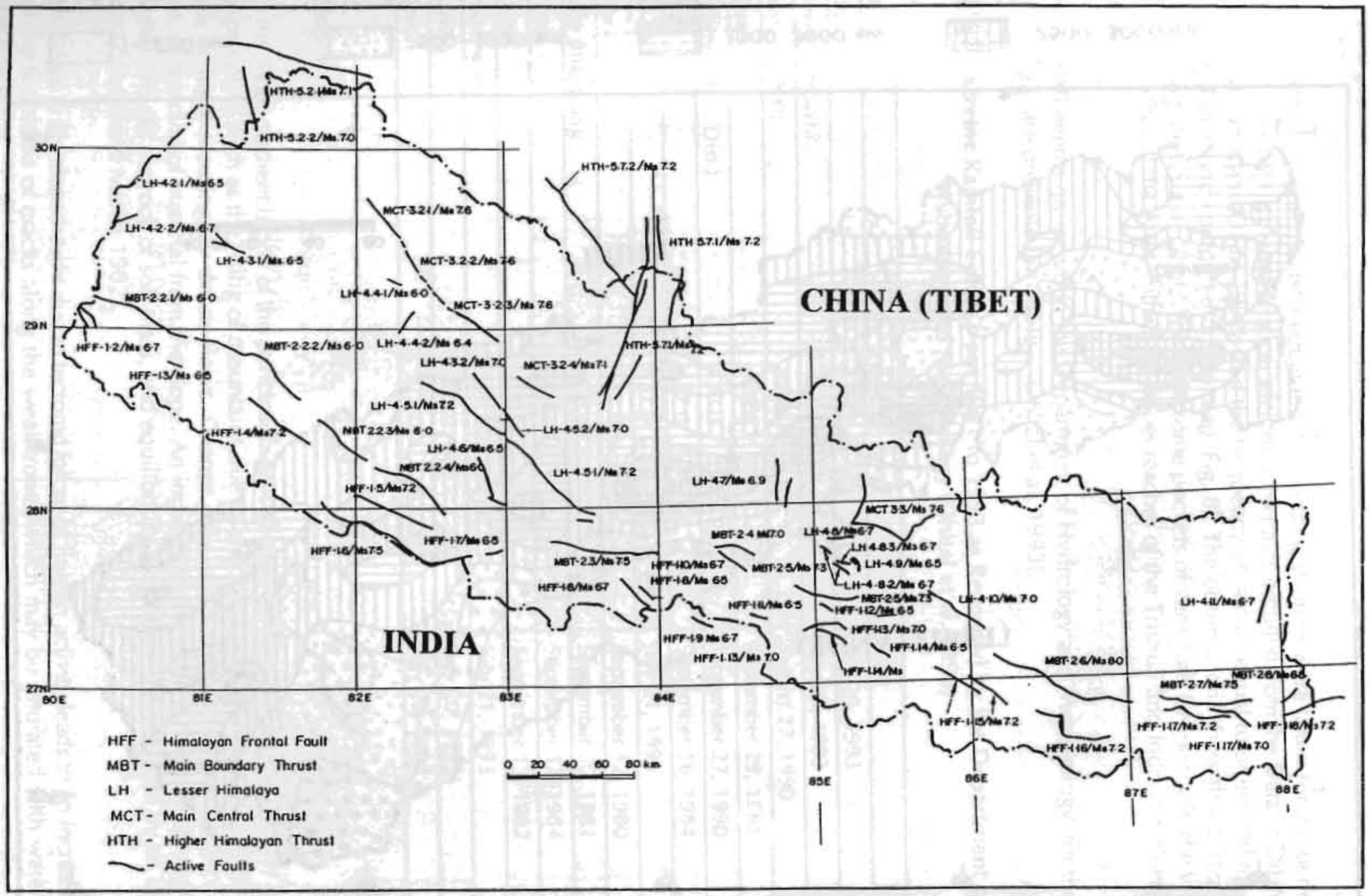
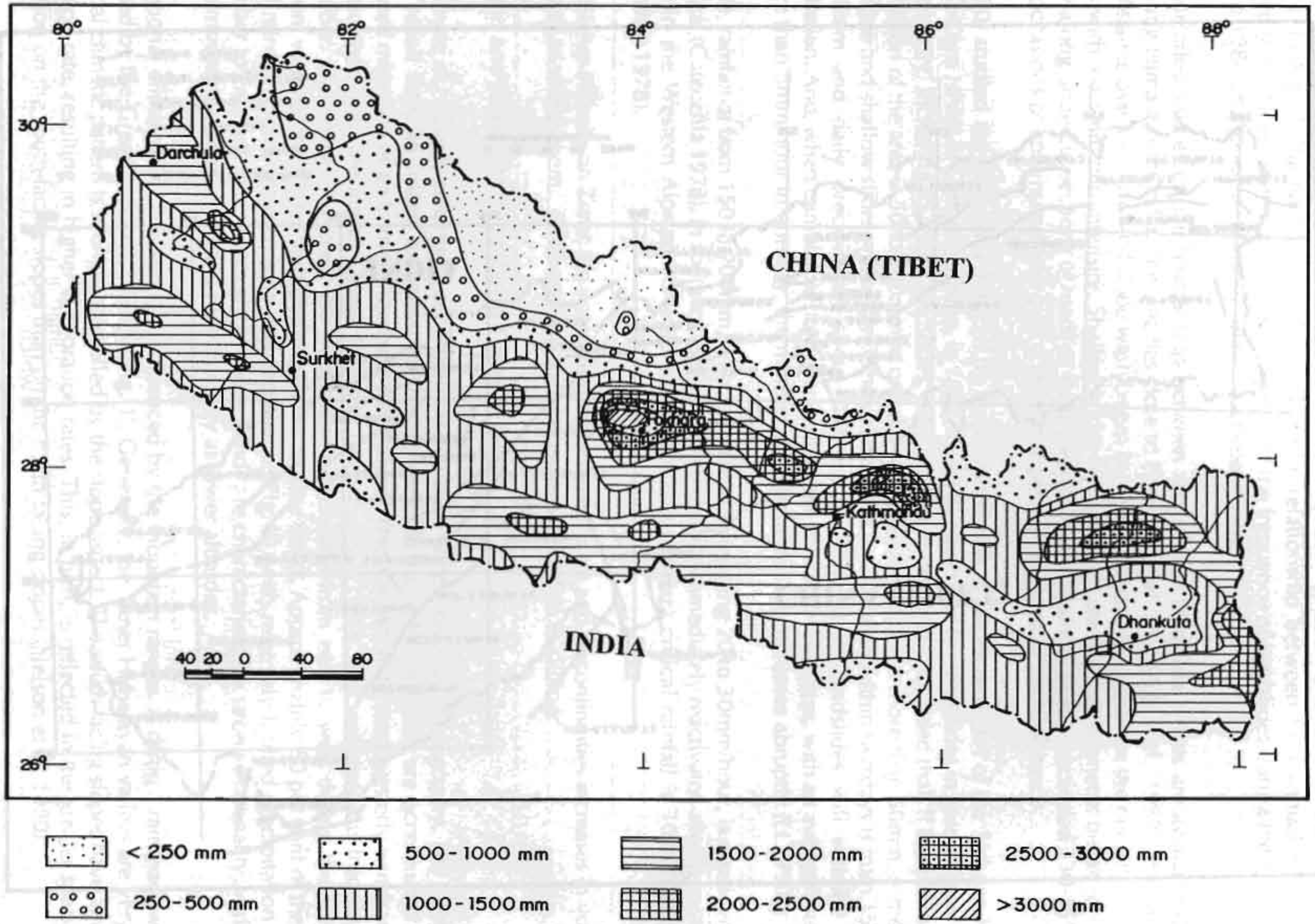


Figure 7: Mean annual precipitation (mm) in Nepal between 1971 and 1985 (DHM 1988)



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

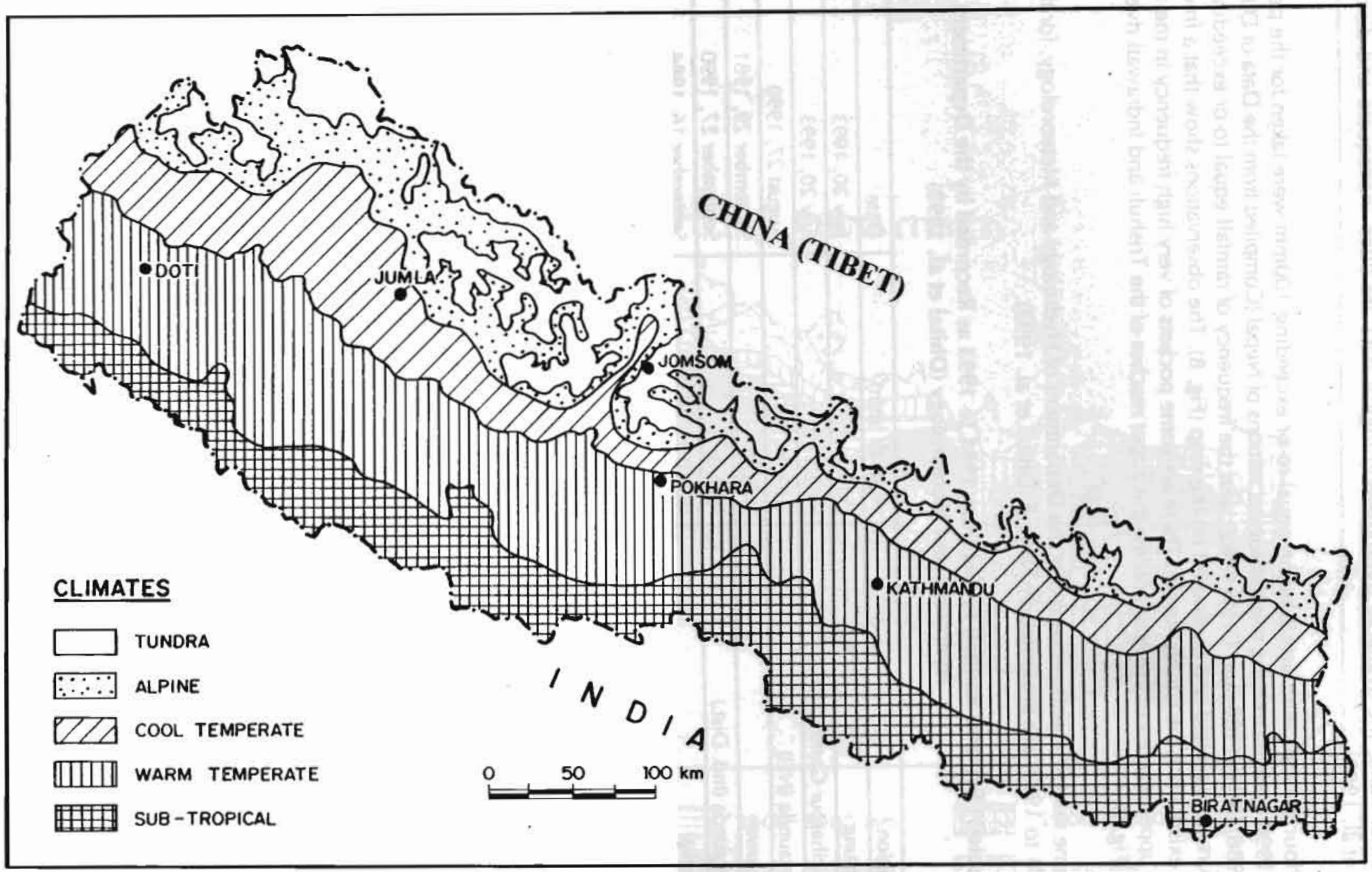
Natural Slopes

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)

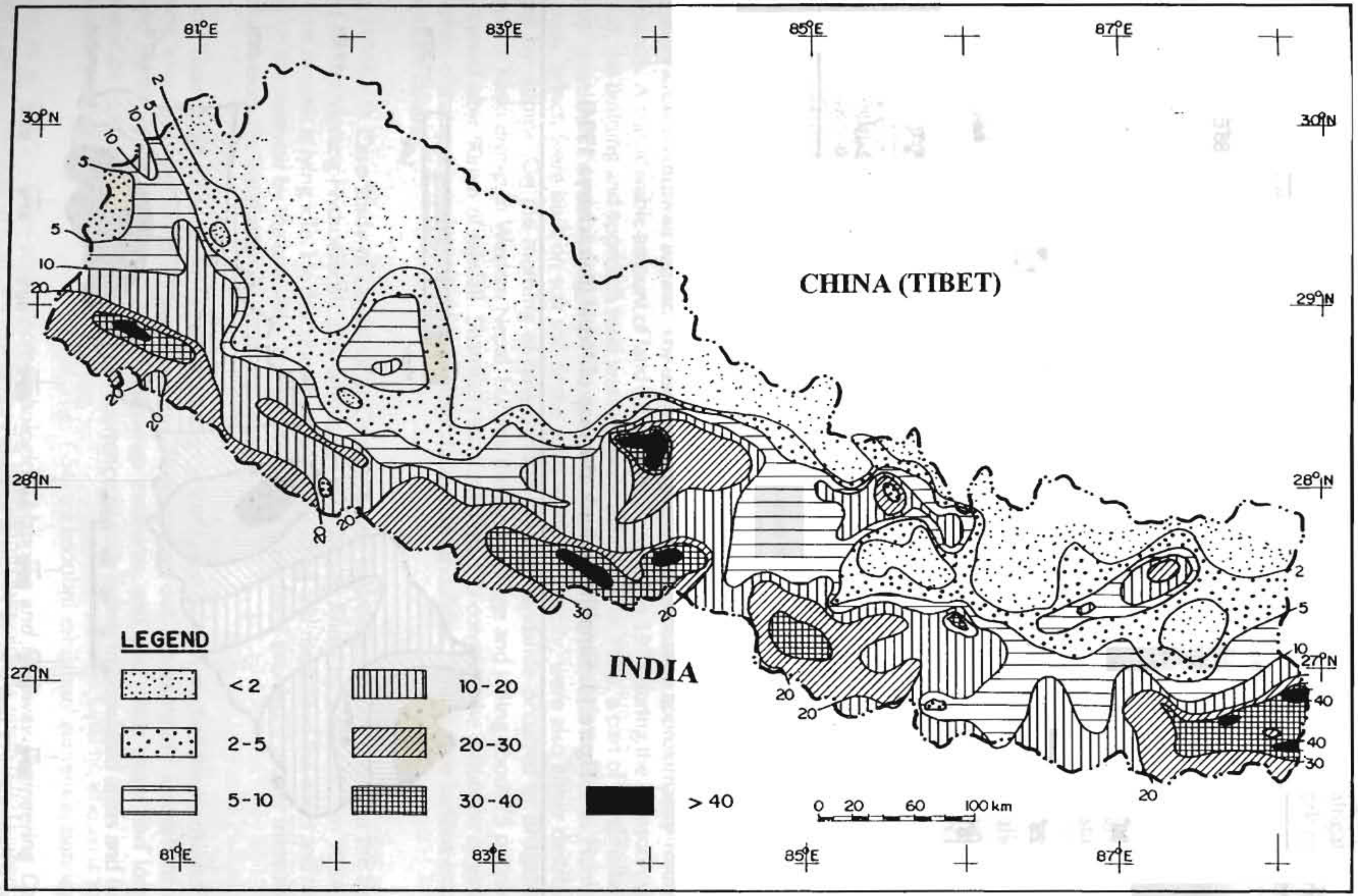


Figure 10: The epicentre distribution of the past earthquakes (M < 4) in Nepal (data between 1911-1993, 830 earthquakes) (Bajracharya 1994)

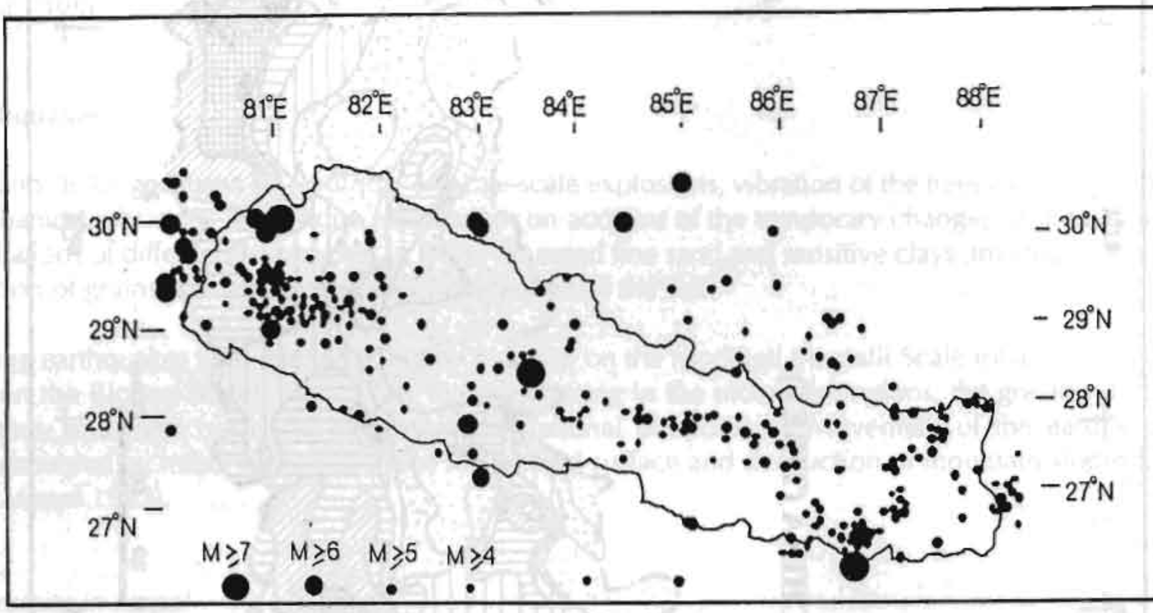
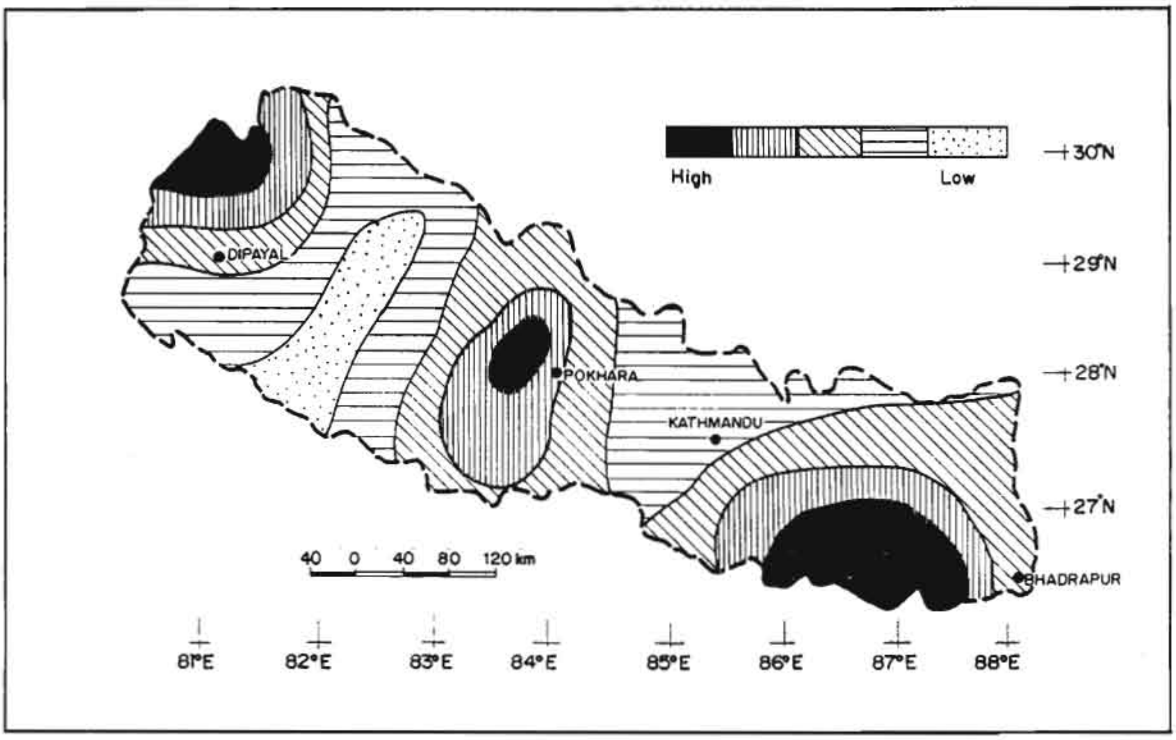


Figure 11: Simplified seismic risk map of Nepal (Bajracharya 1994)



A Short Review of Landslide Studies in Nepal

Though landslides and related disasters occur frequently in the fragile and young Himalayan region of Nepal, there are only a few studies carried out by some institutions or individuals focussing on the extent, type, and causes of such disasters. Very few attempts have been made so far on hazard mitigation and to prepare maps depicting the hazard and/or risk associated with these events. So far, the work on landslide studies in Nepal is widely scattered. The studies are carried out by large cross-sections of government and non-government organisations.

In the above context, an attempt is made to delineate the scientific and technical aspects of natural disaster study and mitigation in Nepal.

According to Auden (1935 - in *Traverses in the Himalayas*), the earthquake of 1934 triggered several landslides in the mountains, some of them dammed the rivers temporarily, and devastating floods occurred in the Indo-Gangetic Plain.

In 1953, at least five earthquakes rocked Far-western Nepal. The epicentres were located either in Nepal or the adjoining Indian Himalayas. Most of the secondary epicentres were near the Main Boundary Thrust or in the Indo-Gangetic Plain (Sharma 1981- *In Landslide and Soil Erosion in Nepal*). Also in the same volume it was reported that a landslide dam was formed at Labu Besi, Central Nepal, on August 1 1968, and it blocked the entire Budhi Gandaki River and created a 60m deep lake for 29 hours. After the breaching of the dam, the debris flow and flood washed away most of the houses and bridges in the low-lying areas. Arughat *Bazaar* suffered heavily; many lives were lost and property destroyed due to this incident. The earthquake of 1969 in Far-western Nepal which took a heavy toll of life and property in the Bajhang area and after which many landslides occurred is also described along with other incidents. The dam on the Pardi *Khola*, at the southern end of Phewa Lake, Pokhara, collapsed in 1970 owing to severed piping on the right abutment (Sharma 1981). The Tansen area of Western Nepal suffered from heavy rainfall in 1971. The rainfall measured 450mm in 24 hours (Sharma 1981) and the Tinau *Khola* flood washed away Khaseuli (Butwal) *Bazaar*. The temple of Dakshin Kali is situated approximately 18km south of Kathmandu. A considerable amount of land subsidence occurred in 1975 during the monsoon season. As a result, the building and approach road were severely damaged. In 1975, a part of Tahamalla *Tol* of Bhaktapur municipality was damaged by slumping. In the same year, several houses in Humat *Tol*, Kathmandu, which were built on soft soil or the solid waste of the city, were also either destroyed or damaged by slumps. On the morning of June 5, 1976, a huge landslide occurred in Bhagabati Tar *Panchayat* of Kaski district in Western Nepal, burying the entire village and killing about 75 people. The slide occurred after 50mm of rainfall. Sharma (1981) attempted to correlate the influence of geologic, topographic, climatic, seismological, and pedologic factors on landslides. He also gave various examples of large slope failures.

