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 geomorphodynamic 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).

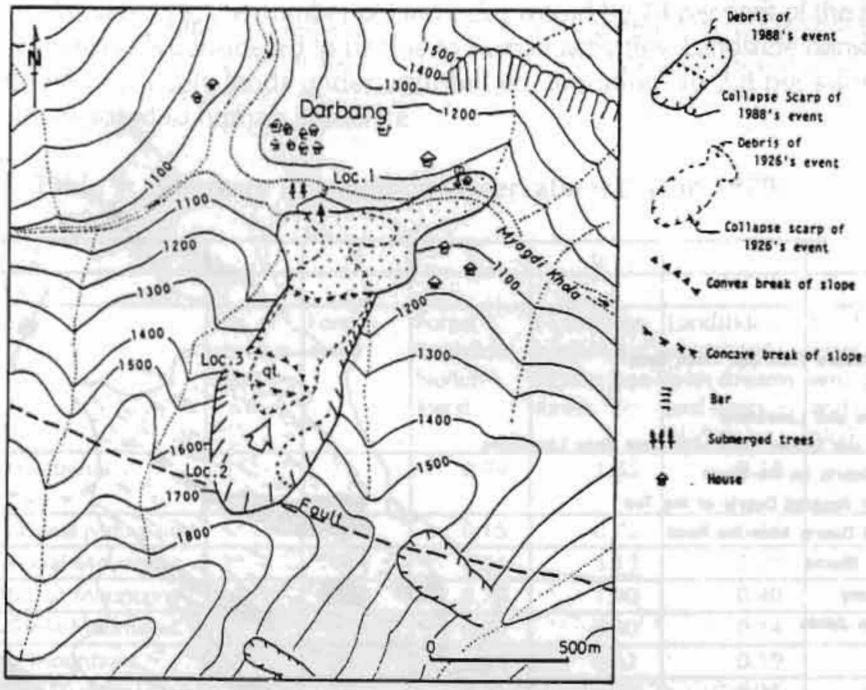
The Darbang rockslide/rockfall is situated at the core of an anticline and the rocks at the base are represented by alternating phyllites and quartzites, whereas the rocks at the crown are made up