Sharma (1966 - 'A Case Study of Landslide at Chisang *Khola* hydroelectric unit') studied the damage inflicted on the Morang Hydroelectric powerhouse in the Chisang *Khola* by a landslide in 1964, since which time the unit is lying idle. He described the causes of sliding and mentioned the effect and damage inflicted on the reservoir by the landslide. The disaster could have been avoided if proper measures had been taken before the installation of the powerhouse.

Rimal and Tater (1968 - *Taplejung Landslide, A Report on Aerial Survey*) studied the landslides in the Taplejung area by undertaking an aerial survey. They carried out a preliminary assessment of the landslide, identified the preventive and/or follow-up measures, and also made short- and long-term recommendations that could help prevent the recurrence of such events in populated areas and in areas of economic interest.

Brunsden et al. (1975 - *Large-scale Geomorphological Mapping and Highway Engineering Design*), prepared a geomorphological map of a part of the Dharan-Dhankuta Road (Leoti *Khola*-Mulghat sector). This map showed various unstable zones along the alignment. As a result, the originally proposed alignment was rejected and a new alignment, with several hairpin stacks on a relatively stable slope, was selected.

Yadav (1976 - *Preliminary Geological Report on Jharlang Area, Central Nepal*) studied a landslide in the Jharlang area of Nuwakot District and identified its major causes. He also recommended that the villages of Wards No. 1, 2, and 3 be shifted immediately to safer places as the area required very expensive and uneconomical measures to control hazards.

Pandey (1976 - *Report on Landslide at Swayambhu Kathmandu*) carried out surface and subsurface investigations of the Swayambhu landslides and found that the weathering of the jointed sandstone, presence of strike slip faults, and presence of weak shale horizons in the section contributed to the development of slip circles due to the stress caused by the massive structure of the temple.

Fleming (1978 - *Classification of Catchments in the Western Development Region of Nepal*) attempted to consider landslide, gully erosion, and related landforms as criteria for evaluating the potential hazards occurring in the Western Development Region of Nepal.

Kojan (1978 - *Report on Landslide Problems, Western Hill Road Project, Godavari to Dandeldhura, Nepal*) studied the landslide problems in Far-western Nepal along the Godavari-Dandeldhura Road.

Laban (1979 - *Landslide Occurrence in Nepal*) undertook a study on the landslide occurrence in Nepal, based on landslide counts from aircrafts. He attempted to provide quantitative data on natural and total landslide density in most of Nepal's physiographic zones (his ecological regions), in order to assess the roles of man and nature in the occurrence of landslides.

Fort (1979 - *Études Sur les Quaternaire de l'Himalaya la haute Vallé de la Burhi Gandaki*) studied the Quaternary landforms and formations of the Upper Budhi Gandaki Valley and the glaciers and dynamic processes operating in the Great and Trans-Himalayan zones.

Thouret (1981 - *Geodynamique des Grands Versants de L'Ankhu Khola, Nepal Central*) studied the landslides and slope dynamics of the Ankhu *Khola* basin in Central Nepal and prepared a geomorpho-dynamic map.

Ives and Messerli (1981 - *Mountain Hazards Mapping in Nepal, Introduction to an Applied Mountain Research Project*) carried out mountain hazard mapping in the Kathmandu-Kakani area and concluded that loss of soil and agricultural land through gullying is occurring more rapidly than the local people with their existing resources can replace them.

Caine and Mool (1982 - *Landslides in the Kolpu Khola Drainage, Middle Mountain, Nepal*) studied the nature of and factors influencing the occurrence of landslides in the Kathmandu-Kakani area in the Kolpu *Khola* drainage basin. They found that the brittle nature of the weathered augen gneiss, biotite schist, and phyllite, in combination with high relief, seasonally high water tables, and deforestation were the main factors contributing to the development of landslides in that area. They also pointed out that weathered and brittle rock played a greater role in landsliding and that the importance of rainfall was slight.

Wagner and Ferel (1982 - *Seismic and Geological Survey of L.J.R. Planning*) tried to find ways to stabilise a landslide that occurred in July 1982 at km42.6 on the Lamosangu-Jiri Road. The authors also recommended a detailed geological survey of the road alignment using seismic refraction and landslide hazard mapping.

Wagner (1983a - *Lamosangu-Jiri Road Project. Geological Survey for Erosion and Instability Potential*) carried out a survey of erosion and instability potentials along parts of the Lamosangu-Jiri road and concluded that the geological structure, lithology, topography, and relief of the area were the predominant factors responsible for the debris and rockslide hazards along the road.

Wagner (1983b - *The Principal Geological Factors Leading to Landslides in the Foothills of Nepal. A Statistical Study of 100 Landslides: Steps for Mapping the Risks of Landslides*) studied more than 100 landslides along the roads, rivers, and hill slopes of South Central Nepal. He studied the geological, geomorphological, morphostructural, and groundwater conditions contributing to the occurrence of landslides in the area and prepared a hazard map.

White et al. (1987 - *Prototype: 50,000 Scale Mountain Hazard Mapping in Nepal*) assessed the geomorphic conditions of Gorkha, Myagdi, and Mustang districts and made geomorphological maps on a scale of 1:50,000 showing landslides, torrents, and surficial deposits. They also classified the region into various hazard and risk categories.

Dixit (1983 - *Report on Preliminary Engineering Ecological Investigation of Landslide and Subsidence in Kerabari and Charchare Area, Siddhartha Highway, Palpa District*) studied the landslides and sink holes at Kerabari along the Siddhartha Highway and found that the possibility of the whole Kerabari Hill sliding was negligible because the lower part of the slope was made up of sound bedrock. He also suggested that the roadside drainage be improved and the road not be backfilled as this might increase the porewater pressure in the tension cracks.

Kienholz et al. (1983 - *Mountain Hazards Mapping in Nepal's Middle Mountains, Maps of Land Use and Geomorphic Damages [Kathmandu-Kakani Area]*, 1984a - *Stability, Instability, and Conditional Instability, Mountain Ecosystem Concepts Based on a Field Survey of the Kakani Area in the Middle Hills of Nepal*, 1984b - *Stability, Instability, and Conditional Instability, Mountain Ecosystem Concepts Based on a Field Survey of the Kakani Area in the Middle Hills of Nepal*) studied the Kathmandu-Kakani area and prepared geomor-phological, slope stability, land use, and mountain hazard maps on a scale of 1:10,000.

Younger et al. (1984 - *Landslides and Their Control for Road Construction in Far West Nepal*) studied the landslides along the Godavari-Dandeldhura Road in Far-western Nepal. They observed that rotational and planar slides, block falls, wedge failures, and gully erosion were common along the road alignment. They proposed a relationship among the rock type, weathering conditions, and type of landslide and also proposed various stabilisation measures.

Dikshit (1985 - *Report on the Engineering Geological Survey of Landslides in Five Panchayat[s] of Dolkha Districts*) studied the landslides of Dolkha District in Central Nepal. Most of the landslides here were of the debris slide-debris avalanche types. The main factors causing these landslides were very steep slopes, high moisture content, deforestation, and unsound agricultural activities. He also recommended large-scale afforestation on the hill slopes.

Marui (1985 - *Landslide Prevention and Control*) described the landslide situation in Nepal and conducted field surveys in a few prominent landslide areas. He also visited some of the concerned agencies in Nepal. Ramsay (1986) reviewed existing information on hill slope processes including mass movements and erosion in the Nepal Himalayas. Zimmermann et al. (1986) studied the mountain hazards in the Khumbu Himal area and prepared a mountain hazard map of the area on a scale of 1:50,000. Gurung and Khanal (1987) studied the slope failures on the Churia Range in Central Nepal. They analysed and evaluated the landscape processes and studied the cause and extent of failures in the region.

Marston and Miller (1987 - *Mass Wasting in the Manaslu-Ganesh and Langtang-Jugal Himals*) studied the mass-wasting phenomena in the Manaslu-Ganesh and Langtang-Jugal Himal regions. They applied the chi-square statistical procedure to test several hypotheses regarding the spatial distribution of the 272 mass wasting scars and concluded that human activities do not account for a disproportionate share of mass wasting. Deforestation is prevalent, although the nature and extent vary from one region of Nepal to the next and, at the same time, devastating mass wasting is occurring. However, the logic linking these two phenomena could not be supported by the data in the study area.

Manandhar and Khanal (1988 - *Study on Landscape Processes with Special Reference to Landslides in Lele Watershed, Central Nepal*) studied the landscape ecology in general and the landslides in particular within the Lele Watershed in the southern part of Kathmandu Valley. They counted 743 landslide scars from the aerial photographs of 1986 and only 93 scars from the aerial photographs of 1972 from the same region.

Wagner et al. (1988 - *Rock and Debris Slide Risk Mapping in Nepal, A User Friendly PC System For Risk Mapping*) developed a computer programme for rock and debris slide hazard mapping for personal computers. They concluded that rock and debris slides in the Nepalese foothills are directly related to the rock structure, topography, and hydrogeology of the slopes. They also subdivided the slope into 'rocky' (if steeper than 35 degrees) and 'non-rocky'(if dipping 35 degrees or less).

In 1988, a huge landslide at Darbang (approximately 200km WNW of Kathmandu) killed 109 people and temporarily dammed the Myagdi *Khola*. The landslide occurred in the Main Central Thrust Zone. About 62 years ago, the same landslide had buried Darbang *Bazaar* and killed about 500 people (Yagi et al. 1990 - *The September 1988 Large Landslide in the Vicinity of MCT, Darbang, Nepal*).

Karmacharya (1989 - *Landslides in Nepal in the Period 1970-1980*) collected and analysed the data on landslides and evaluated the cost of damage by landslides in Nepal from 1970 to 1980. He also carried out a field study along the Butwal-Palpa Road in Western Nepal. His study indicated that most of the landslides along the road were triggered by river incutting.

Dikshit (1987 - *Engineering Geological Mapping for Development Planning in Nepal*) studied geological hazards, their types, and degrees in Nepal and prepared a geological hazard map which he based on the data obtained from various sources and field observations. According to the map, a large part of the country falls in areas with high and very high hazard conditions. The high hazard areas lie in the eastern, central, and far-western regions of the country.

Khanal (1991 - *Historic Landslides of Nepal During 1902-1990 A.D., Extent and Economic Significance*) studied the historical landslides in Nepal that occurred between 1902 and 1990 by collecting information from the *Gorkhapatra*, an important daily newspaper of Nepal, and studied the loss of human lives and property.

Nepal (1992 - *Landslide Hazard Zonation of Kulekhani Catchment Area, Central Nepal*) studied the landslides in the Kulekhani Watershed in Central Nepal and prepared land use, landslide distribution, and hazard zonation maps.

The Department of Roads (DOR) carried out an environmental impact study of the Pokhara-Baglung Road and prepared geological engineering and hazard maps of the entire road alignment (DOR 1992 - *Report on the Environmental Impact Study of Pokhara-Baglung Road*).

Karmacharya (1993 - *Report of the Bungamati Landslide, Lalitpur District, Central Nepal*) studied the landslide at Bungmati, which was creating several problems by breaking the water supply pipeline during the rainy season. The landslide was studied by installing extensometers. The main cause of failure was porewater pressure developed by infiltration from a gravel layer. She suggested that the pipeline be supported by constructing gabion pillars founded below the slip surface of the shallow slide.

Koirala (1993 - *Report on the Landslide Inventory Study of the Central Development Region, Nepal*) carried out a reconnaissance-level landslide inventory study in the Central Development Region, including parts of Nuwakot, Kabhrepalanchok, Sindhupalchok, Sindhuli, Ramechhap, and Dolakha districts and prepared hazard maps. Koirala et al. (1993) also carried out geological engineering investigations in the southern part of Kathmandu Valley .

A team of experts from JICA (1993 - *Report of Japan Disaster Relief Team on Heavy Rainfall and Floods in Nepal*) prepared a report on heavy rainfall and floods in East Central Nepal during the period from 19th to 21st July 1993. The area affected by the disaster extended over 44 districts. The districts of Chitawan, Makawanpur, Sindhuli, Rautahat, and Sarlahi were severely affected. The team also prepared several terms of reference for landslide stabilisation, establishment of hydro-meteorological stations, and early warning systems.

The damage caused by heavy rainfall in East Central Nepal during the period from 19th to 21st July 1993 was also assessed by Dhital et al. (1993 - *The Role of Extreme Weather Events, Mass Movements, and Land Use Changes in Increasing Natural Hazards*), Dangol et al. (1993a - *A Landslide Inventory Study*

[After the Disaster of July, 1993] along the Tribhuvan Highway, Central Nepal), UNDP/HMG (1993 - *Flood Damage Assessment; General Infrastructure*), and the World Bank/HMG (1994). There were numerous rock and soil slides, alluvial fans, and debris flows along the Tribhuvan Highway, Prithvi Highway, Kulekhani-Kunchhal Road, as well as instabilities along the stream and river banks and canals. The event had an adverse impact on the Kulekhani Reservoir and caused severe damage to the penstock pipe in Jurikhet *Khola* and the intake in Mandu *Khola*. The newly-completed Bagmati Barrage was also heavily damaged.

Ito et al. (1993 - *Technical Proposal for Landslide Control and Management in the Hindu Kush-Himalayan Region*) prepared a technical proposal for landslide control and management in the Hindu Kush-Himalayan Region for ICIMOD and concluded that the occurrence of landslides in the HKH region is related to the fragile geology, high precipitation, deeply-weathered rock material, unconsolidated soil characteristics, slope configuration and steepness, as well as human activities.

Dixit (1994a - *Report on the Landslide Inventory Survey in a Part of Bajhang District*, 1994b - *Report on the Landslide Inventory Survey in Bajhang-Baitadi-Darchula Area*, 1994c - *Report on the Landslide Inventory Survey in Parts of Baitadi and Darchula Districts*) undertook a landslide inventory study in parts of Bajhang, Baitadi, and Darchula districts of the Far-western Nepal Lesser Himalayan region. His study indicated that Far-western Nepal, in general, is quite extensively affected by landslides. Dixit (1994d) also conducted studies in parts of Panchthar, Taplejung, Terhathum, Dhankuta, Sankhuwasabha, Okhaldhunga, Bhojpur, Udayapur, and Sindhuli districts in Eastern Nepal.

Shrestha (1990 and 1994 - *Landslide Inventory and Slope Stability Mapping in a Part of Mustang District, Landslide Inventory and Slope Stability Mapping in Seven Districts of Central and Western Nepal*) carried out landslide inventory mapping in parts of Mustang, Gorkha, and Palpa districts and Shrestha and Shakya (1990) carried out a reconnaissance inventory survey along the roads and highways in the areas of Nuwakot, Dhading, Lamjung, Tanhun, Nawalparasi, Chitawan, and Makawanpur districts.

The Water Induced Disaster Prevention Technical Centre (DPTC) and the Central Department of Geology, Tribhuvan University (DPTC/TU 1994a - *Preliminary Survey of Debris Flows and Landslides in the Palung Khola and the Manahari Khola [Makwanpur District, Central Nepal]*, 1994b - *Preliminary Survey of Debris Flows and Landslides in Agra Khola, Belkhu Khola, and Malekhu Khola*) carried out preliminary surveys on debris flows and landslides in Palung *Khola* and Manahari *Khola* in Makawanpur District, and Agra *Khola*, Belkhu *Khola*, and Malekhu *Khola* in Dhading District. The focus was mainly on the impact of the July 19-21 1993 disaster in the area. These studies are among the few comprehensive studies carried out on landslides and debris flows caused by high intensity precipitation in Nepal.

Humagain (1994 - *Geology of the Area between the Rivers Tamakoshi and Khimti with Special Reference to the Engineering Geology of the Khimti II Project*) studied landslides and other types of mass movements in the Khimti Hydropower Project area in Dolakha and Ramechhap districts and prepared an engineering geological map showing a number of landslides and active gullys on the banks of the Khimti *Khola*.

Selected Case Studies on Landslides

Landslide studies in Nepal can be grouped as follows.

1. The study of individual landslides
2. Landslide inventory surveys in a particular region
3. The study of the effect of landslides on infrastructures

The extent and depth of these studies also vary widely. Most of the studies can also be classified as preliminary reconnaissance inventories or state-of-nature types (Einstein 1988). Some of them are landslide susceptibility studies (Brabb 1984) or landslide hazard studies. There are very few cases of landslide risk mapping.

Study of Individual Landslides

The study of individual landslides is carried out either by individual researchers or institutions. Institutions are generally involved when there is a big disaster or considerable damage to infrastructure. Researchers have carried out studies of some very large and catastrophic landslides, most of which resulted in extensive loss of life and/or property. Some of the studies are reconnaissance-type studies and others not only assess the damage but also suggest the methods of slope stabilisation.

The Tsergo Ri Landslide in Langtang Valley

A huge ancient landslide in the Higher Himalayas of central Nepal was studied by Masch et al. (1981), Heuberger et al. (1984), and Weidinger and Schramm (1995). This landslide is on the right bank of the Langtang *Khola*, east of the confluence of the stream from the Lirung Tsang glacier.The landslide mass contains the peak of Tsergo Ri.

Scott and Drever (1953) first described the phenomena of rock fusion in Langtang Valley. Later Masch and Preuss (1974) studied the Tsergo Ri slide and concluded that the rock fusion was caused by the landslide. Masch et al. (1981) calculated the area of the visible portion of the landslide deposit to be about 14 square kilometres. An arbitrary average depth of about 200m was assumed for the failure and it gave a rough volume estimation of three cubic kilometres. According to them, the original volume of the landslide was about 10 cubic kilometres and the angle of sliding was about 6.5 degrees.

The landslide occurred on migmatites, leucogranites, and gneisses. It is very close to the Main Central Thrust Zone. The direction of movement of the landslide was SW and WSW. Hyalomylonite was formed during the movement of the landslide due to rock fusion on the sliding surface. The age of the landslide obtained using the fission track method was approximately 40 thousand years (Weidinger and Schramm 1995).

The Rockslide/Rockfall of Darbang

Darbang is approximately 200km WNW of Kathmandu. The landslide occurred at about 11p.m. on September 20,1988, along the north-facing slope of the NE-SW trending ridge (Yagi et al. 1990). The debris buried all the houses on the right bank of the Myagdi *Khola*, damming it and burying two more houses on the left bank (Fig. 12). It killed 109 people. The landslide was about 650m high and the maximum width of the debris was about 500m. About 500 million cubic metres of debris was assumed to have been produced by the slide. The landslide was not triggered by rainfall; there had been no rain for the previous three days nor was there any noticeable earthquake whithin proximity of the landslide (Yagi et al. 1990).

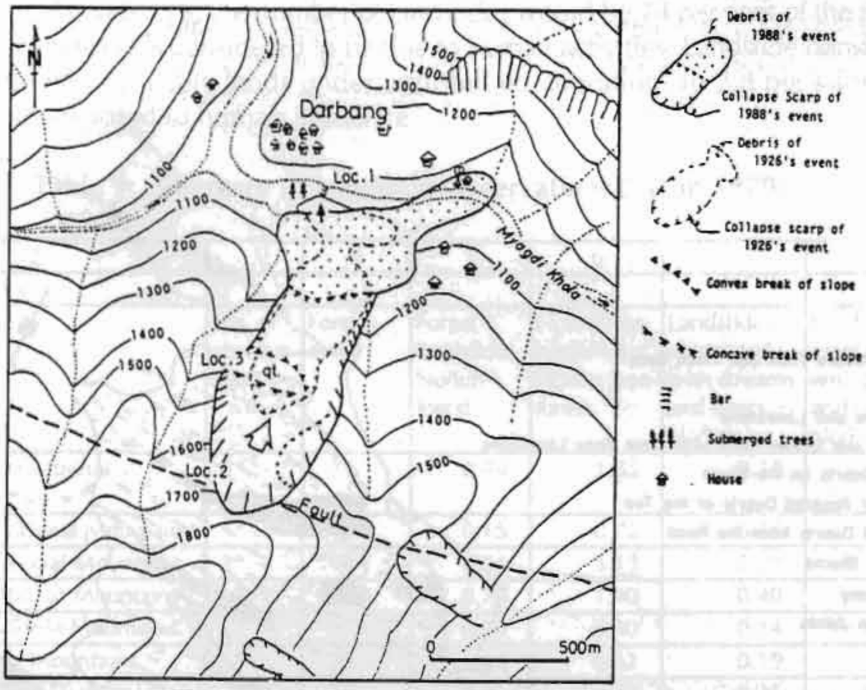
The Darbang rockslide/rockfall is situated at the core of an anticline and the rocks at the base are represented by alternating phyllites and quartzites, whereas the rocks at the crown are made up of biotite schist. The two rock units are probably separated by a fault which passes close to the crown. The landslide lies near the Main Central Thrust Zone and is probably related to the activity of the Main Central Thrust. About 62 years earlier, the same landslide buried Darbang *Bazaar* and killed about 500 people (Yagi et al. 1990).

The Jogimara Rockslide

The rockslide of Jogimara is located on the Prithvi Highway, approximately 90km west of Kathmandu. It lies on the left bank of the Trishuli River. The Jogimara landslide is probably the most hazardous landslide on the Prithvi Highway. It has already carried down two buses with passengers into the Trishuli River and many lives have been lost. The slide is about 150m long at the toe and 190m high (Fig. 13). Its toe lies on the road near the river.

The rockslide occurred on the Benighat Slates with the Jhiku Limestone bands (Stöcklin 1980). It lies on the counter dip slope of the interbedded slate and limestone. The steep slope, cliffs, and overhangs of

Figure 12: Geomorphological map of the Darbang rockslide/rockfall (Yagi et al. 1990)



limestone and slate are related to the orientation of discontinuities in the rock mass. The rock is highly jointed and the joint spacing varies from a few centimetres to tens of centimetres in the slate and from tens of centimetres to a few metres in the limestone. The natural slope is from 40 degrees to vertical and the failed slope is generally steeper than 45 degrees and sometimes exceeds 60 degrees (Dhital et al. 1993).

The statistical analysis of 631 discontinuities in the rockslide zone and the adjacent region revealed that there are three genetically distinct sets of joints in the rocks (SWK 1994). One set is parallel to the cleavage and bedding, two mutually perpendicular sets are extension joints, and two sets are represented by shear joints. The bedding/cleavage plane is dipping 70 degrees due 196 degrees. One of the joint sets (34/50) is gentler than the natural slope and is the most developed set. The failure is strongly controlled by this joint. On the other hand, another joint set (262/80) forms a central wedge with the foliation which dips out of the slope when the slope is steeper than 65 degrees (SWK 1994).

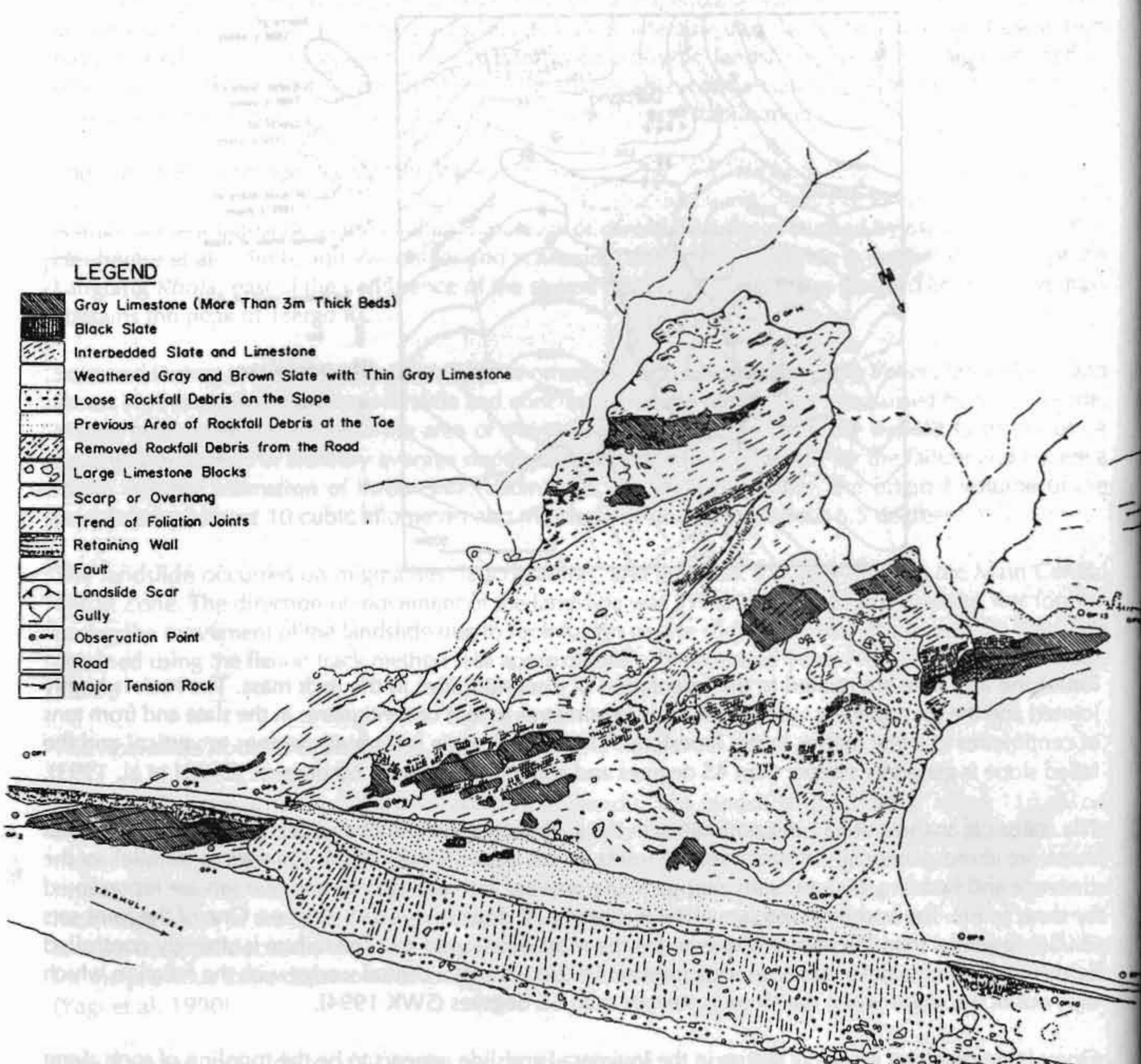
One of the important causes of failure in the Jogimara Landslide appears to be the toppling of rock along the steep counter dip slope. During the monsoon season, the rainwater and subsurface water percolate into the slope through the fractures and joints and are blocked by the impervious black slate bands. As a result, a high porewater pressure is built up and slope failure ensues (SWK 1994).

There is a limestone quarry west of the rockslide. The quarry operation began about 18 years earlier and continued until 1989. The construction of the approach road and the blasting in the limestone quarry may have aggravated the situation.

Landslide Inventory Studies

Reconnaissance landslide inventory maps show places that appear to have failed due to landslide processes over broad areas (Brabb 1984). These maps are commonly prepared by cursory field survey and/or by studies of aerial photographs and satellite imagery. In Nepal, most of the inventory studies are carried out along the roads, canals, proposed road alignments, and in the areas affected by earthquakes

Figure 13: The geological engineering sketch map of the Jogimara rockslide, the Prithvi Highway, Central Nepal (SWC 1994)



and high-intensity precipitation. Inventory sudies are also carried out in some areas as part of research projects. These studies were carried out by individual researchers and institutions and most of the studies were made after high-intensity rainfall and slope failures caused by the earthquakes. A few examples are given below.

Laban (1979) carried out a preliminary study on landslide occurrence in Nepal, covering most parts of the country and based on landslide counts made from aircrafts. He tried to provide quantitative data on natural and total landslide density in most of Nepal's physiographic zones (his ecological regions) to find an indication of the roles of man and nature in the occurrence of landslides. His observations are summarised in Table 9. On the basis of the survey, he concluded that, on an average, the number of landslides has increased by a factor of 1.35 from a natural landslide density. This means that, if Nepal were under fully natural conditions, the number of landslides would be 74 per cent of the present existing total. The 26 per cent increase is considered to be due to human activities. Landslide density ranged from 0.2 per linear kilommetre on stable lands under undisturbed conditions to 2.8 per kilometres on very susceptible lands fully exposed to human influence.

Table 9: Summary of Landslide Observations (Laban 1979)

1	2	3	4	5	6	7	8	9
GEOLOGICAL REGION								
Symbol	Name	No. of observa-tions	Forest cover	Forest landslides No/km forest	Non-forest landslides No/km non-forest	Landslides associated with streams and rivers No/km	Landslides associated with roads and trails No/km	No. of total landslides
I.A	Far-western Transitional Mountains**	5*	25	0.44	1.55	0.12	0.18	(1.57)
I.C	Western Transitional Mountains	5*	40	0.15	0.72	0.16	0.02	(0.67)
I.D	Central Transitional Mountains	2*	45	0.84	5.13	0.88	0.04	(4.12)
I.E	Eastern Transitional Mountains	9	40	0.70	1.40	0.40	0.01	1.53
II.A&B	Far-western Middle Mountains	13	25	0.40	0.40	0.14	0.03	0.57
II.C	Piuthan Middle Mountains	8	20	0.60	0.61	0.19	0.02	0.82
II.D	Baglung Middle Mountains	9	35	0.23	1.43	0.35	0.03	1.39
II.E	Central Middle Mountains	14	25	0.32	0.49	0.35	0.04	0.84
II.F	Kathmandu Middle Mountains	14	15	0.67	1.11	0.33	0.06	1.43
II.G	Eastern Middle Mountains	10	25	0.36	1.24	0.20	0.04	1.26
II.H	Far-western Middle Mountains	9	20	0.40	0.73	0.20	0.07	0.94
Average Middle Mountains		77	24	0.41	0.79	0.24	0.04	0.96
II.K&L	Eastern Mahabharat *Lekh*	13	40	1.28	1.67	0.36	0.05	1.92
II.M	Central Mahabharat *Lekh*	2*	40	0.43	4.78	0.48	0.09	(3.61)
II.N	Western Mahabharat *Lekh*	9	25	0.44	0.44	0.28	0.06	0.75
II.P	Far-western Mahabharat *Lekh*	10	75	0.17	0.60	0.31	0.06	0.65
Average Mahabharat *Lekh*		32	48	0.70	1.01	0.32	0.06	1.21
IV.A	Western Siwaliks*	12	85	0.73	0.40	0.13	0.03	(0.84)
IV.B	Central Siwaliks**	9	75	0.83	0.26	0.19	0.06	(0.94)
IV.C	Eastern Siwaliks	14	80	1.15	2.75	0.53	0.02	2.02
AVERAGE OF ALL		130	36	0.58	1.12	0.31	0.04	1.20

* This number of observations is considered to be too low. These figures are therefore not used to calculate averages.

** The figures for these ecological regions are not used for further calculations, except for the number of total landslides within the same ecological region.

He also observed that five per cent of landslides in Nepal are associated with roads or trails. Since the percentage of the land surface covered by roads is very small, this figure must be taken seriously in the context of road network development in Nepal. The results of this study also showed that the eastern Siwaliks, the eastern Mahabharat *Lekh*, and the Transitional Mountains (the northern part of the Midlands adjacent to the Higher Himalayas or Fore Himalayas (Fig. 1) have the highest natural susceptibility to landslides, whereas the highest total landslide densities are found in the eastern Siwaliks, the Central Mahabharat Range, and the Central Transitional Mountains.

Disaster in the Lele-Bhardeo Area, Lalitpur District (1981)

On the morning of 30th September, 1981, a big disaster occurred in the Nakhu *Khola* Watershed situated about 17km south of the Kathmandu Valley. The disaster, caused by debris flows, floods, and landslides, took more than 70 lives and destroyed many houses, agricultural land, irrigation infrastructure, and so on (Rajbhandari 1993). The main disaster area was confined to the sub-watersheds of the Nallu *Khola*, Lele *Khola*, and Burunchuli *Khola*, with a total area of 47.5 square kilometres.

The main cause of the disaster was five days of (Sept 25-30) continuous rainfall, followed by 40 minutes of high intensity rainfall (September 30) exceeding 56.1 mm/hour (Manandhar and Khanal 1988; Rajbhandari 1993). Rainfall data from the nearby Godavari meteorological station showed that the mean annual precipitation was 1,900mm and the total annual precipitation fluctuated. On the day of the disaster, the Godavari station recorded exceptionally heavy precipitation of nearly 169mm in 24 hours, which was the highest recorded at the station. The rain finally triggered landslides and debris flows in the watershed. Manandhar and Khanal (1988) counted 743 landslide scars on the Lele Watershed from aerial photographs taken in 1986, while there were only 93 on the 1972 aerial photographs. Most of the landslides were shallow (1-2m). The aerial coverage of the landslide scars was 0.74 per cent of the total area of the watershed and the landslides contributed to a total soil loss of 131,400 cubic metres. This loss amounts to 10mm of denudation on the hillslopes as a whole and 9mm by the single event of September 30, 1981 (Manandhar and Khanal 1988).

Tiwari (1990) calculated the surface runoff and the soil erosion rate in the Nakhu *Khola* Watershed using the Universal Soil Loss Equation (USLE) and found that the estimated average potential soil erosion rates in the watershed vary from 5.56tonnes/ha/year in forest areas to 173.11 tonnes/ha/yr in the grazing fields. The average value for the whole watershed was estimated at 44.13 tonnes/ha/yr.

Disasters in 1984 and 1986 in the Budhi Rapti River Basin

The upper reaches of the Budhi Rapti River in Central Nepal (north of Hetauda) experienced high intensity precipitation in 1984 and 1986. In 1984, torrential rainfall triggered numerous landslides (Fig. 14) and debris flows and also caused severe gully erosion and river/stream bank undercutting (NEA 1989). From 14th to 17th September, 1984, a total rainfall of 743.7mm and 725.5mm was recorded at Nibuwatar and Chisapani Garhi respectively. The maximum hourly rainfall at Chisapani was 53mm. Similarly, in 1986, the rainfall from 5p.m. on 26th August to 5p.m. on 27th August, as recorded at Nibuwatar, was 329.5mm and the maximum continuous 24-hour rainfall during the same event was 296mm (NEA 1989).

In 1984, the upper catchment of the Budhi Rapti River was devastated by landslides and debris flows. During that incident, 10 people were killed and 225 were made homeless. The Tribhuvan Highway was blocked in 31 places and 20 bridges were washed away (NEA 1989). The Kulekhani Hydroelectric Power Station was also heavily damaged. Similarly, the disaster in 1986 triggered many landslides on the upper reaches of the Budhi Rapti River and many facilities were heavily damaged, as in 1984.

In addition, there were large flood events in 1927, 1954, 1970, and 1974. They also caused considerable damage to infrastructure and property (NEA 1989). Even more severe high-intensity precipitation occurred in July 1993; the event is described below.

Mass Movements in Central Nepal Caused by the Cloudburst in July 1993

From 19th to 21st July, 1993, there was heavy rainfall in a concentrated area approximately 30km southwest of the Kathmandu Valley. The rainfall pattern of this event shows that there were two peaks of rainfall. According to the records from Nibuwatar (Fig. 15a) in the Rapti River Basin, the maximum rainfall intensity was between 17:00 and 18:00 hours on 19th July and between 20:00 and 21:00 on 20th July, with 60 and 64mm of rainfall respectively. At Tistung in the upstream portion of the Kulekhani *Khola* (Fig. 15b), the rainfall peaked between 21:00 and 22:00 hours on 19th July and 4:00 and 5:00 on 20th July, when hourly precipitations of 65mm and 50mm were recorded respectively. During the same period, rainfall at Simlang (the Kulekhani Reservoir) was 75mm and 28mm respectively (Fig. 15c). The total continuous precipitation during that period was more than one third of the annual precipitation in that area. The isohyetal map of 20th and 21st July shows two maxima of concentrated rainfall (Fig.16). Two characteristics of this heavy rainfall that caused the disaster were (JICA 1993) as follow.

1. There was little rainfall during the day, with the peak period of concentrated rainfall occurring at night.
2. The area of rainfall appeared to be concentrated in the middle mountains.

Figure 14: The landslide distribution on the upper reaches of the Budhi Rapti watershed (NEA 1989, redrawn)

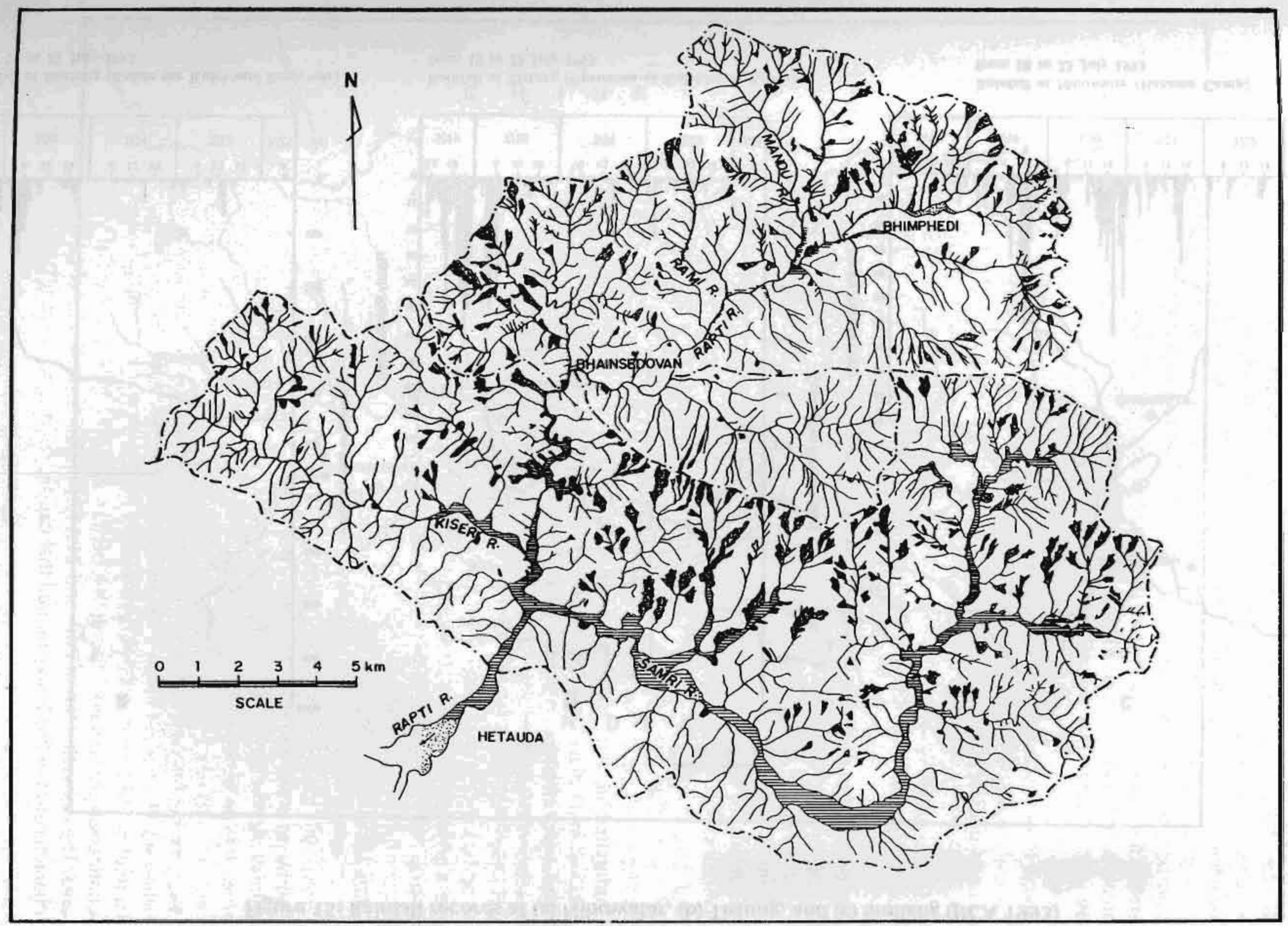
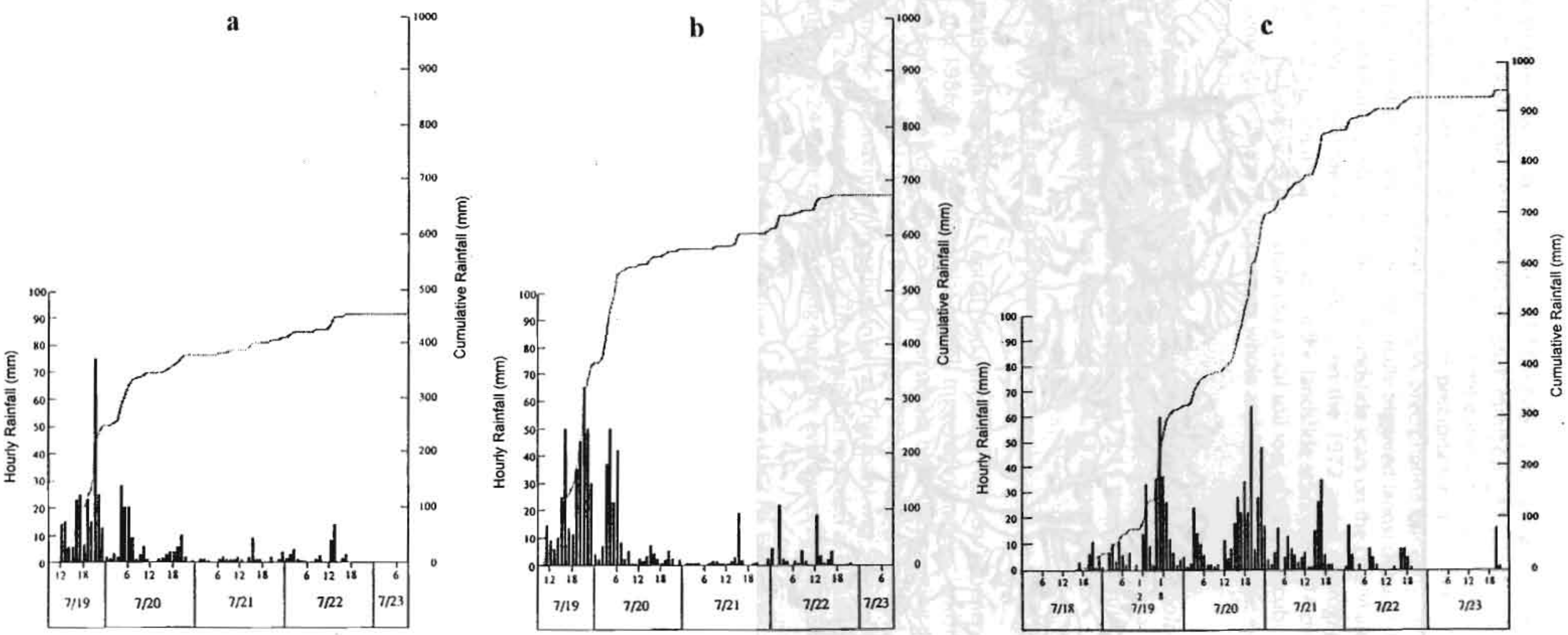


Figure 15: Rainfall records at (a) Nibuwatar, (b) Tistung, and (c) Simlang (JICA 1993)

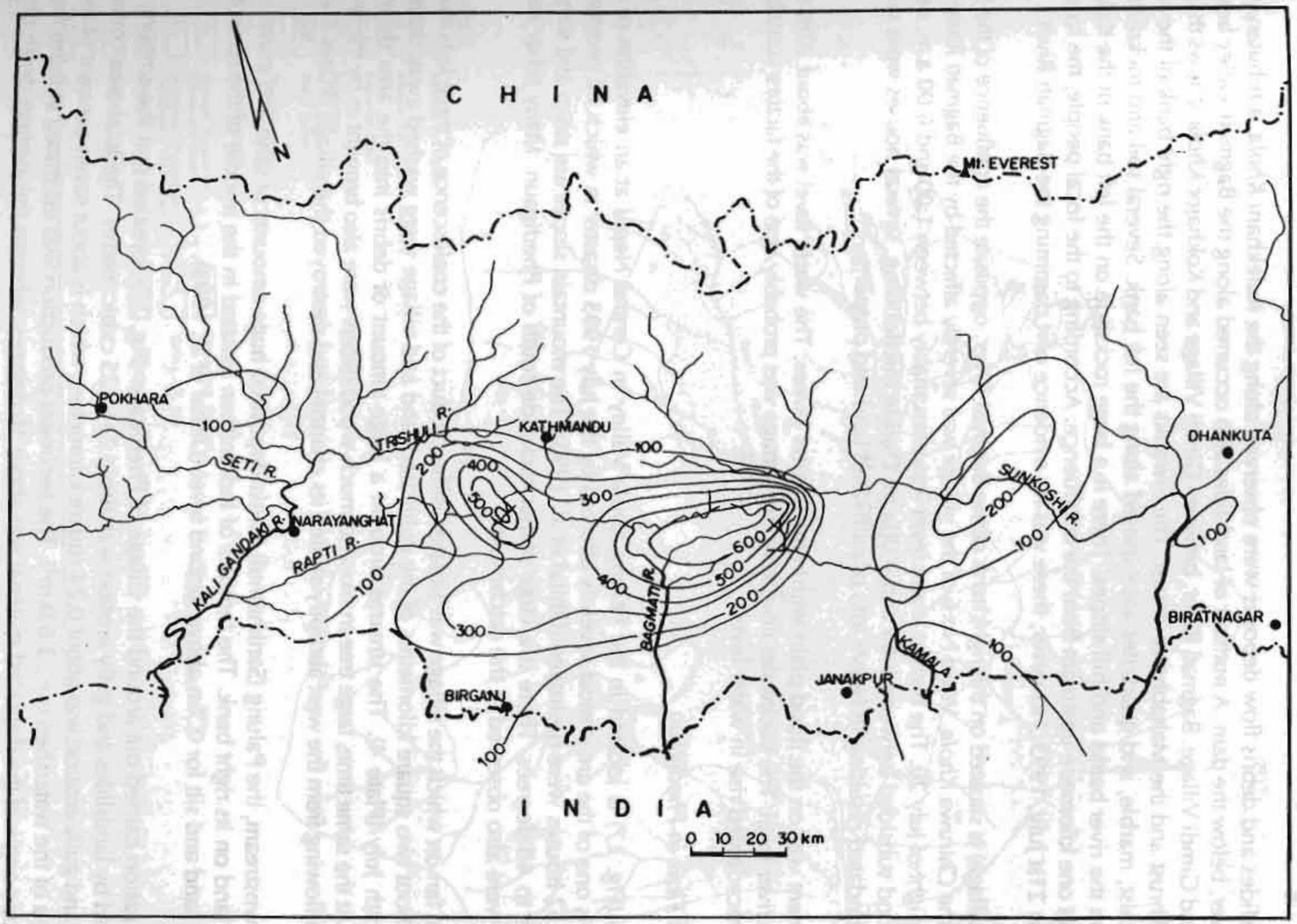


Rainfall at Simlang (Beside the Kulekhani Reservoir) from 19 to 23 July 1993

Rainfall at Tistung (Upstream of Kulekhani Khola) from 19 to 23 July 1993

Rainfall at Nibuwater (Hazama Camp) from 18 to 23 July 1993

Figure 16: The isohyetal map of the July 20-21 rainstorm in Central Nepal, 1993 (JICA 1993, redrawn)



The number of landslides and the extent of inundation, during the rainstorm that took place from July 19 to 21, 1993, were extraordinarily high for that region (Dhital et al. 1993). Apart from heavy rainfall, the inadequate design of the barrage, inappropriate location of the powerhouse and the penstock, deforestation, steep slope cultivation, and encroachment on highly hazardous areas were the other factors that caused the heavy loss of lives, infrastructure, and property.