of biotite schist. The two rock units are probably separated by a fault which passes close to the crown. 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).

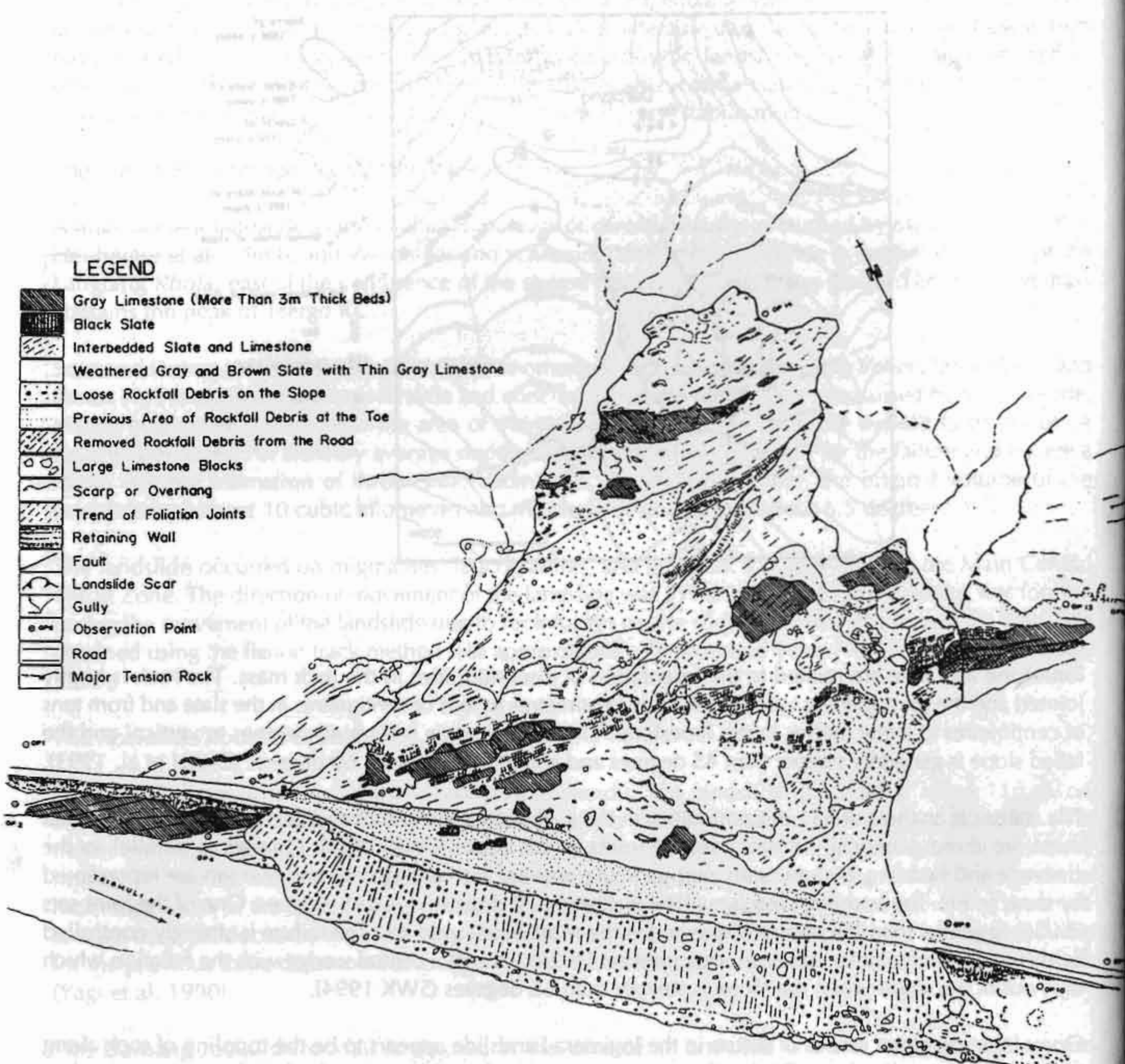
One of the important causes of failure in the Jogimara Landslide appears to be the toppling of rock along the steep counter dip slope. During the monsoon season, the