Disaster along the Bagmati Valley

Many landslides and debris flow deposits were observed along the Kulekhani *Khola*, a tributary of the Bagmati River, below the dam. A number of landslides also occurred along the Bagmati Valley between Ipa *Khola* and Gimdi Village. Bagmati River, between Gimdi Village and Kokhajor *Khola* follows the Main Boundary Thrust and the Mahabharat Thrust. The Siwaliks are seen along the right bank of the valley, whereas schist, marble, and quartzites are exposed along the left bank. Several soil and rockslides are observed on the river banks and hill slopes. There is a large rockslide on the left bank of the Kokhajor *Khola*, about one kilometre upstream from the confluence. According to the local people, the landslide occurred on 21st July, 1993. However, there was no evidence of it damming the Bagmati River.

Rai *Gaun* (village) is situated on the right bank of the Bagmati River, opposite the confluence of the Marin *Khola* and the Chiruwa *Khola*. Ward No 6 of the village was severely affected by the Bagmati River flood during the night of July 20. The highest water level was presumably between 1:00 and 6:00 a.m. on 21st July; the flood subsided between 6:00 and 7:00a.m. During the flooding, several houses were washed away or inundated resulting in heavy loss of cultivated land and property.

The settlement was on the flood plain within the natural levees. The water level was about 20m above the present river level. The backwater flow from the barrage was probably one of the factors contributing to the unprecedented rise in water level.

The Debris Flow in Phedigaun

Phedigaun (Fig. 17) is located in the Palung *Khola* Valley in Central Nepal at an elevation of about 1,830m. It is one of the areas most severely affected by the July 1993 disaster in which 62 people were killed and 52 houses were destroyed (Dhital et al. 1993). The mountain slopes are steep and vary from 30 degrees to 40 degrees. There is a large planar rockslide south of Phedigaun. Many other soil and rockslides were also observed in the catchment.

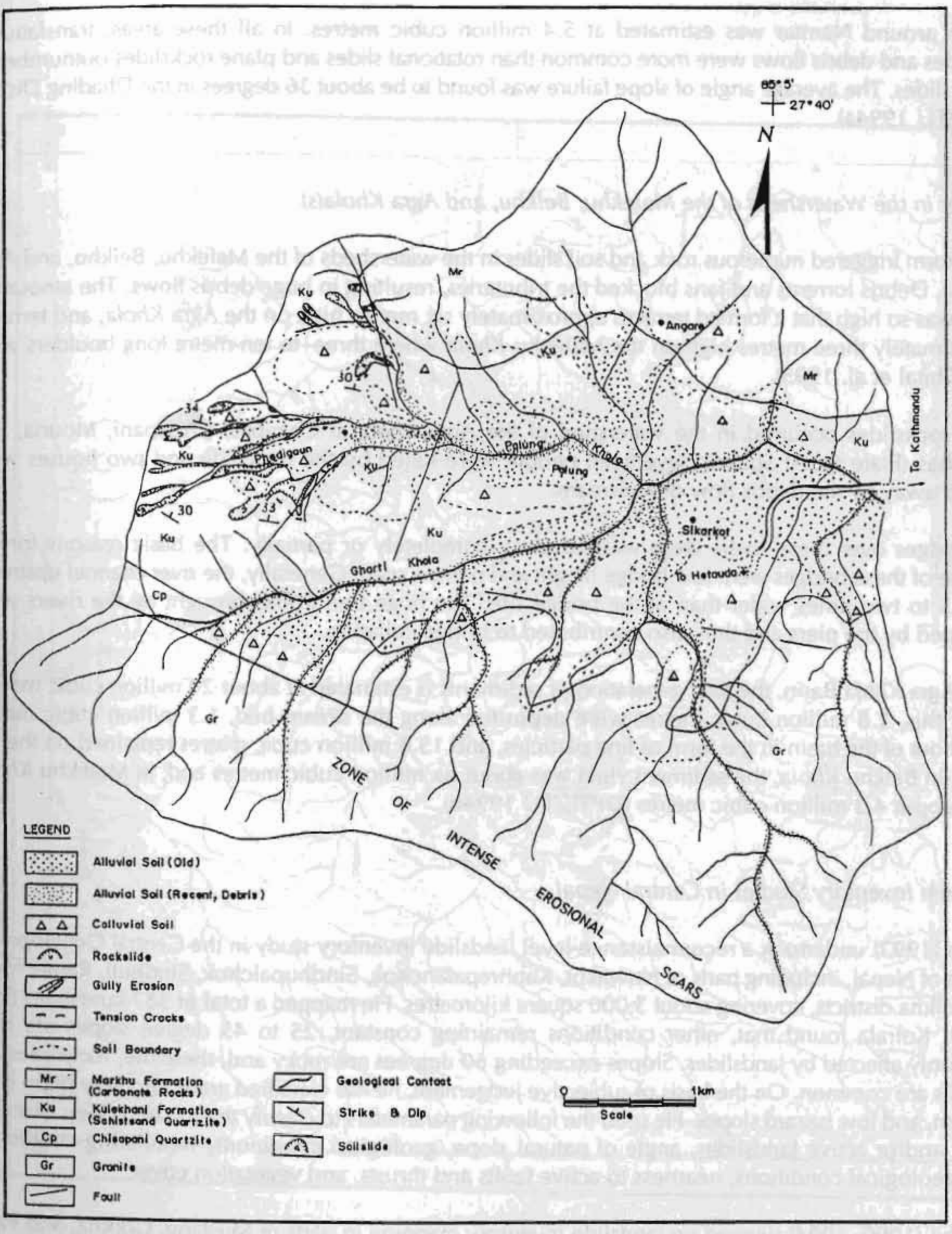
The alluvial fan on which the village was situated is the product of the coalescence of three fans from the streams. About two square kilometres of the cultivated land and village were washed away during the night of 19th July (Plate 4). The streams brought a huge amount of debris into the area during the rainstorm. At the same time, large tree trunks and much wood debris were also brought in by the streams. The stream flowing from the west abruptly shifted its channel and destroyed the village (Plates 4 and 5).

Further downstream, the Palung (Sankhamul) *Khola* deposited huge amounts of sand and gravel on the cultivated land on its right bank. The temples of Indrenithan situated in the middle of the terrace were filled with sand and silt for 0.7m above ground level (Dhital et al. 1993).

An investigation carried out around the village of Phedigaun (Fig. 17) revealed that the amount of soil yield caused by landslides and gully erosion was about 741,125 cubic metres. The total area covered by landslides and gully erosion was about 0.24 square kilometres, which is about seven per cent of the total surface area of the watershed (i.e., 3.63km^2). The sediment production was estimated at 0.2m^3/m^2. The average slope angle of the displaced material was about 36 degrees, whereas the average depth of failure was about three metres (DPTC/TU 1994a).

The studies showed that landslides occurred on all types of land, including cultivated dry land, irrigated land, barren land, and also thick forests. The intensity of landslides was found to be higher in barren land, followed by cultivated dry land and forest area. The amount of debris deposited at the disaster site in Phedigaun was estimated to be nearly 0.4X10^{6}m^3, including the reworked material (DPTC/TU 1994a).

Figure 17: Debris flow and landslides at Phedigaun (DPTC/TU 1994a)



Disaster in the Manahari Khola Watershed

In Kali *Khola* (a tributary of the Manahari *Khola*), the total amount of displaced material was 1.6 million cubic metres and 2.6 per cent of the area was covered by landslides and gully erosion. In Namtar, the debris flow washed away 62 houses and a suspension bridge. The soil yield due to landslides and gully erosion around Namtar was estimated at 5.4 million cubic metres. In all these areas, translational landslides and debris flows were more common than rotational slides and plane rockslides outnumbered wedge slides. The average angle of slope failure was found to be about 36 degrees in the Dhading District (DPTC/TU 1994a).

Disaster in the Watersheds of the Malekhu, Belkhu, and Agra Khola(s)

A rainstorm triggered numerous rock and soil slides in the watersheds of the Malekhu, Belkhu, and Agra *Khola*(s). Debris torrents and fans blocked the tributaries, resulting in huge debris flows. The amount of debris was so high that it formed terraces approximately six metres high on the Agra *Khola*, and terraces approximately three metres high on the Malekhu *Khola* where three- to ten-metre long boulders were seen (Dhital et al. 1993).

Major rockslides occurred in the watershed of the Agra *Khola* at Chaubas, Chisapani, Mouria, and Dandabas (Plate 6). At Sulikot, seventeen people were killed by the rockslide and two houses were washed away by the debris flow downstream.

The bridges over these rivers were washed away completely or partially. The basic reasons for the collapse of these bridges were low bridge height and narrow span. Generally, the river channel upstream was 1.5 to two times wider than at the bridge site. The huge tree trunks brought by the rivers were entrapped by the piers and thus also contributed to bridge collapse.

In the Agra *Khola* Basin, the total generation of sediments is estimated at about 20 million cubic metres. Out of this, 2.8 million cubic metres were deposited along the stream bed, 1.3 million cubic metres moved out of the basin in the form of fine particles, and 15.8 million cubic metres remained on the hill slopes. In Belkhu *Khola*, the sediment yield was about six million cubic metres and, in Malekhu *Khola*, it was about 4.3 million cubic metres (DPTC/TU 1994b).

Landslide Inventory Studies in Central Nepal

Koirala (1993) undertook a reconnaissance-level landslide inventory study in the Central Development Region of Nepal, including parts of Nuwakot, Kabhrepalanchok, Sindhupalchok, Sindhuli, Ramechhap, and Dolkha districts, covering about 3,000 square kilometres. He mapped a total of 587 landslides (Figs. 18,19). Koirala found that, other conditions remaining constant, 25 to 45 degree slopes are most commonly affected by landslides. Slopes exceeding 60 degrees are rocky and, therefore, rockslides and rockfalls are common. On the basis of subjective judgement, he has classified areas into very high, high, medium, and low hazard slopes. He used the following parameters to classify the hazard zones: existence of old and/or active landslides, angle of natural slope, geological conditions, weathering conditions, hydrogeological conditions, nearness to active faults and thrusts, and vegetation cover.

Shrestha (1990, 1994) worked on landslide inventory mapping in parts of Mustang, Gorkha, and Palpa districts and Shrestha and Shakya (1990) carried out reconnaissance inventory surveys along the roads and highways of Nuwakot, Dhading, Lamjung, Tanahun, Nawalparasi, Chitawan, and Makawanpur districts. The Jharlang Village landslide in Dhading District, on the left bank of the Ankhu *Khola* (a tributary of the Budhi Gandaki River), is one of the largest landslides in the region. It is 4.5km in length and one kilometre wide with a slope angle of 40 degrees. The landslide occurs in the phyllite and is a wedge failure. Similarly, the Burang Village landslide in Dhading district is also relatively large, measuring 1.7km in length and 40m wide. It is a plane rockslide.

Figure 18: Landslide inventory map of Central Nepal between the Roshi *Khola* and Sunkoshi rivers (Koirala 1993, redrawn)

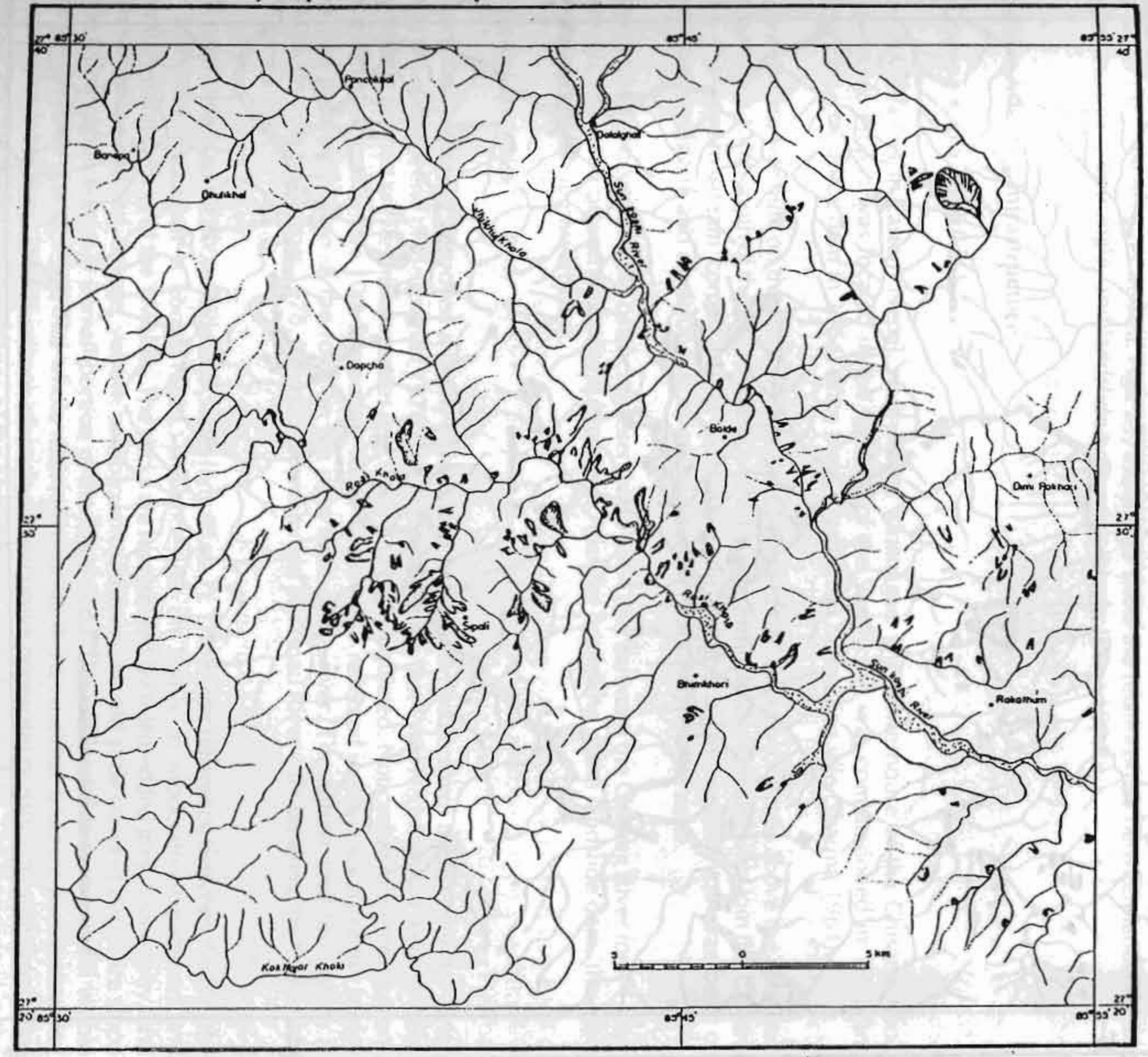
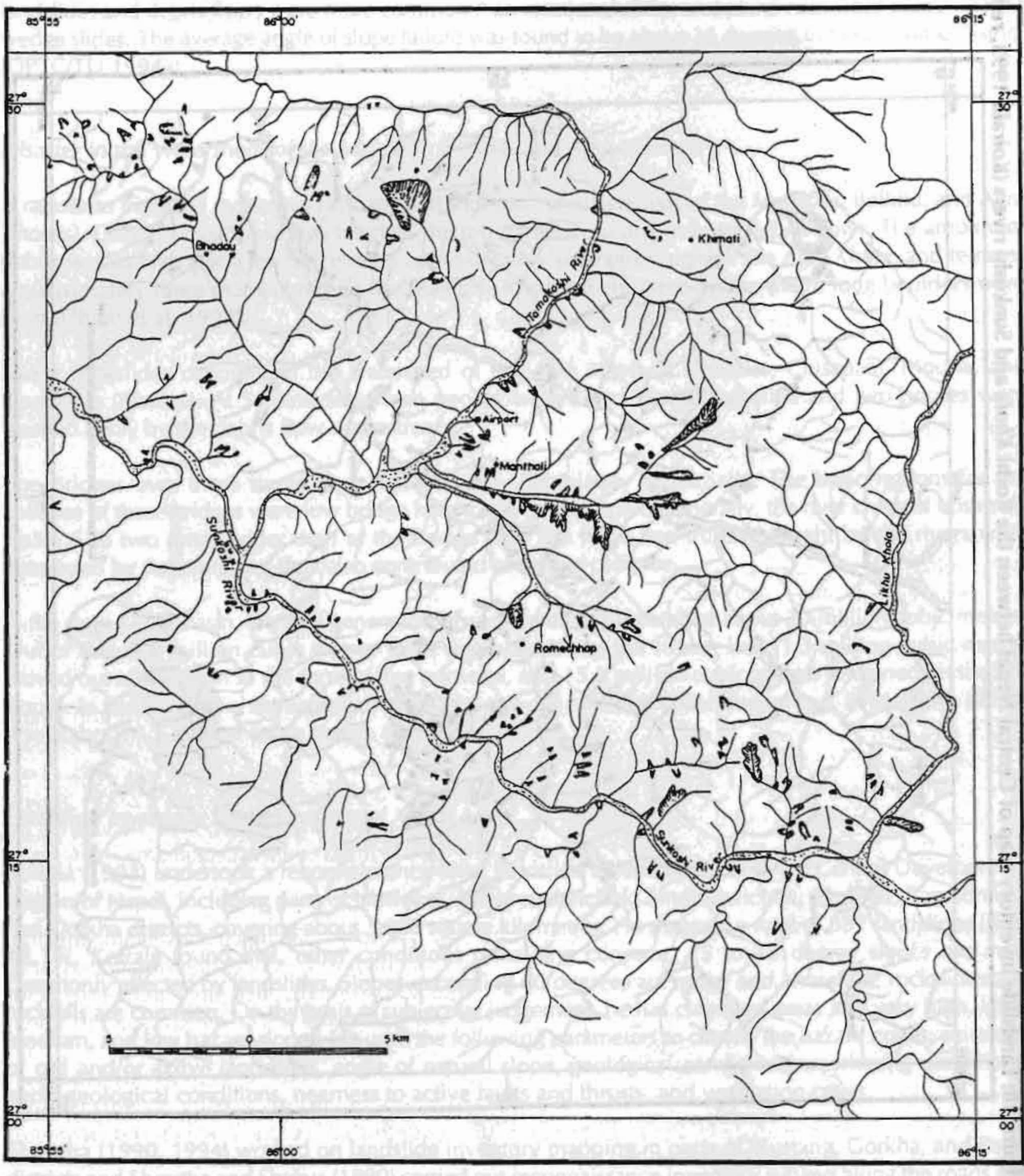


Figure 19: Landslide inventory map of Central Nepal between the Sunkoshi and Tamakoshi rivers (Koirala 1993, redrawn)



Landslide Inventory Studies in Far western Nepal

Dixit (1994a,b,c) carried out landslide inventory studies in parts of the Bajhang, Baitadi, and Darchula districts of the Far-western Nepal Lesser Himalayan region (Fig. 20). His study indicated that Far-western Nepal is quite extensively affected by landslides, contrary to the conclusion made by Laban (1979). The landslides were mapped with the help of aerial photographs and field verifications of the majority of landslides. Over 500 landslides were used for the statistical analysis. The number of landslides versus area, volume, lithology, land-use type, landslide type, and slope angle were studied. The results showed that most of the landslides were smaller than a hectare in aerial coverage. However, several landslides were larger than five hectares in area. Figs. 21, 22, and 23 show the relationships between landslide and population, area, slope angle, and landslide type, respectively (Dixit 1994b).

Landslides Affecting Infrastructure

The Chisang Khola Landslide

Chisang *Khola* lies in Eastern Nepal, northeast of Biratnagar. The powerhouse of the Chisang *Khola* Hydroelectric Project was located in the foothills of the Siwaliks. It was commissioned in 1942 and damaged by a landslide dam in 1964; since then, the unit has been lying idle (Sharma 1981).

The powerhouse was built on the flood plain of the Chisang *Khola*, about two metres above the river bed. Approximately 130m south of the powerhouse, two active streams from the east and west join the Chisang *Khola*. The eastern stream comes from a landslide zone and the balancing reservoir was built on interbedded sandstone and mudstone rocks of the Siwaliks near the landslide zone.

A huge landslide occurred in the balancing reservoir in 1964 and dammed the Chisang River for 14 days. As a result, the entire powerhouse was submerged. After the breaching of the landslide dam, the main river underscoured the powerhouse.

The Butwal Rockslide

The rockslide in Butwal destroyed a newly-constructed and reinforced concrete bridge over the Tinau River at the northern end of the town in 1978. The bridge along the East-West Highway had recently been completed at the cost of five million rupees and was yet to be inaugurated. Noticeable movements along the slip surface began before 10th September 1978. These were reflected in the cracking of the bridge pillars and the deformation of the road on the right bank of the river. The failure itself took place at 12:00a.m. on 10th September 1978. It temporarily dammed the Tinau River after breaking the bridge into two (Sharma 1981).

The Butwal slide is about 200m wide and 300m long (Plate 7). The height difference between the toe (the river bed) and the crown is about 150m. The slide lies on highly to moderately-weathered and moderately-jointed rocks of the Siwaliks. The rocks are represented by interbedded grey, green-grey, and brown sandstone and red, orange, yellow, and brown mudstone. An old slide covered the entire slope and the failed region was only a small portion of the larger slide. The old landslide scars are still visible above the landslide scar of 1978. The whole rock mass constitutes a synclinal structure gently plunging due east towards the river. The failure took place due to excessive porewater pressure of more than 100m high head, and the geological conditions of the area strongly controlled the slip. The landslide is in the vicinity of the Main Frontal Thrust. The slip occurred along the impervious mudstone bed.

The Landslide in the Seti Khola, Pokhara

The 33-metre long steel truss bridge over the Seti *Khola*, Pokhara, Western Nepal, collapsed on the 2nd of February 1991 (Fig. 24). The bridge was destroyed as a result of bank failure caused by extensive cracks that had developed on the right (western) bank of the river (Dhital and Giri 1993). The bridge site was also studied by Deoja and Dhital (1991), Maskey et al. (1991), and Shrestha et al. (1992).

Figure 20: Landslide inventory map of Bajhang District, Far-western Nepal (Dixit 1994a, redrawn)

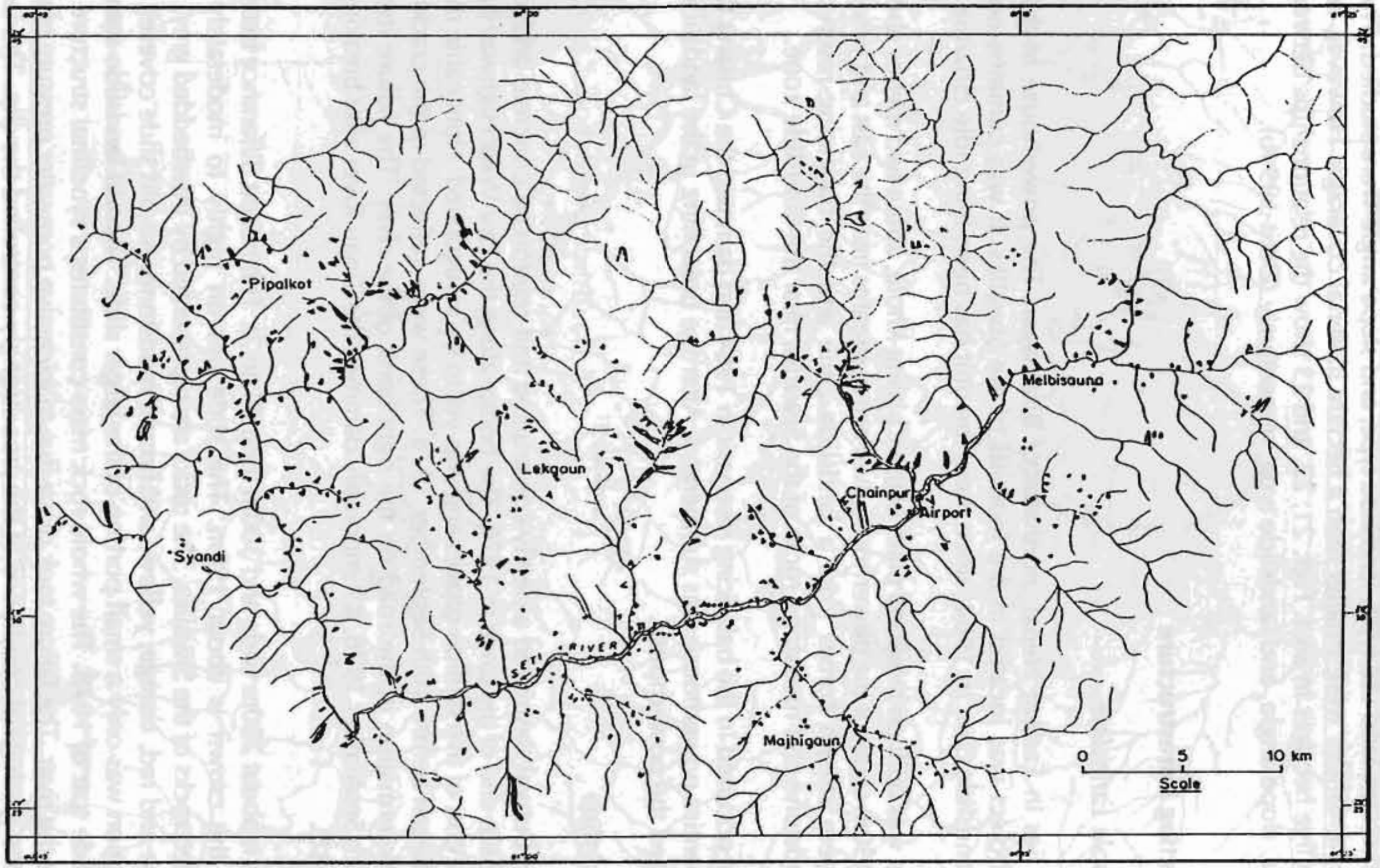


Figure 21: The relationship between the area covered by landslides and the landslide population, Bajhang District, Far-western Nepal (Dixit 1994b, redrawn)

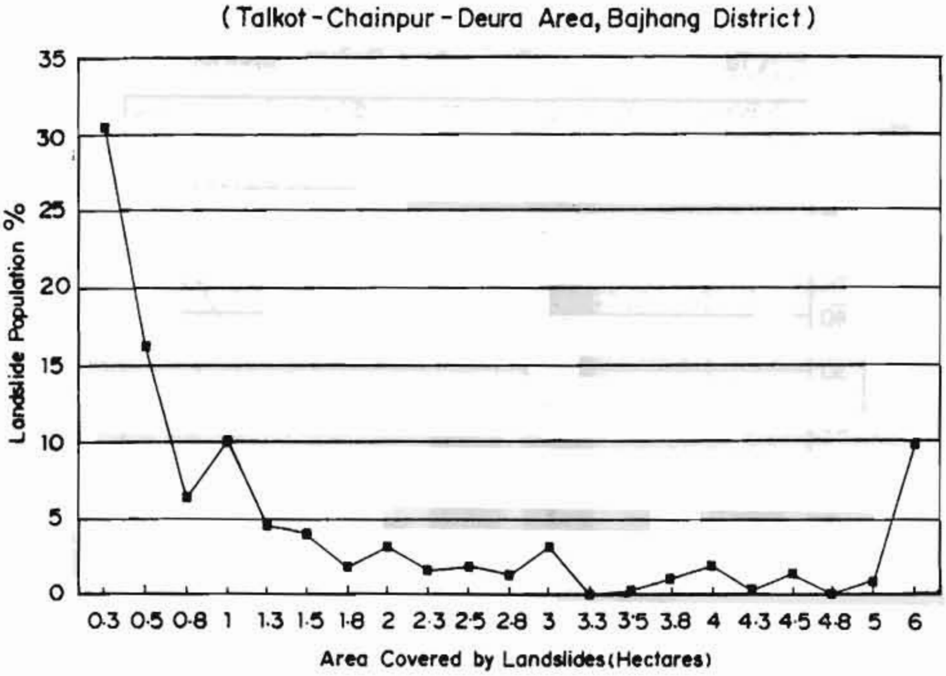


Figure 22: The relationship between the slope and the landslide population, Bajhang District, Far-western Nepal (Dixit 1994b, redrawn)

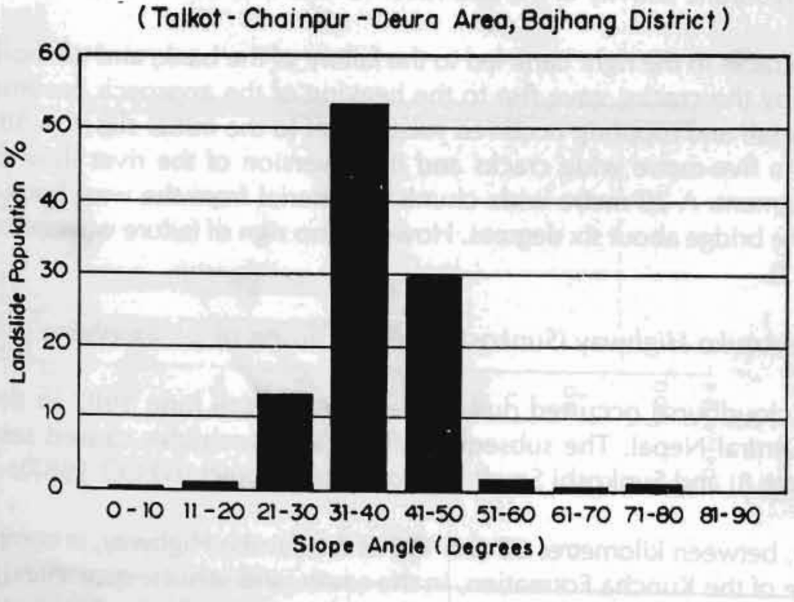
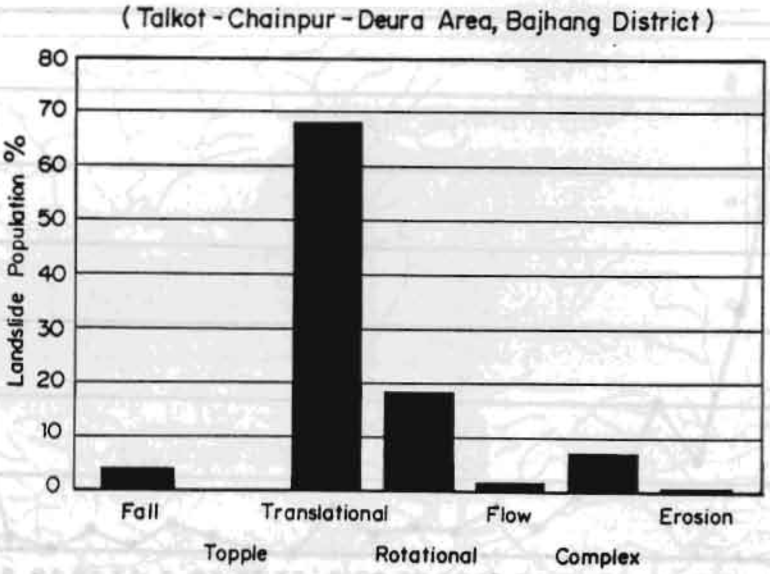


Figure 23: The relationship between landslide types and landslide population (Dixit 1994b, redrawn)



The soil at the bridge site is made up of breccia with sub-rounded to angular clasts of schist, gneiss, quartzite, granite, and phyllite belonging to the Ghachok Formation (Fig. 24). The failure was probably related to the joint pattern and geotechnical properties of the Ghachok Formation, the groundwater conditions, and the hydraulic activity of the Seti River (Dhital and Giri 1993).

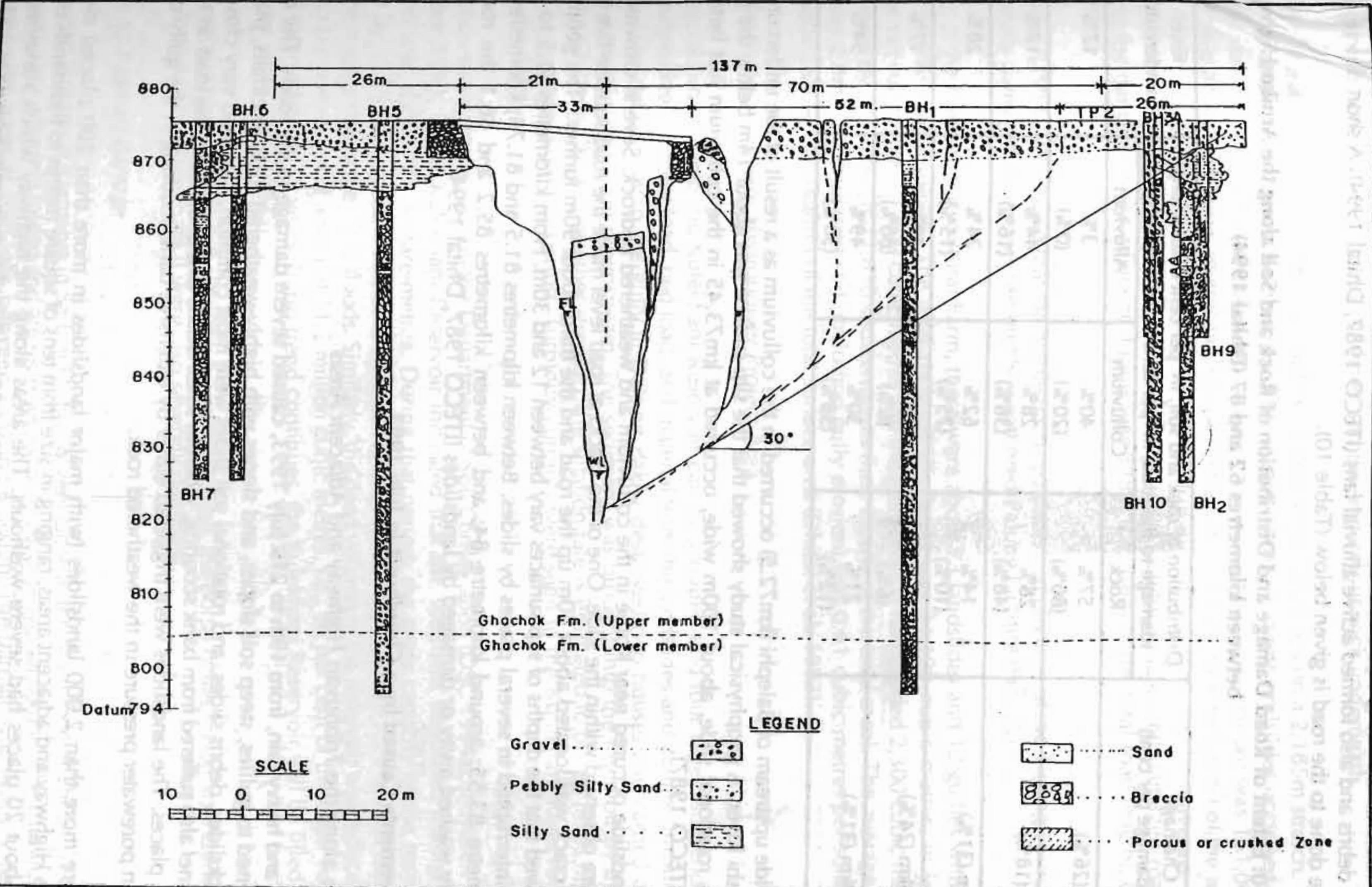
The development of cracks in the right bank led to the failure of the bank, and the horizontal component of the slip, induced by the cracks, gave rise to the heaving of the approach pavement adjacent to the bridge. The failure by fall and toppling occurred subsequent to the initial slip. On 5th September 1993, it resulted in three- to five-metre wide cracks and the diversion of the river flow to the new channel behind the west abutment. A 20-metre wide chunk of material from the west bank subsided by about three metres, tilting the bridge about six degrees. However, no sign of failure was noticed on the east bank (Dhital and Giri 1993).

Landslides along the Arniko Highway (Sunkoshi Valley) Caused by a Cloudburst in 1987

A heavy rainstorm (cloudburst) occurred during the night of 30th June 1987 in the catchment of the Sunkoshi River in Central Nepal. The subsequent flood and landslides caused severe damage to the Arniko Highway (Plate 8) and Sunkoshi Small Hydroelectric Project (ITECO 1987).

The Sunkoshi Valley, between kilometres 62 and 109 of the Arniko Highway, is comprised of grey-green phyllite and quartzite of the Kuncha Formation, in the south, and schists, quartzites, and gneisses in the north (Stöcklin 1980, Dhital 1994). An anticline is found near Balephi (km72). Apart from this, several small-scale folds are also present.

Figure 24: Geological cross-section of the collapsed bridge axis, the Seti *Khola*, Pokhara (Dhital and Giri 1993)



Owing to the southerly dips between kilometres 62 and 72, plane rockslides along the foliation planes are common. On the other hand, wedge rockslides and debris slides predominate in the rest of the alignment. Severe damage to the road was caused by rotational slides on the colluvium and highly-weathered rock. Extensive gully erosion was another cause of road damage. Gullies brought a large quantity of debris and also formed active alluvial fans (ITECO 1987, Dhital 1994). A short description of the damage done to the road is given below (Table 10).

Table 10: Extent of Road Damage and Distribution of Rock and Soil along the Arniko Highway between kilometres 62 and 87 (Dhital 1994)

Chainage (total damage per cent)	Distribution of rock and soil, in per cent of total length (damage to the road, in per cent of the total length)			River undercutting
	Rock	Colluvium	Alluvium	
62-65km (26%).	57% (80%)	40% (20%)	3% (0%)	17%
65-72km (18%)	28% (48%)	28% (36%)	44% (16%)	17%
72-75.2km (31%)	14% (10%)	62% (75%)	24% (15%)	28%
75.2-81.8km (24%)	14% (6%)	14% (6%)	72% (88%)	17%
81.8-87.0km (31%)	21% (12%)	30% (58%)	49% (30%)	54%

The landslide upstream of Balephi (km72.5) occurred in the colluvium as a result of toe undercutting by the Sunkoshi River. A geophysical study showed that the slip surface was about 14m below the ground surface. A rotational slide, about 100m wide, occurred at km73.45 in the colluvium just beside the bedrock (ITECO 1987).

A large landslide occured near Kothe in the colluvium and weathered bedrock. Several crowns of slip surface were observed within the slide. One of the cracks at road level made the road subside five metres. A second crack was located about 40m up the road and the third about 90m further. The geophysical study showed that the depths of slip surfaces vary between 12 and 30m. From kilometres 81.5 to 86, the road was interrupted in several places by slides. Between kilometres 81.5 and 81.75; kilometre 83.15, and kilometre 83.55; around kilometre 84; and between kilometres 85.2 and 86.1 the road was completely washed away or damaged by landslides (ITECO 1987, Dhital 1994).

Mass Movements Caused by a Cloudburst in July 1993

Landslides along the Tribhuvan Highway and Adjacent Areas

The flood and heavy rain, from 19th to 21st July 1993, caused severe damage to the roads. The damage was confined to gullies, steep soil slopes, and slopes with highly-weathered rock. Rockfalls, plane and wedge rockslides, debris slides, and rotational soil slides were most common. The road very close to the river channel also suffered from bank scouring, whereas small debris fans debauched the load on the road in several places. The landslides were triggered either by extensive bank scouring in the gully or by an increase in porewater pressure in the weathered rock.

There were more than 2,000 landslides (with major landslides in more than 200 places) along the Tribhuvan Highway and adjacent areas, ranging in size from tens of square metres to thousands of square metres. About 20 places had severe washouts. The areas along the highway which sustained heavy damages were at Naubise (26km), around Jhapre (49 to 53km, Fig. 22), between Sikharkot and Daman (71-76km), between Aghor and Mahabhir (89-98km), around Bhainse Dobhan, and at Bulbule (122-123km). More than 100m of retaining walls and 23 culverts were damaged. The bridges at Mahabhir, Bhainse, and Trikhandi were completely washed out, and the bridges over the Sopyng *Khola* and the Sankhamul *Khola* were partially damaged. A large plane rockslide occurred at km 64 on the highway.

For the purpose of assessing the extent of damage in the area, a small portion of the Tribhuvan Highway was taken on the climb section between Sikharkot and Daman. The study was carried out on the switchbacks. Moderately to highly-weathered granite is the only rock type on the site. The soil depth varies from one to four metres. The stereographic projection of joints reveals that they are oriented randomly (Dhital et al. 1993). Most of the landslides were triggered by the porewater pressure built up at the interface between the pervious soil layer and the impervious rock underneath.

There were about 44 rock- and soil-slides and four major torrential gullies on a 2,185m stretch. The total surface area around the road was about 297,500 square metres, and the landslides occupied 109,200 square metres, in which the total displaced material (excluding the gully erosion) was 161,000 cubic metres. This is about 0.54 cubic metres per square metre (i.e., 1,680x0.54 = 907kg/m^2) of the total area. The landslides and gullies occupied about 36 per cent of the total surface area. The average depth of failure was 1.5m, whereas the average natural slope was 31 degrees. The total damaged road length (including the damage on the adjacent slopes) was 828m (i.e., 38% of the total road length), (Dhital et al. 1993).

Dangol et al. (1993a) also found that the highly-fractured slates and phyllites of the Tistung Formation had been heavily damaged, as well as the highly-weathered Palung Granite (Fig. 25).

Similarly, at the Daman Horticultural Farm, there were about 73 landslides and 12 gullies within a total area of 51,600 square metres. The total rock/soil displaced was 34,100 cubic metres, in which the landslide had contributed 31,800 cubic metres and the gully erosion had yielded 2,300 cubic metres. The area covered by landslides is 11,650 square metres (i.e., 22.6% of the total area). The average depth of failure was 0.8m. The displaced soil (including gully erosion) was 0.61 cubic metres per square metre (i.e., 1,680x0.61 = 1,014kg/m^2) of the total surface area (Dhital et al. 1993).

Landslides in the Kulekhani Hydropower Project Area

The material brought into the Kulekhani Reservoir can be grouped into four types: suspended wood debris, suspended sediment load, bed load, and material from the landslides and gullies surrounding the reservoir. The debris flow in the gully at Dalsing *Pakha* destroyed two houses and carried away two children approximately 75m downstream. The sediment was brought into the reservoir by the Palung *Khola*, the Chitlang *Khola*, and other streams. The siltation rate is estimated to be ten times higher than during the average monsoon period. Turbidity currents were seen in the Kulekhani Reservoir flowing towards the dam.

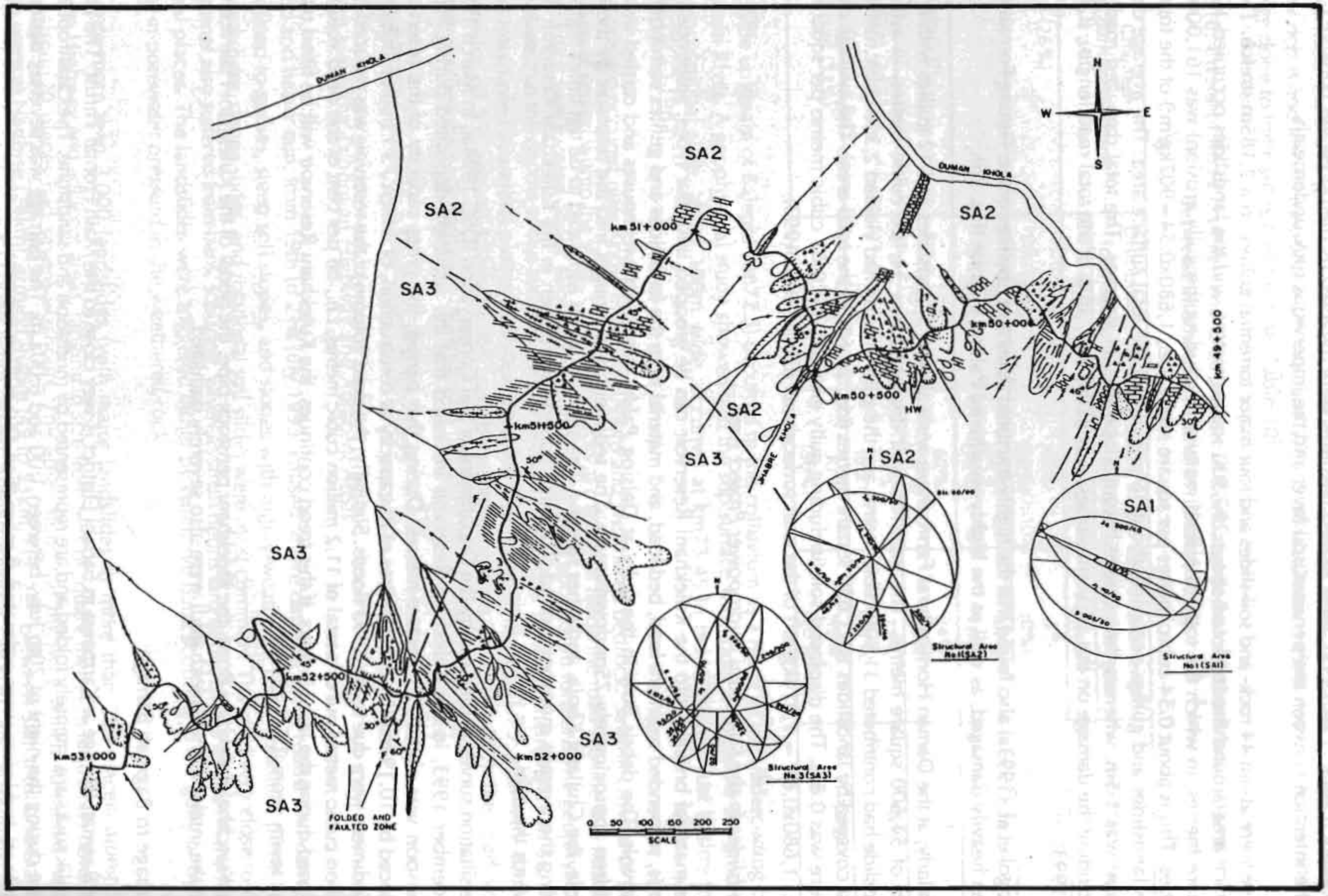
The siltation survey carried out by the Department of Soil Conservation (DSC 1994a), in March 1993 and December 1993, in the Kulekhani Reservoir indicated that the sediment deposited during the 1993 monsoon was about 771 hectare-metres. During that period, the gross capacity of the reservoir was reduced by 10.19 million cubic metres of its capacity at construction, of which 7.71 million cubic metres of sediment were due to the 1993 floods. Similarly, the dead volume of the reservoir was reduced by 7.39 million cubic metres out of a total of 11.2 million cubic metres, i.e., 66 per cent of the dead volume was reduced during the last 13 years. If this trend continues, the Kulekhani Reservoir will be filled up in the next seven years (DSC 1994a).

The Kunchhal-Kulekhani Road, the Kulekhani penstock pipe, the portal of the Kulekhani I tailrace tunnel, and the intake of the Kulekhani II were also severely damaged.

Damage to Bagmati Barrage

The Bagmati Barrage at Karmaiya in Sarlahi District is very close to the Main Frontal Thrust. The adjacent Siwalik rocks are intensely folded and are represented by mudstone and sandstone. The catastrophic flood came during the night of 20th July, between 1:00 and 6:00a.m. The barrage was severely damaged by the flood and losses were estimated at more than 150 million rupees.

Figure 25: Engineering geology map of the Trivbhuvan Highway from km 49-53 (Dangol et al. 1993)



Mitigation of Landslide Hazard

Landslide Hazard Mapping

Varnes (1984) has defined natural hazards as the probability of occurrence, within a specific period of time and within a given area, of a potentially damaging phenomenon. Varnes also pointed out that the French word 'risque' could be regarded as equivalent to the English word 'hazard'. 'Hazard' and 'risk' are used interchangeably in most reports on geological processes, but they must be clearly differentiated. Landslide risks signify the expected number of lives lost, persons injured, damage to property, or disruption of economic activity due to a landslide (Brabb 1984).

Hazard evaluation may also be classified as a relative hazard (based on mapping alone or in combination with calculations and used to rate the slide susceptibility), absolute hazard (e.g., factor of safety based on calculations), empirical hazard (based on existing knowledge and often used when it is very difficult to make a relevant calculation), and monitored hazard (connected to internal processes of the slope, such as ongoing movements, or to external factors, such as rainfall or seismic activities) (Hartlen and Viberg 1988). Relative hazard is assessed by assigning (ratings?) to different factors contributing to a hazard.

Different approaches to landslide hazard assessment have been developed. There are three main groups of techniques (Jones 1984).

1. Geotechnical investigations, involving detailed analyses of surface and subsurface conditions and ground materials
2. Direct mapping, involving the analysis of landforms and identification of existing landslides so that areas of past instability can be identified, thereby facilitating extrapolation from areas of recognised past instability to similar situations which may suffer slope failures in the future
3. Indirect mapping, which requires the collection of data on the causes and mechanisms of landsliding, so that slope stability can be assessed through the application of known landslide-inducing parameters.

To these may be added the fourth approach of Land System Mapping, which is intermediate between direct and indirect mapping

Among the several methods available for landslide hazard mapping, the method proposed by Deoja et al. (1991) is summarised below. This method has been applied in several landslide hazard mapping projects in Nepal, especially along road corridors.

This landslide hazard mapping method requires the preparation of maps which deal with engineering geological concerns such as slope and aspect as well as hydrogeological features. The landslide hazard map is finally prepared by superimposing all of the above maps and other relevant data. It can show not only the hazard level (i.e., low, medium, high, and very high) but also the main type of failure, extent, and direction of movement in case of failure.

The **engineering geological** map is prepared in the field and it depicts rock and soil types, bedding/foliation and joint characteristics (stereographic projections), major faults, folds, and other important geomorphic features related to landslides. On the same map active, ancient, and dormant landslides are also shown (Fig. 25).

The **slope map** shows the natural slope angles at appropriate intervals. It is prepared by using existing topographic maps, and appropriate corrections are made in the field.

The **aspect map** divides the natural slope into more or less uniform faces with consistent sloping directions. Various rock and soil structural boundaries can also be shown on it.

The **hydrogeological map** includes all the surface and groundwater conditions relevant to landslides.

Broadly speaking, hazard assessment is mainly based on the study of the state of nature (rock, soil, geomorphology, and so on), danger (old, recent, dormant landslides, etc), and types of landslide trigger (cloudburst, earthquakes, GLOF, landslide-dam failures, etc). For the production of the final hazard map, ratings are given to the state of nature, average annual rainfall, danger, and triggers. The maximum and minimum values of the total ratings will be between 1.0 (highest hazard) and 0.0 (no hazard). In this method, soil slope hazard maps and rock slope hazard maps are prepared separately. The hazards are categorised as low, medium, and high depending upon the total value of ratings.

Computer-assisted landslide hazard mapping has been used increasingly in recent years (Brabb 1984; Wagner et al. 1988 and 1990). Wagner et al. (1988, 1990) developed the computer programme SHIVA, based on studies in Nepal, to make soil and rock hazard maps. The method takes into account the slope angle, lithology, rock structure, soil type, soil depth, hydrology, hydrogeology, and tectonics. The maps are digitised and ratings are given as described above. The programme superimposes different maps and data and produces the hazard maps. Hazard maps of a few areas in Nepal were prepared using this (SHIVA) software.

Landslide Hazard Mapping in Nepal

Landslide susceptibility maps show the areas likely to experience landslides in the future by correlating some of the principal factors that contribute to landsliding (Brabb 1984). Landslide hazard maps, on the other hand, show the probability of occurrence of the danger (e.g., landslide, gully erosion) in that area (Einstein 1988). The following are a few examples of landslide susceptibility and hazard mapping in Nepal

Hazard Mapping in the Ankhu Khola Basin, Central Nepal

Thouret (1981) studied the slope evolution in the Ankhu *Khola* area and prepared a map on a scale of 1:7500 depicting slope attributes, various types of mass movement, structural and erosional landforms, glacial landforms and deposits, and dynamic processes on various landforms. He prepared hazard maps of the lower and upper reaches of the Ankhu *Khola*. He also studied the mechanism of failure of landslides at Jharlang, Khading, Chalis, Hindung Pul, and other places in the basin.

Landslide Hazard Mapping of Roads in Rapti Zone

A detailed study of roads in Rapti Zone in Midwestern Nepal was carried out by DOR/USAID (1986). The alignments studied were the roads from Tulsipur to Salyan, Ghorahi to Pyuthan, and Pyuthan to Libang. During the study, the road alignments were divided into zones with low, medium, high, and very high rock or soil failure and gully erosion hazards. For this purpose, the existing geological, engineering geology, geomorphological, and surface and groundwater conditions were analysed in detail and the slope was divided into more or less uniform zones of similar hazard types and levels (DOR/USAID 1986).

Hazard Mapping along the Baitadi-Darchula Road

The Baitadi-Darchula Road, which is under construction, lies in Far-western Nepal. The alignment was studied in the prefeasibility, feasibility, and detailed stages. During the study, hazard maps were prepared along the road corridor for the feasibility and detailed stages. The hazard maps of the feasibility stages showed the general hazard level along the road alignment, whereas the hazard maps of the detailed stage depicted the hazard type and its level (Dhital et al. 1991). The morphostructural map and the hazard map of part of the road corridor are shown in Figures. 26 and 27 respectively.

Hazard Mapping in the Charnawati Valley

Charnawati Valley is in eastern Nepal (45.8km from Lamosangu). High-intensity rainfall in 1987 caused severe damage to the Lamosangu-Jiri road and triggered several landslides on the surrounding slopes. Several gullies were also reactivated.

Figure 26: Feasibility stage morphostructural map of a part of the Baitadi-Darchula Road alignment (Dhital et al. 1991)

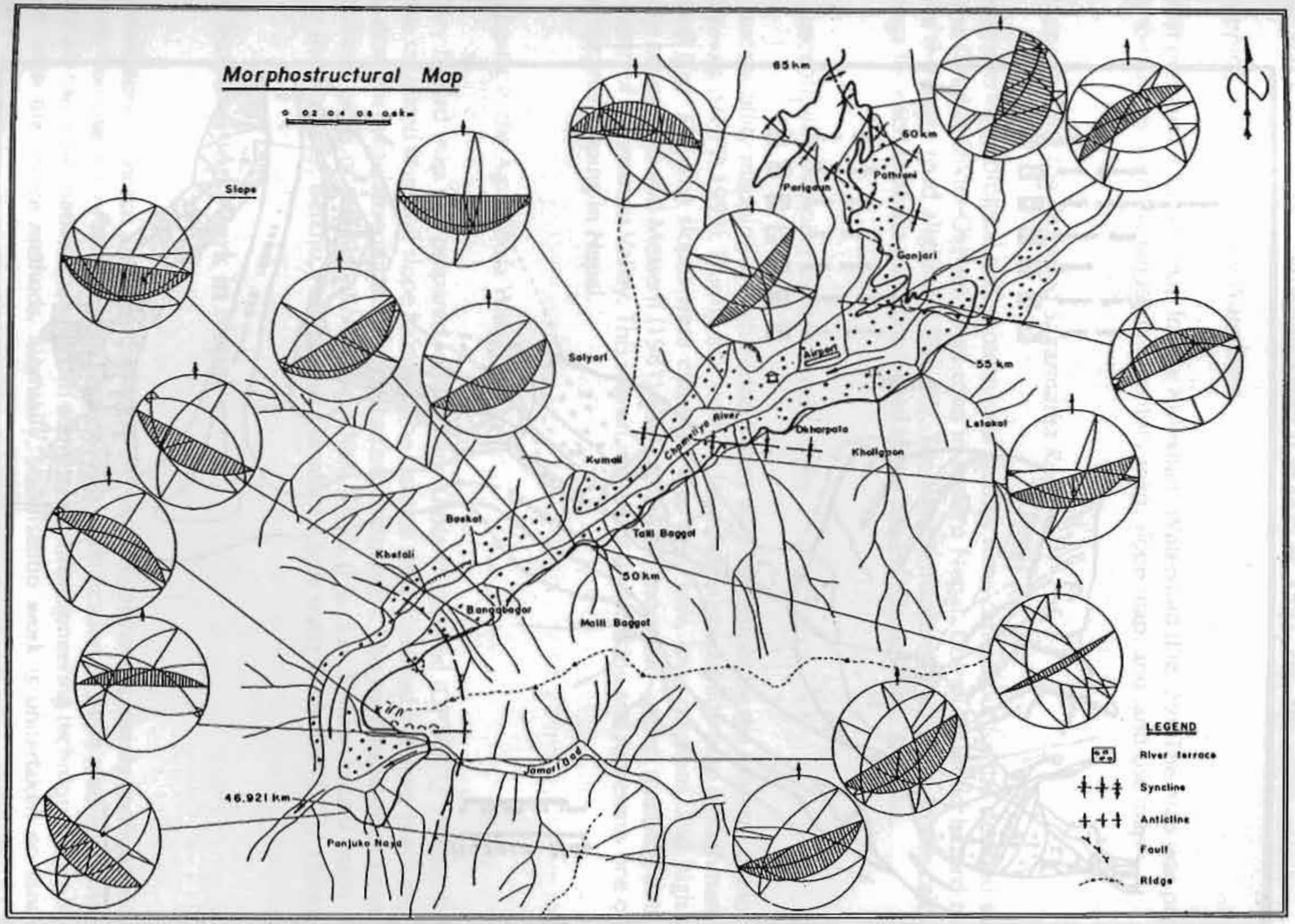
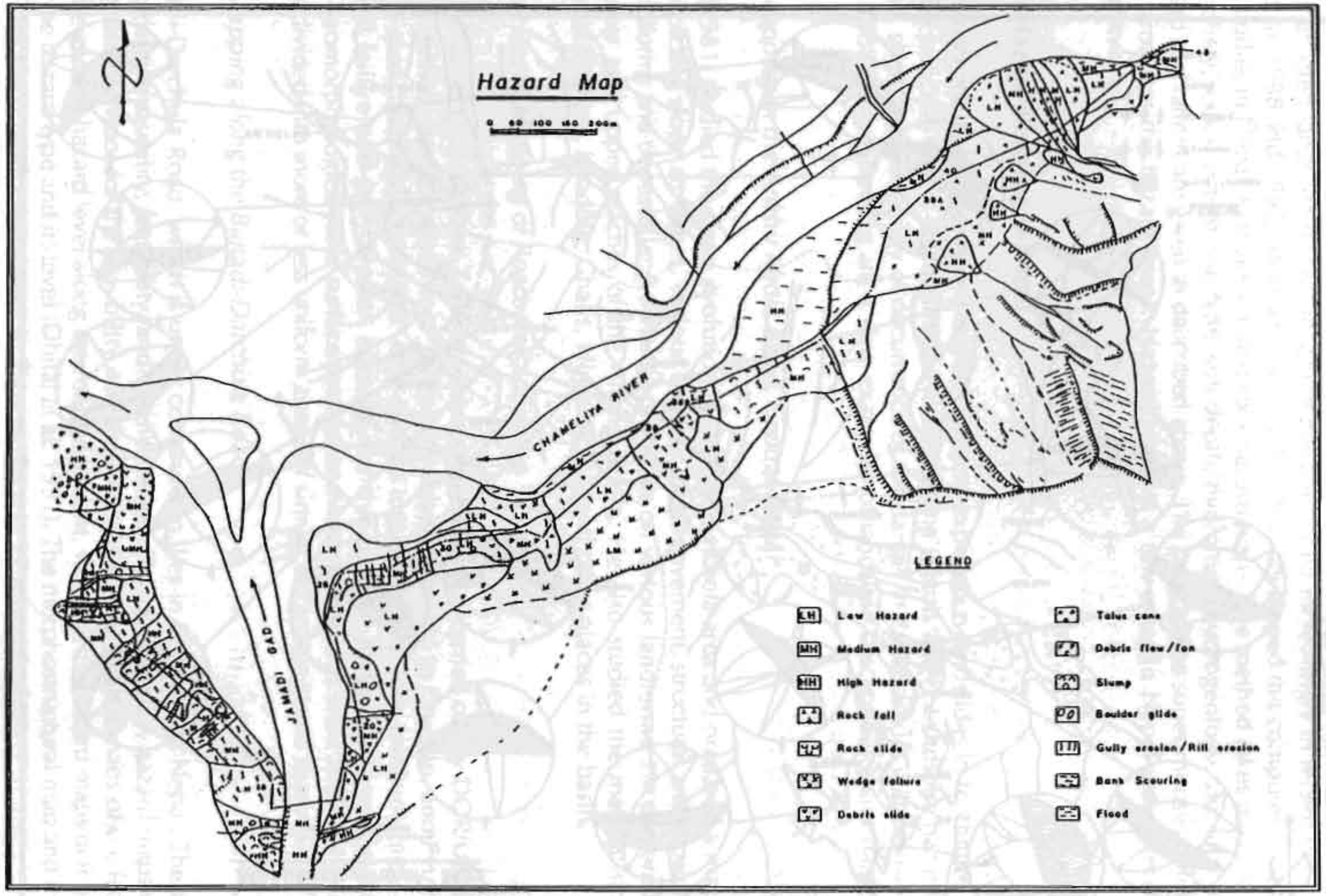


Figure 27: Detailed stage hazard map of a part of the Baitadi-Darchula Road alignment (Dhital et al. 1991)



The Charnawati region is characterised by the presence of thick colluvial and debris flow deposits on the highly weathered gneiss. A flash flood in the Charnawati Stream triggered several slides on its banks and washed away its bridge. Most of the damage was on the left bank of the river. At the same time the Kalimati Gully, a tributary of the Charnawati Stream, also experienced a very high concentration of runoff, resulting in deep gully erosion. More than 17 houses were destroyed overnight and several people were killed. A large slump on the left bank of the road blocked the traffic (Dhital 1994). A computer-aided hazard map was prepared for Charnawati Valley (Deoja et al. 1991, Fig. 28).

Hazard Mapping in the Kulekhani Watershed

Nepal (1992) prepared a hazard map for the Kulekhani Watershed (Fig. 29). The map was prepared by combining the ratings from the landslide inventory map, slope map, and land-use map.

Hazard Mapping along the Proposed Sagarmatha Road

Detailed engineering-geological and geotechnical studies were carried out for the detailed survey and design of the Gaighat-Diktel-Okhaldhunga road in eastern Nepal. Computer-aided hazard maps were prepared for the entire road alignment (Fig. 30). The hazard mapping was based on the calculation of hazard ratings for each attribute that contributed to the hazard (Dangol et al. 1993b).

Landslide Susceptibility Mapping in Kathmandu Valley

Landslide susceptibility mapping in Kathmandu Valley was carried out by the Ministry of Housing and Physical Planning (MHPP 1993). During that study, a landslide susceptibility map of Kathmandu Valley was prepared (Fig. 31). The slopes were classified into very low, low, medium, and high landslide susceptibility zones. Ives and Messerli (1981) also carried out mountain hazard mapping in the Kakani area to the north of Kathmandu Valley. This was an important undertaking and represents one of the early attempts at hazard mapping in Nepal.

Hazard Mapping in the Agra Khola Watershed

A preliminary hazard map was prepared for the Agra *Khola* Watershed (DPTC/TU 1994b). Rock slope hazards were separated from soil slope hazards. The hazards were classified into low, medium, and high depending upon the cumulative impact of each hazard component. The most hazardous areas were the upper catchment areas of the Agra *Khola* and Chalti *Khola* (Fig. 32). Similar hazard maps were also prepared for the Malekhu, Belkhu, Palung, and Manahari *Khola* watersheds (DPTC/TU 1994a,b).

Landslide Stabilisation Work in Nepal

Landslide stabilisation work has a very recent history in Nepal. Such work is mainly confined to important road corridors. Construction of retaining and breast walls, modification of slope gradients, and drainage management are the main methods applied. In some cases, bioengineering techniques are also used in combination with the above methods. Normally, stabilisation work is undertaken on landslides of moderate to small size.

Currently, the Department of Soil Conservation, HMG, is trying to help local people in the hills control and stabilise landslides by using various low-cost methods such as afforestation, checkdams, and use of local materials. Small landslides occurring on agricultural land are, in most cases, managed by the villagers themselves. Some of the important landslide stabilisation works in Nepal are summarised below.

Figure 28: Computer aided soil slope hazard map of Charnawati area, Lamosangu-Jiri Road, Central Nepal (Deoja et al. 1991)

Figure 29: Hazard map of the Kulekhani Watershed (Nepal 1992, redrawn)

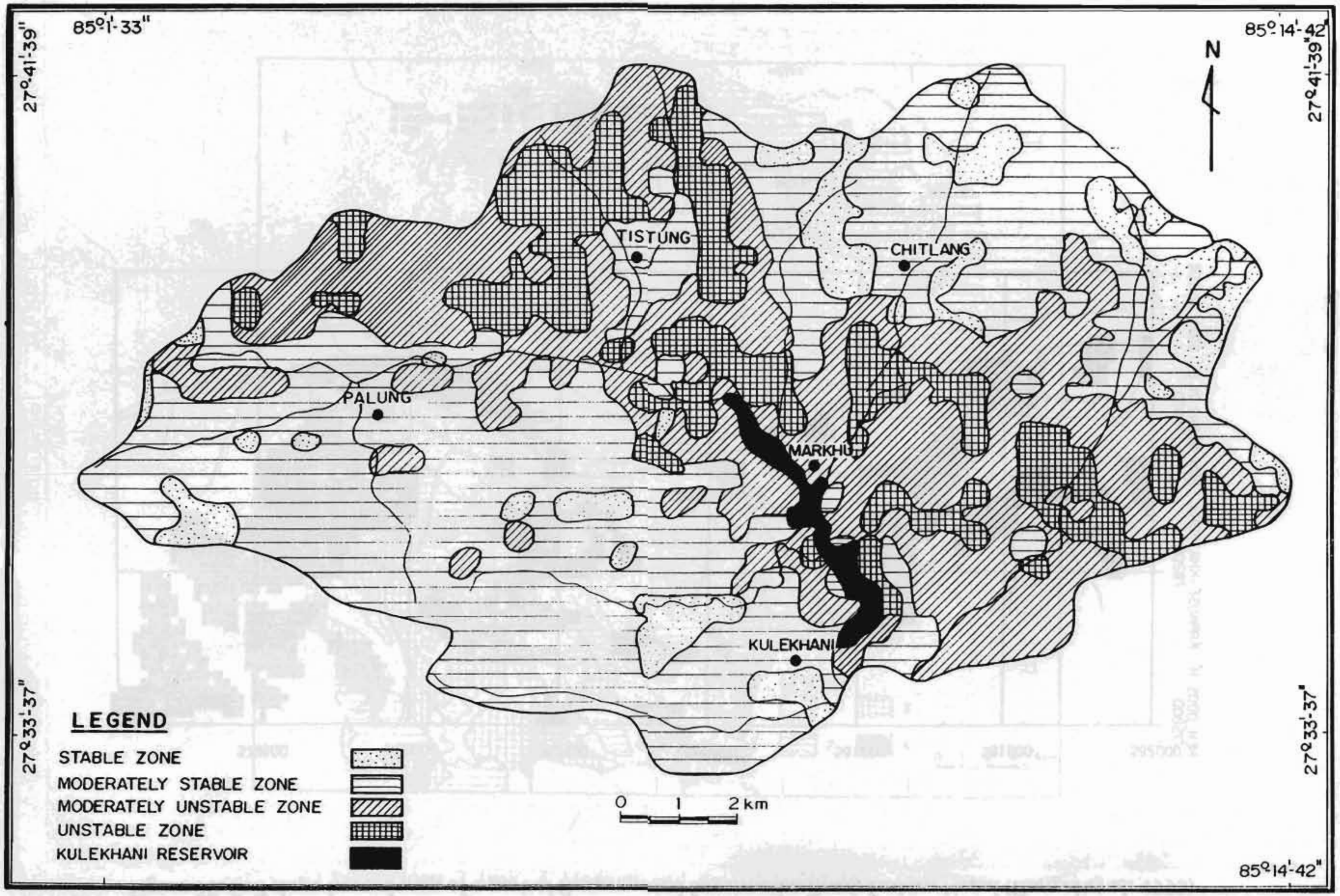


Figure 30: Soil slope hazard map of a part of the proposed Sagarmatha Road, Eastern Nepal (Dangol et al. 1993)

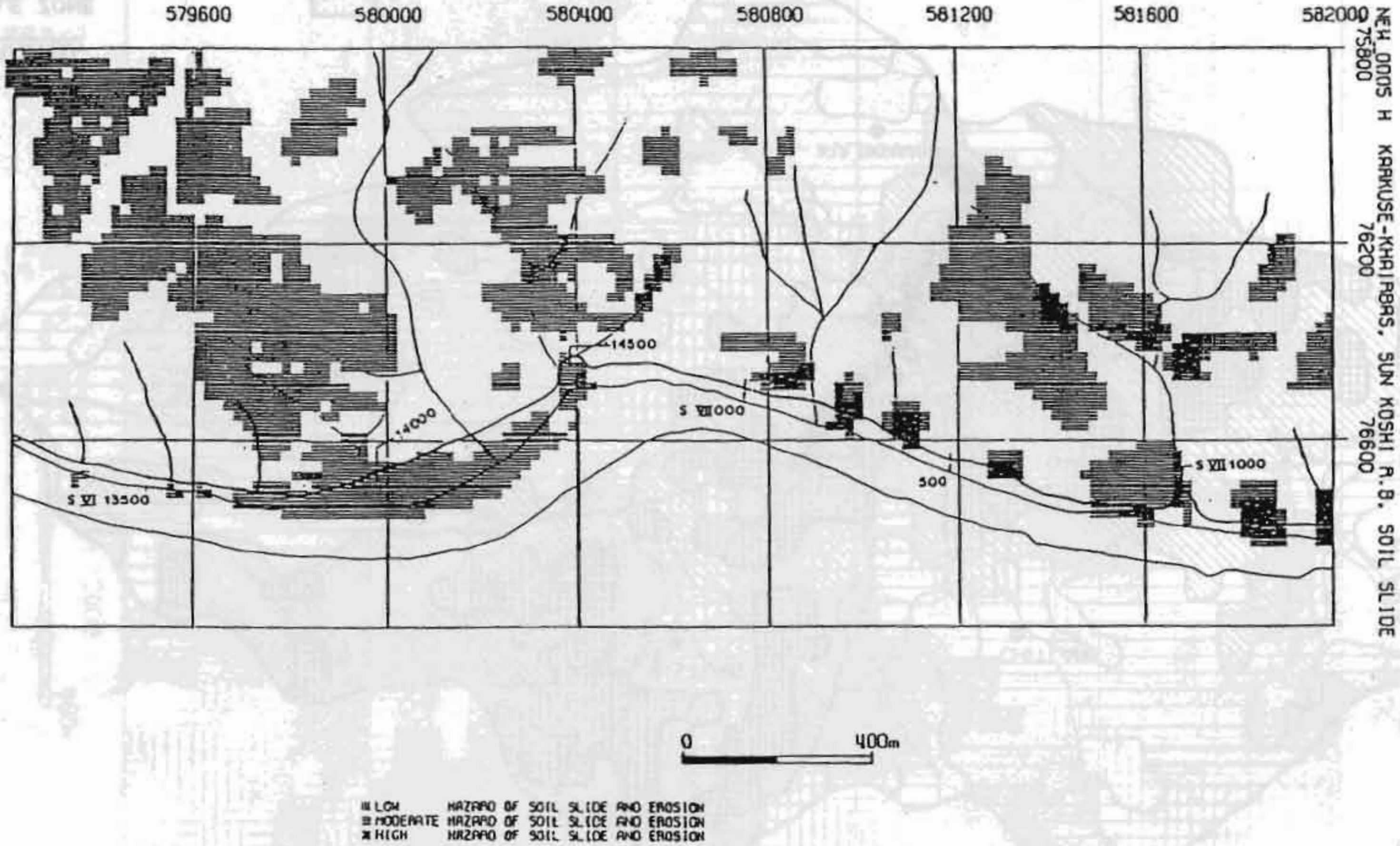
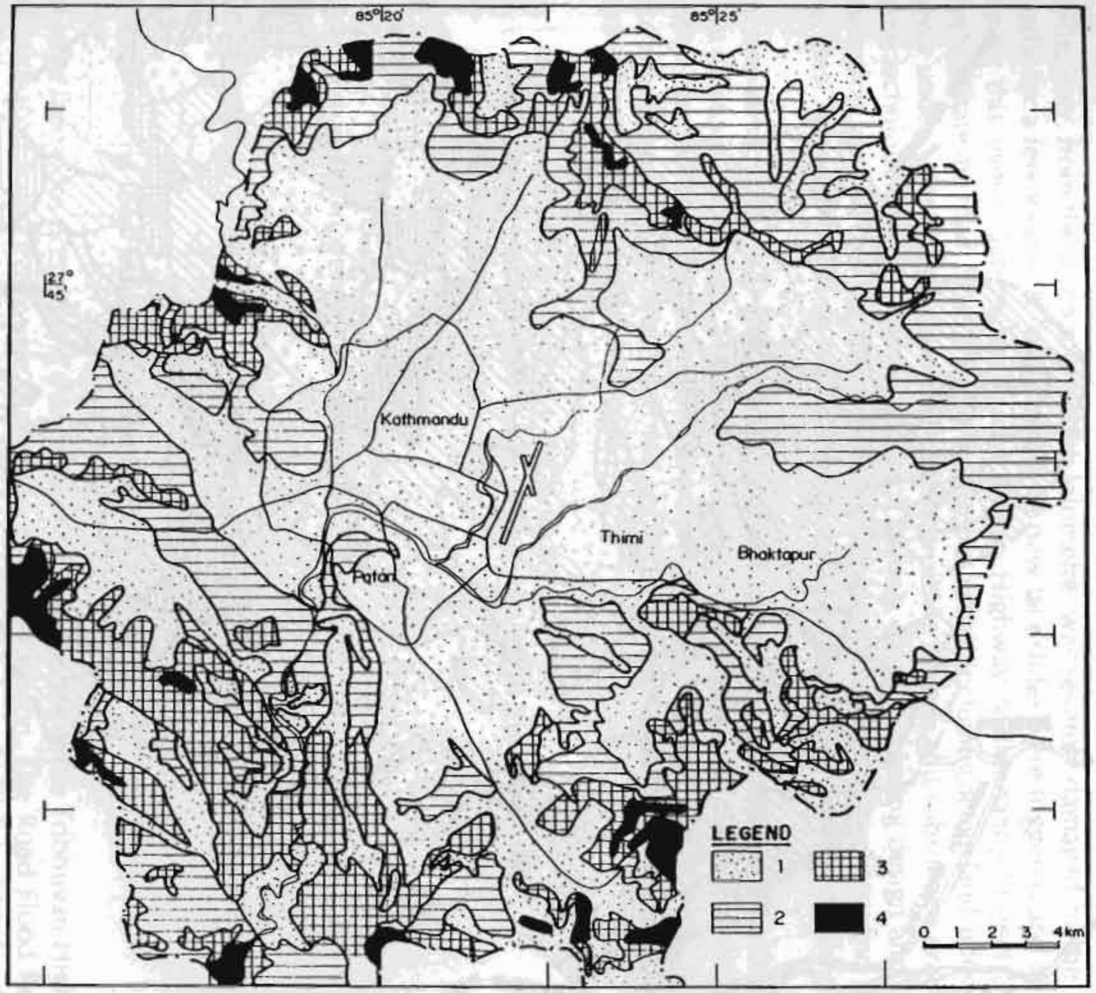
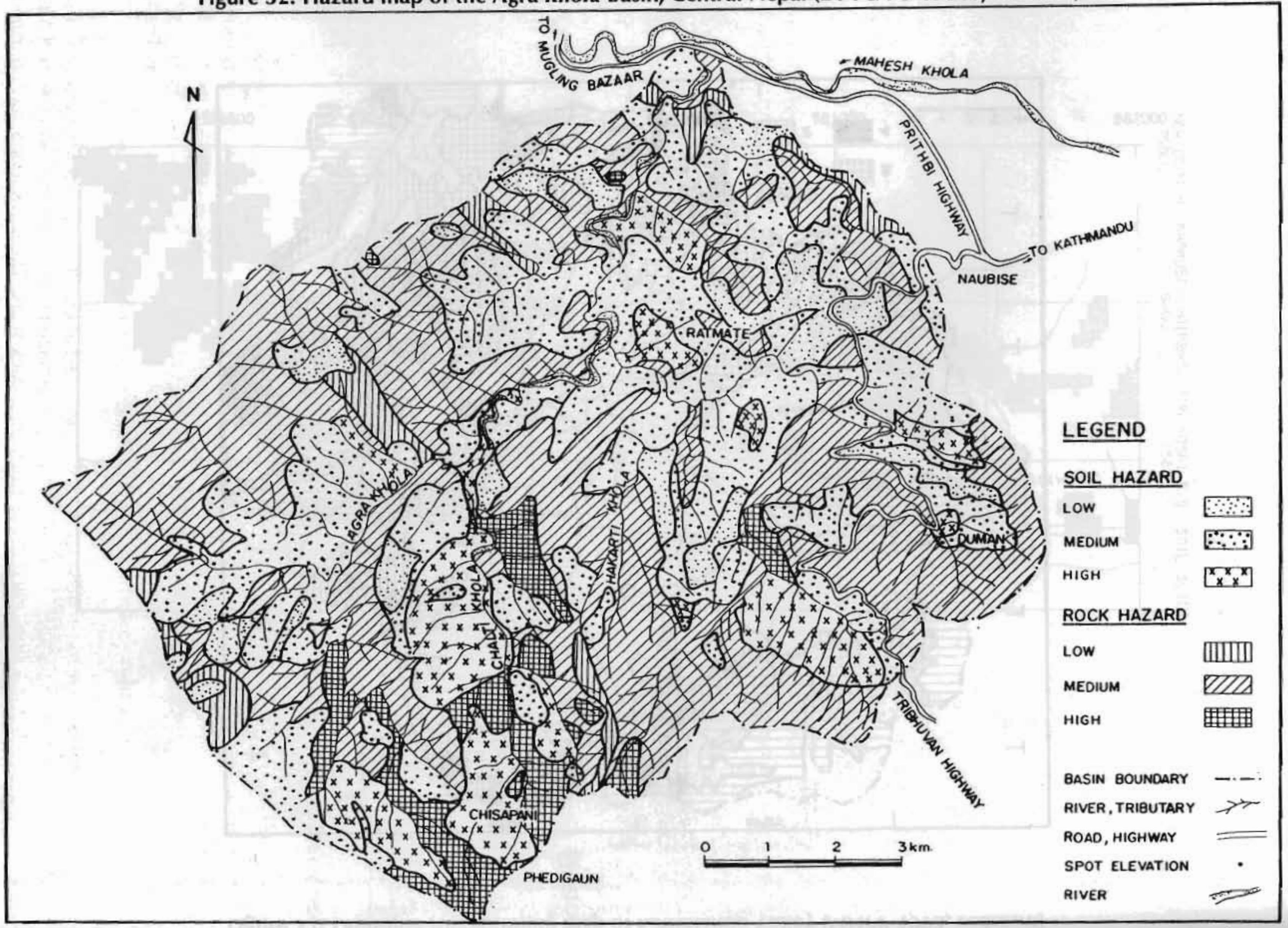


Figure 31: Landslide susceptibility map of Kathmandu Valley (MHPP 1993, redrawn)



1. Very low; 2. Low, 3. Medium, and 4. High landslide susceptibility

Figure 32: Hazard map of the Agra *Khola* Basin, Central Nepal (DPTC/TU 1994b, redrawn)



Slope Stabilisation in Charnawati Valley

The first major effort at landslide stabilisation and gully erosion control in Nepal, using modern technology (such as anchoring, surface and subsurface drainage management, bioengineering, and use of large concrete tetrapods), was carried out in the Charnawati Valley of Dolkha District along the Lamusanghu-Jiri road (Plate 9). The 1987 cloudburst damaged nearly three kilometres of the road lying in a thick zone of colluvium and debris deposit, by triggering a number of landslides and gully erosion. Landslide stabilisation work and gully erosion control were completed at a cost of about Rs 190 million (approximately 38 million US$) (Deoja 1993). Local consultants and contractors gained valuable experience and knowledge from this project.

Landslide Stabilisation Work along the Arniko Highway

The Arniko Highway, from the 62nd to the 87th kilometre, was severely damaged by the 1987 flood, disrupting traffic for a few weeks. A large number of new landslides were triggered and old landslides activated during this event. Subsequently, the Arniko Highway Maintenance Project (AHMP) was launched to rehabilitate the road. Several highly hazardous zones (including active landslides, gullies, and areas with river undercutting) were stabilised by constructing surface and subsurface drains, applying bioengineering techniques, and anchoring and rock bolting. The engineering design and construction work for stabilisation were carried out after extensive geological, engineering geology, and geotechnical studies of the sites. A typical landslide stabilisation work along the road is described below.

The landslide between km 72+300 and 72+500 is about 100m high. The toe of the landslide is on the river bed. It is a rotational debris slide. The slide material is mainly composed of fine-grained colluvial and eluvial deposits. The landslide is affected by the perched groundwater, weak bedrock, steep road cut slope, surface runoff into the landslide, and toe undercutting by the Sunkoshi River. To stabilise the landslides, the following measures were taken.

- Construction of lined catch drains above the landslide
- Construction of a network of tributary drains (French drains) in the landslide
- Horizontal drains for draining subsurface water
- Extensive use of bioengineering

There has been noticeable movement in the landslide zone after the first monsoon, and it seems to be under control (Plate 6).

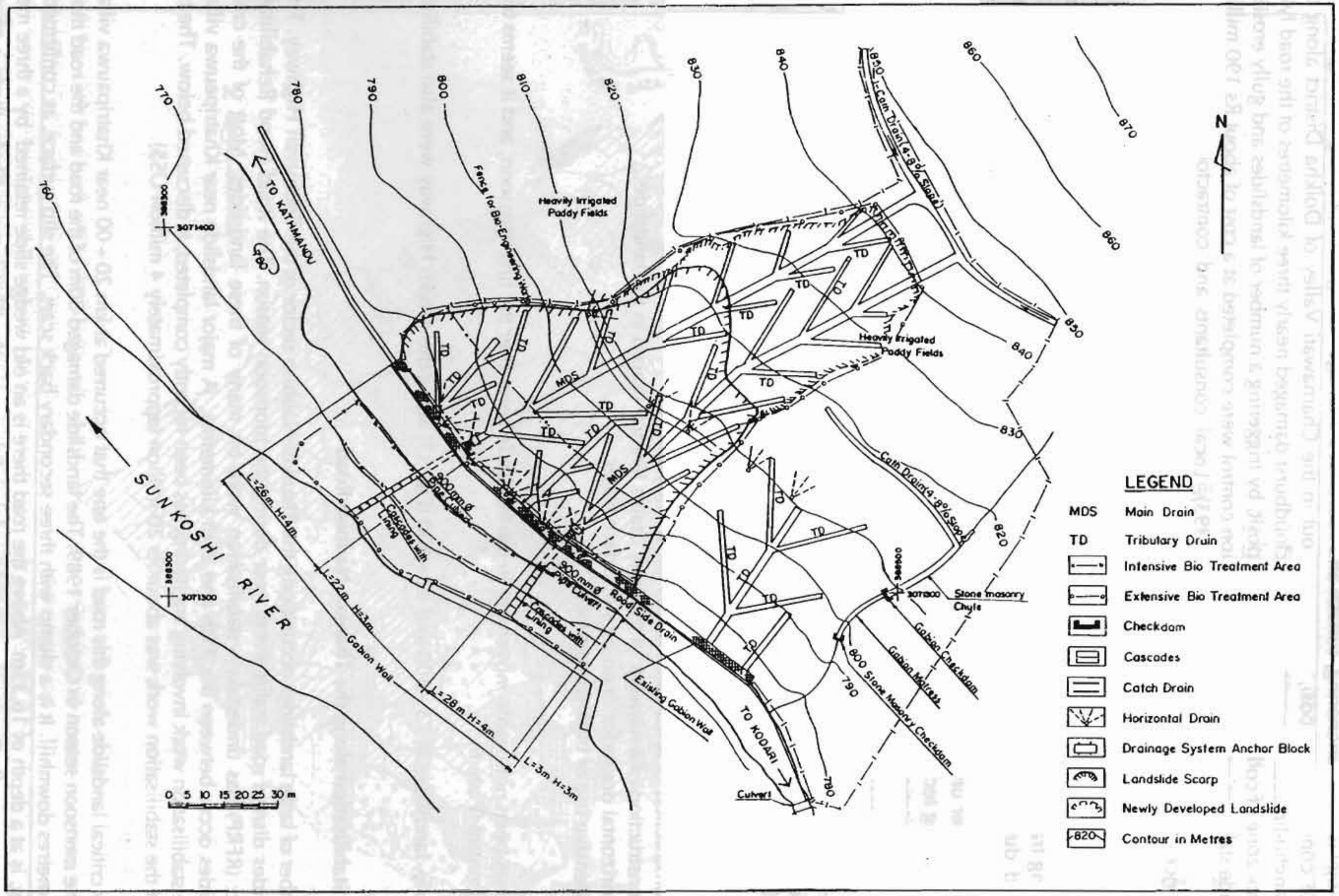
Similarly, landslides at 73+300 and 82+800 (Fig. 33) along the Arniko Highway were also stabilised.

Slope Stabilisation along the Thankot-Naubise Road

A number of large landslides occur along the Thankot-Naubise sector of the Tribhuvan Highway. These landslides disrupt road traffic every year during the monsoon season. The Road Flood Rehabilitation Project (RFRP) has undertaken stabilisation work on many of these landslides. Most of the critical landslides occur between the 11th and 26th kilometres. A major landslide near Khatripauwa village, where stabilisation work involving anchoring has been recently completed, is discussed below. The total cost of the stabilisation work was about Rs 20 million (approximately 4 million US$).

A very critical landslide along this road is the one that occurred at km 20+00 near Khatripauwa village, after the monsoon season in October 1989. The landslide damaged 80m of the road and the road moved three metres downhill. It is a slump with three secondary back scars. The slip surface, as confirmed by drilling, is at a depth of 16.35m. Above the road there is an old wedge slide retained by a three metre-high masonry wall. On the opposite side of the slide across the Khatripauwa *Khola*, there is another shallow rockslide initiated by rock quarrying in the past (DOR 1990).

Figure 33: Detailed design for the landslide stabilisation work between km 82+800, the Arniko Highway (DOR 1990, redrawn)



The landslide is in the Sopyang Formation of the Phulchowki Group of the Kathmandu Complex (Stöcklin 1980). It is composed of moderately to highly weathered phyllite and metasandstone with foliation dipping into the slope. The depth of the weathered zone is 8-12m, as indicated by the seismic refraction survey. Several prominent joint sets are found and their orientations have made the slope favourable for wedge and plane failures (DOR 1990).

The stabilisation work was completed recently and the first monsoon had no adverse effect on the stability of the area. The landslide was stabilised by constructing a composite toe wall, French drains, horizontal drains, diversion catch drains, and rock anchors (Plate 10). The anchors are 20-30m deep and each is designed to take a load of 25 tons.

Landslide Monitoring and Warning System

There are very few examples of landslide monitoring in Nepal. The landslides on the slopes of the Kulekhani Reservoir near the intake were monitored by the NEA before the stabilisation work (1989). A few large slope areas along the left bank of the Charnawati River (Valley in the original) are being monitored after its stabilisation. The Water Induced Disaster Prevention Technical Centre has selected a few landslides for monitoring along the Kathmandu-Trishuli Road from the 19th to the 48th kilometres (km19 and km48), at Kharani Tar (Nuwakot), near the Sunkoshi Hydropower Station, and near the large landslide at Butwal (Amao and Sunuwar 1993).

Engineering geology mapping of the landslide at the 19th kilometre along the Kathmandu - Trishuli Road was carried out before monitoring. A borehole of 32m was drilled and two rows of moving piles, a rain gauge station, two extensometers, and a tiltmeter were installed for monitoring (Amao and Sunuwar 1993).

So far, no attempt has been made to develop a warning system for landslide disasters in Nepal.

Landslide-dam Outburst Floods

Landslide dams are formed by the blockage of rivers and streams by the materials produced from landslides on either banks. The dams may remain for several minutes, days, months, or years. When they fail, they cause catastrophic floods in downstream areas. In the Himalayas, the narrow and steep river valleys and their fragile slopes contribute to frequent landslide damming.

Nepal, with its many large rivers and numerous smaller streams, suffers from landslide-dam outbursts and consequent floods. However, no systematic studies on such events have been made in Nepal so far and there is no proper emergency planning. Damming of large rivers in the deep gorges of the Higher Himalayas seems to be a common phenomenon in Nepal's geological history (Hanisch 1995). The landslide dam formed in the Budhi Gandaki River in 1968 created a 60m deep lake within 29 hours; it then breached, the resulting flood causing great damage downstream (Sharma 1981). Similarly, the Trishuli River was also dammed in the past, causing similar damage. The Tinau River in western Nepal was dammed many times in the recent past, causing great damage to Butwal *Bazaar,* lying downstream at the foot of the Siwaliks. In the past, the Nepalese army's help was taken to breach these dams (e.g., during the Trishuli River damming) by using explosives.

Public Awareness

In spite of frequent landslide disasters in Nepal, the people are still not very aware of their causes and mitigative measures. Such awareness could save many lives and much property. Villages situated on old flood plains of rivers and streams and in the areas susceptible to landsliding and debris flows have suffered from disasters. Prevention of gully erosion in the initial stage by using local materials and low cost techniques (such as *sabo* dams) may help avoid serious landslides and gully-erosion problems in the future. Local people are very unaware about such matters and there are hardly any public awareness programmes. Recently, the Water Induced Disaster Prevention Technical Centre (DPTC) has started conducting roving seminars in different districts and village centres to make the authorities and local representatives aware of water-induced disasters, including landslide problems.

Technical Consulting Services

In recent years, quite a number of technical consulting services have been actively engaged in the field of landslide studies, stabilisation, and landslide hazard mapping. The number of qualified and experienced persons/professionals in engineering geology, applied geophysics, geotechnical engineering, civil engineering, bioengineering, etc, available for landslide studies and management in the country, is rather limited.

Institutions Concerned with Landslide Research, Monitoring, Warning, Management and Training

Public Agencies

Department of Mines and Geology

The Department of Mines and Geology of His Majesty's Government of Nepal was established in 1941. It is responsible for the geological mapping of the country, mineral exploration work, mining, petroleum exploration, and study and mitigation of natural hazards such as landslides, debris flows, soil erosion, and earthquakes. There are over 40 geologists working in the Department. It has a separate engineering geology section responsible for the study of landslides and related phenomena and supported by a well-equipped geotechnical laboratory. There is also a well-equipped seismological centre. The Department started systematic landslide inventory survey and slope stability mapping in 1986 to get an overview of those areas of Nepal most affected by landslides as a basis for future infrastructural planning. New landslide inventory sheets were introduced based on the IAEG recommendations, after having been adapted to the special conditions of the Himalayan range. A database on the landslides of Nepal has been maintained. The German Technical Assistance Programme in the Department aims to investigate and monitor selected landslides, create a landslide inventory in the Lesser Himalayas by using remote sensing and Geographical Information Systems' (GIS) technology, and prepare the engineering and environmental geological maps of Kathmandu Valley. The Department is also carrying out a detailed study and monitoring of a landslide in Chalnakhel in the southern part of the Kathmandu Valley.

The Department of Mines and Geology, with its geologists, engineering geologists, geotechnical engineers, mining engineers, and a well-established geotechnical laboratory and infrastructure, has a very wide scope for advanced studies on landslides and soil erosion, as well as hazard and risk mapping, in Nepal.

Department of Roads

The Department of Roads is actively engaged in the study, monitoring, and mitigation of landslide hazards along road corridors. The Road Flood Rehabilitation Project (RFRP), the First and Second Road Improvement Projects, and the Arniko Highway Maintenance Project (AHMP) are some of the important projects run by the Department, and they have completed a considerable amount of work on landslide stabilisation, particularly along the Arniko Highway and the Kathmandu-Mugling section of the Prithvi Highway. The Department has a Maintenance and Rehabilitation Control Unit (MRCU) which has introduced a slope monitoring programme with the help of a database created for the Naubise-Mugling section of the Prithvi Highway.

The rapid expansion of roads during the last four decades has had an adverse impact on the physical environment of Nepal. The initiation of a large number of landslides and increase in soil erosion, which has degraded the quality of the physical basis of the influence area, are the price the country is paying for the development of road transport. Many of the roads were built unplanned, follow geologically unfavourable alignments, and they are environmentally disastrous. More recently, the Department of Roads has realised the importance of carrying out a terrain-evaluation study before the final selection of the alignment of any road. Studies in engineering geology and hazard mapping have now become routine tasks for planning and designing mountain roads.

The Department has a well-equipped geotechnical laboratory. Though the Department is working extensively on landslide studies, monitoring, and mitigation, there are no full-time engineering geologists working.

Water-induced Disaster Prevention Technical Centre

The Water-induced Disaster Prevention Technical Centre (DPTC) was established in 1991 under the Ministry of Water Resources, with the objective of strengthening His Majesty's Government of Nepal's capacity to cope with water-induced disasters through technology development, provision of training, and establishment of databases. The Centre carries out activities related to watershed management with emphasis on erosion control, landslide study and prevention, and river training. One activity of the Centre is the provision of in-country training to various professionals in related fields. The Centre has a modern experimental laboratory for hydraulics at Godavari and a training centre in Kathmandu. The Centre is presently undertaking studies in various parts of the country on river training work as well as the study and monitoring of landslides along the Kathmandu-Trishuli road and in Butwal. Regular training courses are being conducted for engineers and overseers.

The Centre has no permanent staff of its own and is run by Japanese experts and personnel deputed from various ministries and government departments.

Department of Soil Conservation

The Department of Soil Conservation was established under the Ministry of Forest and Soil Conservation in 1974. The main objectives of the Department are to contribute to maintaining ecological balance by reducing pressure from natural hazards, such as floods and landslides, through proper watershed management and to assist in maintaining land productivity by implementing soil conservation activities (DSC 1994b). The Department has 42 District Soil Conservation Offices that plan, implement, and monitor soil conservation and watershed management activities.

The Department of Soil Conservation is basically engaged in the stabilisation of natural and cut slopes through afforestation, reforestation, and construction of checkdams and other low-cost structures.

The Bagmati Watershed Project is one of the projects of the Department of Soil Conservation. It is helping the local people of the Bagmati Watershed in slope stabilisation and soil erosion control. After the disaster of 1981 in the Lele-Bhardeo area, the Bagmati Watershed Project has been actively engaged in the stabilisation of landslides and control of debris flows and gully erosion.

Department of Irrigation

The majority of the hill irrigation projects in Nepal have suffered severely from canal failures caused by landslides and seepage. Inadequate geological investigations are the main causes of such failures (Sharma 1981). In recent years, there has been a great increase in the demand for hill irrigation projects in the country. The problem of landslides and seepage will further aggravate the situation if proper investigation and construction methods are not enforced. Seepage along the canals is also becoming a frequent landslide-triggering agent in many areas. The Department of Irrigation has prepared a survey and mapping manual (DOI 1990) for irrigation projects in Nepal, which includes geotechnical studies for canal routes and headworks.

Nepal Electricity Authority

The Nepal Electricity Authority (NEA) conducts prefeasibility, feasibility, and detailed studies of the country's hydropower projects. During various stages of the study, the Authority assesses the slope stability of dam sites, reservoir sites, and powerhouse sites. The Authority has several geologists, geophysicists, and geotechnical engineers working on various aspects of slope and underground excavation stability, and it also has a well-equipped geotechnical laboratory.

The stability of the slopes surrounding the Kulekhani Reservoir was studied by the Authority, and a few slope-stabilisation measures were implemented for active landslides in October 1983 when the Kulekhani Reservoir was about to experience its first ever full-supply level. Some landslides were found to be active on the slopes just upstream from the intake. To stabilise the slide, removal of material from the crown, cable anchoring, sub-horizontal drains, crack filling, and improvement of surface drains were carried out by the Authority (Marui 1985). Similarly, the landslides near the Sunkoshi Hydropower Project were also studied and stabilised.

Tribhuvan University

The Department of Geology was established in 1967 at the Tri-Chandra Campus, Tribhuvan University, Faculty of Science, to teach geology at the undergraduate level (B.Sc.). The graduate course (M.Sc.) was added later, in 1974. At present, the M.Sc. course is conducted at the Central Department of Geology, Kirtipur Campus, and the B.Sc. course at Tri-Chandra Campus. Together, the departments have about 25 geologists. The Central Department of Geology has well-equipped laboratories for engineering-geology, petrology, geophysics, and hydrogeology. The Department is strengthening its laboratory and human resources for research in the field of engineering geology. It publishes a regular bulletin containing research papers on geology and engineering geology.

The Institute of Engineering, Tribhuvan University, teaches a Bachelor of Civil Engineering (B.E.) course which includes engineering geology. The Institute has a well-established geotechnical laboratory run by geotechnical engineers.

International Organisations

International Centre for Integrated Mountain Development

The International Centre for Integrated Mountain Development (ICIMOD) is the first centre of its kind in the field of mountain area development. It was established in 1983 and began its professional activities in 1984. The recognition of the alarming environmental degradation of mountain habitats and consequent increasing impoverishment of mountain communities led to the establishment of the Centre. As an institution focussing on integrated mountain development, ICIMOD is concerned with the identification of hazardous areas, hazard mitigation, and improving disaster preparedness.

The Mountain Risk Engineering (MRE) programme was introduced and a manual was prepared by ICIMOD during 1988-1989, and a nine-week long pilot training programme was conducted for engineers and geologists from the HKH countries. A Mountain Risk Engineering Handbook was published in 1991 (Deoja et al. 1991), and a second training course was conducted. The Centre has also conducted several training programmes on slope stability, hazard assessment, and the use of GIS technology for Mountain Risk Engineering. It has published several occasional papers and publications on erosion, landslide, GLOFs, and other mass movements. It has also conducted workshops and seminars on similar topics.

Other National and International Organisations

The Home Ministry, His Majesty's Government of Nepal; National Committee on the International Decade for Natural Disaster Reduction (IDNDR); National Committee for Man and the Biosphere (MAB);

Environmental Protection Council (EPC); Water and Energy Commission (WEC); Nepal Geological Society, the World Conservation Union (IUCN); and Economic and Scientific Commission for Asia and the Pacific (ESCAP) are some of the national and international organisations that also deal with various environmental issues, natural hazards, and their mitigation.

Scope for Research and Training in Nepal

Research Programmes

The study of natural disasters, such as landslides, should be based on an integrated approach and should include specialists such as geologists, engineers, geotechnicians, hydrologists, and geophysicists. The International Centre for Integrated Mountain Development (ICIMOD) can play a vital role in this respect. ICIMOD can conduct training courses in the study and management of landslides for this region and facilitate the exchange and dissemination of relevant information among the HKH countries. ICIMOD could be a focal point for research within the region. In collaboration with the institutions and universities of the HKH Region, it can also conduct research programmes and develop academic curricula suitable for the study and management of landslides. Government and non-government organisations, as well as academic institutions in the region, should place more emphasis on landslide study and research. The long-term output of such studies and research will undoubtedly improve the overall level and skill of landslide study and management in the region. Preparation and wider dissemination of audio-visuals to generate awareness among the people about landslide disasters are equally important.

The research programme should focus on the following aspects.

1. Working out the unified landslide classification and study methodology suitable for this region; landslide related data collection, storage, integration, and distribution within the region; and preparation of landslide study and management handbooks, manuals, and instructions for various target groups

2. Study of active and old landslides; development of programmes for landslide mapping (landslide inventory study) on a scale of 1:25,000 or more in the vulnerable parts of the country (especially where important infrastructures or settlements are located); and preparation of hazard maps and risk maps

3. Study of and research on the relationship between various factors (i.e., rock type, slope, geological structure, soil type, rainfall, and seismicity) and the occurrence of landslides in various physiographic regions of the country; classification of rocks and soil according to their landslide susceptibility and geotechnical properties

4. Programmes for the systematic study, monitoring, and control of selected active landslides; research on the appropriate measures to be taken for effective landslide mitigation and control (i.e., engineering and bioengineering methods)

5. Exchange of experiences on landslide studies in various countries, development of appropriate academic curricula, and their implementation through academic institutions

Training Programme

At present, Nepal is facing serious problems due to landslides and related mass movements. According to the data provided by the Home Ministry, every year more than 1,000 people lose their lives as a result of landslides and related phenomena. The average annual loss of property as a result of these disasters is estimated at Rs 10,000 million, which is about 20 per cent of the GDP of the country. This clearly indicates that there is an urgent need for landslide study, mapping, management, and training in the country.

Target Groups

The training course should be focussed on the following five target groups.

1. Engineers and geoscientists directly involved in the study, mitigation, monitoring, and control of landslides affecting important infrastructures
2. Junior technicians involved in landslide study and management
3. Planners, decision-makers, politicians, media, and other agencies involved in landslides and related disaster management
4. Villagers and volunteers at the grassroots' level directly affected by landslides and related problems

The training programmes should be conducted first by implementing pilot training programmes for qualified personnel (i.e., engineers and geoscientists), junior technicians, and villagers. There should be a sound evaluation mechanism for trainees as well as trainers to improve the training programme in the future. Planners, decision-makers, politicians, and persons from the mass media should be involved in the workshops and seminars. A short description of the programme for each target group is given below.

Target Group 1: Implementation of from four to six weeks' training programmes for qualified personnel (engineers and geologists), with classroom lectures, seminars, laboratory work, and field work for one week. At the end of the programme, the trainees should submit a project assignment.

Target Group 2: Organisation of from three to four weeks' training programmes for junior technicians, with classroom lectures, seminars, laboratory work, and field visits

Target Group 3: Organisation of one week-long on-the-spot workshops, seminars, and training programmes for grassroots' level persons responsible for the management of landslide disasters (e.g, school teachers, local-level NGOs, and members of district and village development committees).

Target Group 4: Organisation of from three- to four-day workshops for planners, decision-makers, politicians, media representatives, and other agencies involved in landslides and related disaster management.

Currently, the Central Department of Geology and Institute of Engineering, both under Tribhuvan University, teach engineering geology within the framework of the Master of Science (M.Sc) (Geology) and Bachelor of Engineering (B.E.) curricula, respectively. The engineering geology courses are given in the Annex.

Conclusions and Recommendations

Landslides and related mass-movement phenomena are very common in Nepal and are also among the most common natural hazards. Every year, they cause heavy losses of life and property. They also damage the natural environment. Landslides often occur during the monsoon season, but some large landslides also occur at other times.

In Nepal, landslide studies are carried out by various organisations and research groups. The methods and details of landslide studies vary widely. Most of the studies are of the inventory type, a few of them deal with the hazard itself, and there are hardly any studies on risk assessment. There is no organisation responsible for landslide hazard mapping, mitigation, and control. Generally, all the efforts are concentrated after the disaster and very often the efforts are confined to easily accessible areas.

To minimise the adverse effects of landslides and related mass movements in the future, it is necessary to identify and study the hazardous areas of the country by integrating knowledge and information from various disciplines, such as geology, geomorphology, geophysics, engineering, meteorology, and hydrology, and to formulate plans and programmes for implementation.

Instead of the current unplanned and scattered studies on landslides, there should be systematic landslide studies and hazard mapping in the country. Initially, the study should focus on the most vulnerable areas. Existing laws and institutional capabilities for landslide hazard mitigation and control should also be strengthened. There should be good coordination among the organisations and institutions involved in landslide study, monitoring, mitigation, and control.

Government and non-government organisations should formulate programmes to educate and create awareness in the hill communities about natural hazards. In this respect, the mass media can play an important role. The role of the media is also vital for early warning about hazards.

This study shows that most engineers, other technical personnel of the country, and hill communities are not aware of landslide hazards and, hence, the infrastructures and settlements often suffer from disasters. Therefore, it is recommended that proper training and awareness programmes be conducted for those directly dealing with landslides and related mass movements. At the same time, research activities on landslides should be intensified.

Course of Study in Engineering Geology

Central Department of Geology, Tribhuvan University (M.Sc.Geology Course)

Introduction, its role in planning, design, construction and maintenance of infrastructures. Engineering geological maps: types and contents, scale. Hazard maps, method of preparation.

Site investigation: use of the knowledge of other branches of geology in site investigation. Report writing.

Elements of soil mechanics. Engineering properties of soil. Unified Soil Classification System. Stress within an earth mass. Mohr's Circle. Stress distribution in a loaded earth mass, failure criteria for soils. Consolidation, compaction, settlements.

Elements of rock mechanics. Engineering properties of rocks, rock mass classification, RMR and Q systems, analysis of rock slope stability, use of stereographic projections, failure criteria for rocks.

Rock and soil as construction materials. Requirements for selecting borrow areas, searching and exploration of construction materials, and use of geological, engineering geological, and topographic maps and aerial photographs, application of geomorphology in searching for construction materials. Properties of construction materials.

Engineering geologic investigation for dams: classification, terminology, geologic investigations for dam site selection, engineering geological mapping of dam sites, subsurface exploration, geophysical methods for exploration, construction materials. Dam foundation. Seepage and settlement, consolidation and curtain grouting, bearing strength of foundation, reservoir geology, problem of erosion and siltation.

Engineering geological studies for irrigation canals: site selection, problems of instabilities, erosion and sedimentation, measures for their control.

Engineering geological studies for tunnels: classification and nomenclature, exploration for tunnel alignment, determination of rock loads, methods of tunnelling including NATM, case histories.

Engineering geological studies for roads and bridges: location and site selection, use of geologic maps and aerial photographs for road corridor studies. Problem of slope stability and erosion, drainage, landslide hazard maps, stable cut slopes in soil and rocky areas. Subsurface exploration for bridge foundation, construction materials.

Landslides: classification, factors controlling landslides, analysis and control of landslides, problem of landslides and Glacial Lake Outburst Floods (GLOFs) in Nepal, methods for mitigation.

Earthquakes: mechanism of earthquakes, magnitude and intensity, liquefaction, landslides due to earthquakes, seismicity in Nepal, and mitigation of earthquake hazard.

Engineering Institute, Tribhuvan University
(Bachelor of Engineering course)

1.0 Introduction

1.1 Scope of geology in civil engineering
1.2 Basic review of earth sciences
1.3 The earth: its structure and environment
1.4 Various landforms on the surface of the earth: mountains, plateaus, shields

2.0 Changes in the Faces and Structure of the Earth
2.1 Plate tectonics
2.2 Seismicity
2.3 Causes and effects of earthquakes
2.4 Volcanism
2.5 Fold mountains

3.0 Geology in Civil Engineering
3.1 Definition of engineering geology
3.2 Different branches of geology
3.3 Scope and objective of engineering geology
3.4 Importance of engineering geological studies in Nepal
3.5 Relationships between geology and earth sciences

4.0 Crystallography and Mineralogy
4.1 Arrangement of atoms in crystals, crystal forms and habits, and crystal classes
4.2 Definition of minerals
4.3 Physical properties of minerals: habits, cleavage, hardness (Moh's hardness scale) and specific gravity
4.4 Other properties for classification and identification of minerals

5.0 Rock Forming Minerals
5.1 Important rock-forming minerals and their engineering significance
5.2 Quartz, feldspars, mica, chlorite, epidote, hornblende, pyroxene, olivine, serpentine and pyrite.
5.3 Other rock-forming minerals: calcite, dolomite, opal, limonite, gypsum, clays, barytes,bauxite.

6.0 Petrology
6.1 Definition
6.2 Petrographic classification: igneous, sedimentary and metamorphic rocks
6.3 Engineering significance of the three rock classes
6.4 Macroscopic study of the basic physical and engineering properties of rocks
6.5 Study of igneous rocks: granite, rhyolite, gabbro, and basalt
6.6 Study of sedimentary rocks: clay, shale, limestone, dolomite, sandstone, and conglomerate
6.7 Study of the metamorphic rocks: slate, phyllite, schist, gneiss, marble, quartzite

7.0 Structural Geology
7.1 Rock deformation and reasons
7.2 Study of folds, faults and joints, cleavage
7.3 Introduction to dip, strike, and outcrop
7.4 Unconformity
7.5 Orientation of geological strata using geological map, planes, and cross-sections
7.6 Planes of discontinuities in rock masses
7.7 Engineering classification of rock masses

8.0 Mass Movement and Rock Slope Engineering
8.1 Types of landslides and factors affecting slope stability
8.2 Preventive measures for landslides and corrective means for maintaining stability
8.3 Rockfall, rockslide and mud flow

9.0 Hydrogeology
9.1 Morphology of river channel, transportation, and deposition
9.2 Groundwater movement and its origin
9.3 Permeability and porosity
9.4 Aquifer, aquiclude, water level, and piezometric levels
9.5 Confined and unconfined aquifers
9.6 Springs and reservoirs

10.0 Site Investigation
10.1 Interpretation of topographic maps
10.2 Aerial photographs and geologic maps
10.3 Geophysics and use of engineering geological maps for terrain evaluation
10.4 Site exploration: drilling, test methods, and borehole logs
10.5 Geological investigations for dams and reservoirs, roads and pavements, foundations, bridges and tunnels

11.0 Engineering Geology of Nepal
11.1 Geological divisions of Nepal
11.2 Distribution of different rock/soil types
11.3 Geological structures and their engineering significance

Laboratories:

Six laboratory exercises will be performed in this course, in addition to two site visits and one 3-day field trip. The Laboratory exercises are listed below.

a) Identification of rocks and minerals
b) Study of rock structures
c) Study of effects of weathering and outcrop
d) Study of topographic maps, preparation of profiles, interpretation of geologic maps and cross-sections and stratum contours
e) Preparation of interpretative engineering geological maps
f) Study of fault and fold maps, borehole and three point problems
g) Brunton compass
h) Schmidt's hammer

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Plates

Plate 1: Strongly developed gully erosion in Hungung Village, Arun Valley, eastern Nepal, gradually destroying the agricultural land and threatening the stability of the village.

Plate 2: Rockslide in the highly crushed zone near Jhakri *Danda*, Kanti Rajpath, Central Nepal.

Plate 3: A large landslide formed by wedge failure in quartzites and phyllites (location: Far-western Nepal).

Plate 4: Phedigaun devastated by the disaster of July 19-21, 1993. Notice an island in the middle of the fan with a few houses. The previous river channel was confined to the west of the island, but, during the disaster, it shfted to the right (north) and swept away many houses - view towards the west.

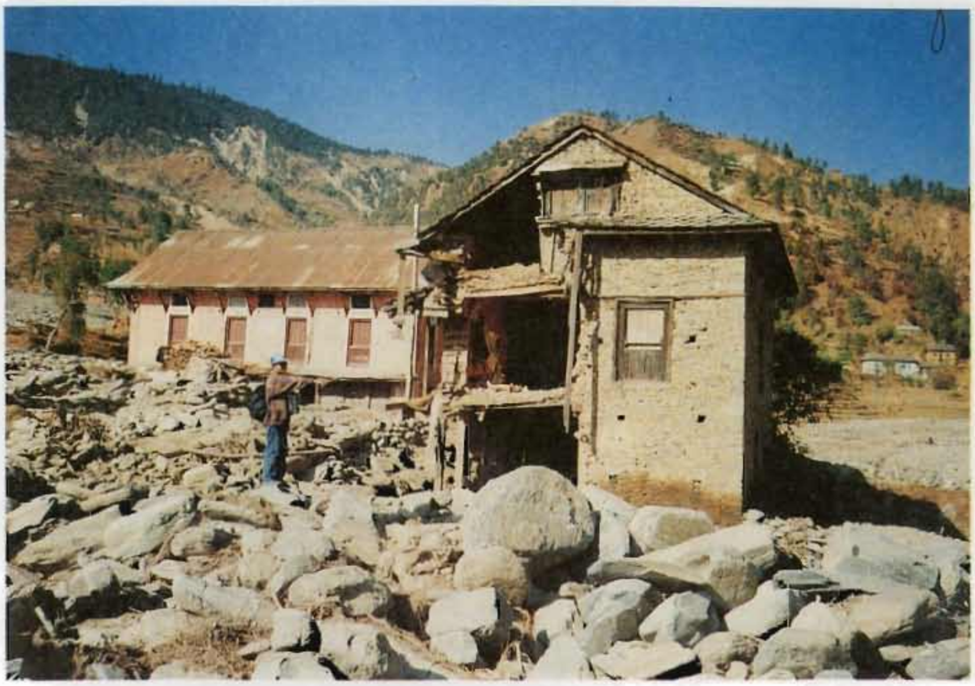

Plate 5: A closer view of the houses at Phedigaun damaged by the disaster of July 19-21, 1993 - view towards the west.

Plate 6: Landslides in the Agra *Khola* Watershed (Central Nepal) triggered by the cloudburst of July 19-21, 1993 - view towards the southwest.

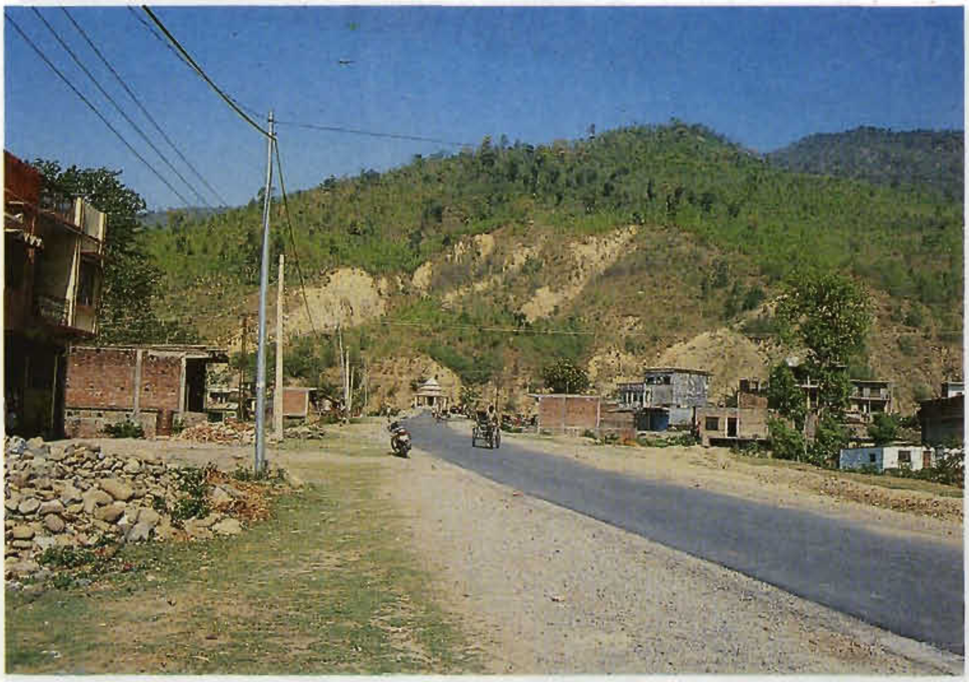

Plate 7: The Butwal landslide on the right bank of the Tinau River near Butwal Bazaar. Note the large rockslide block (Siwalik sandstone and mudstone) in the middle of the landslide (Photo by Rabindra Thanju).

Plate 8: Soil slides at Daklang (about 2km north of Chaku *Khola*) along the Arniko Highway).

Plate 9: Gully erosion protection work in the Charnawati Valley using concrete lining on the stream floor, to make cascades, concrete retaining structures along the banks, and large tetrapods along the streambed and the banks

Plate 10: Landslide stabilisation meaures (retaining walls, rock anchoring, surface and subsurface drains, and bioengineering works) applied at the Khatripauwa Landslide along the Thankot-Naubise road, Central Nepal - view towards the southwest.

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- Landslide Hazard Management and Control in Pakistan
- Landslide Hazard Mapping and Management in China
- Landslide Hazard Management and Control in India
- Climatic Atlas of Nepal

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