rainwater and subsurface water percolate into the slope through the fractures and joints and are blocked by the impervious black slate 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)

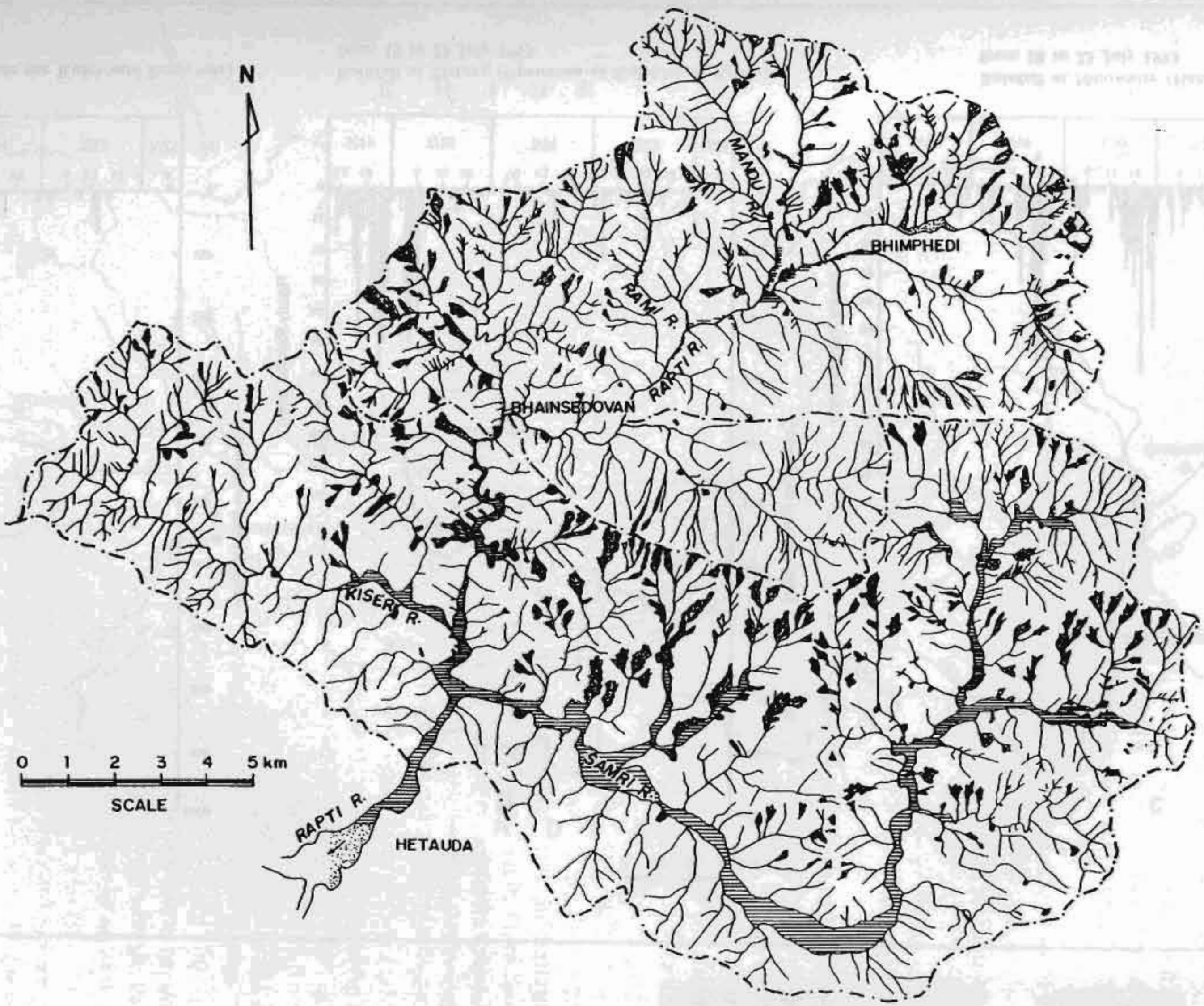
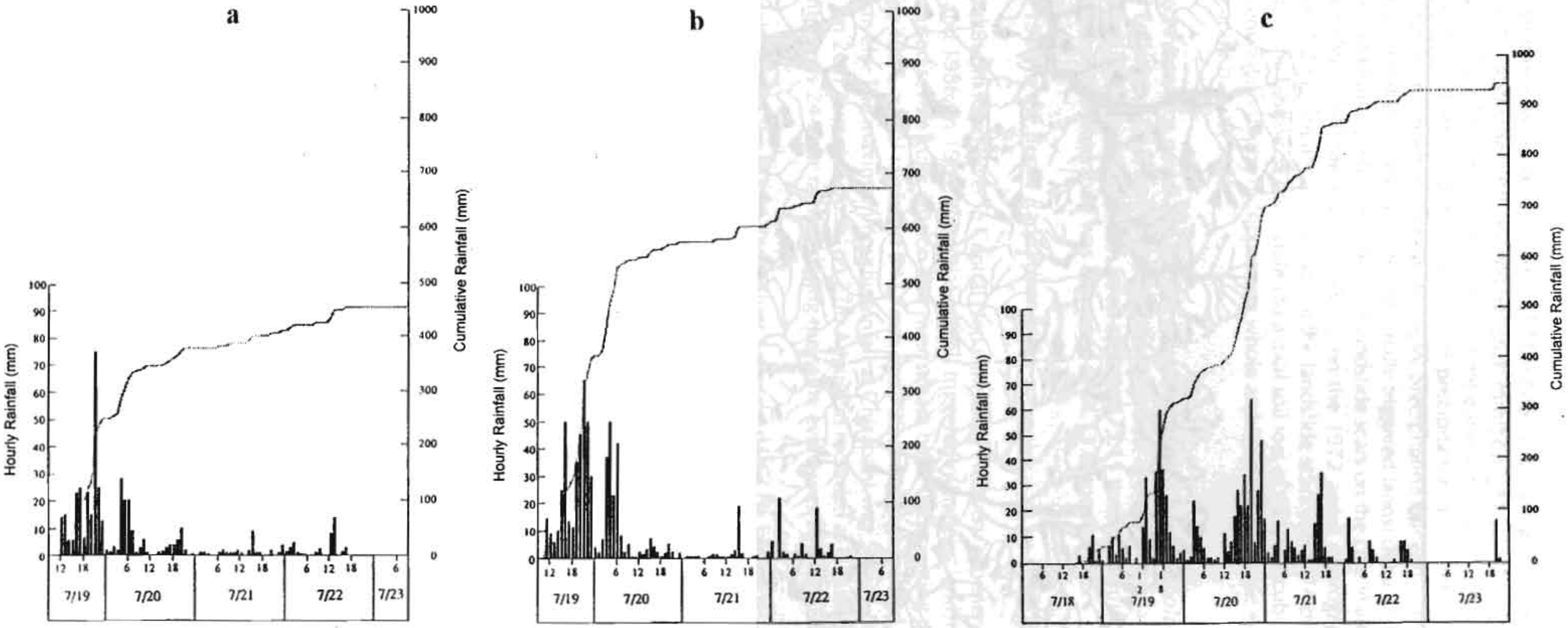


Figure 15: Rainfall records at (a) Nibuwatar, (b) Tistung, and (c) Simlang (JICA 1993)

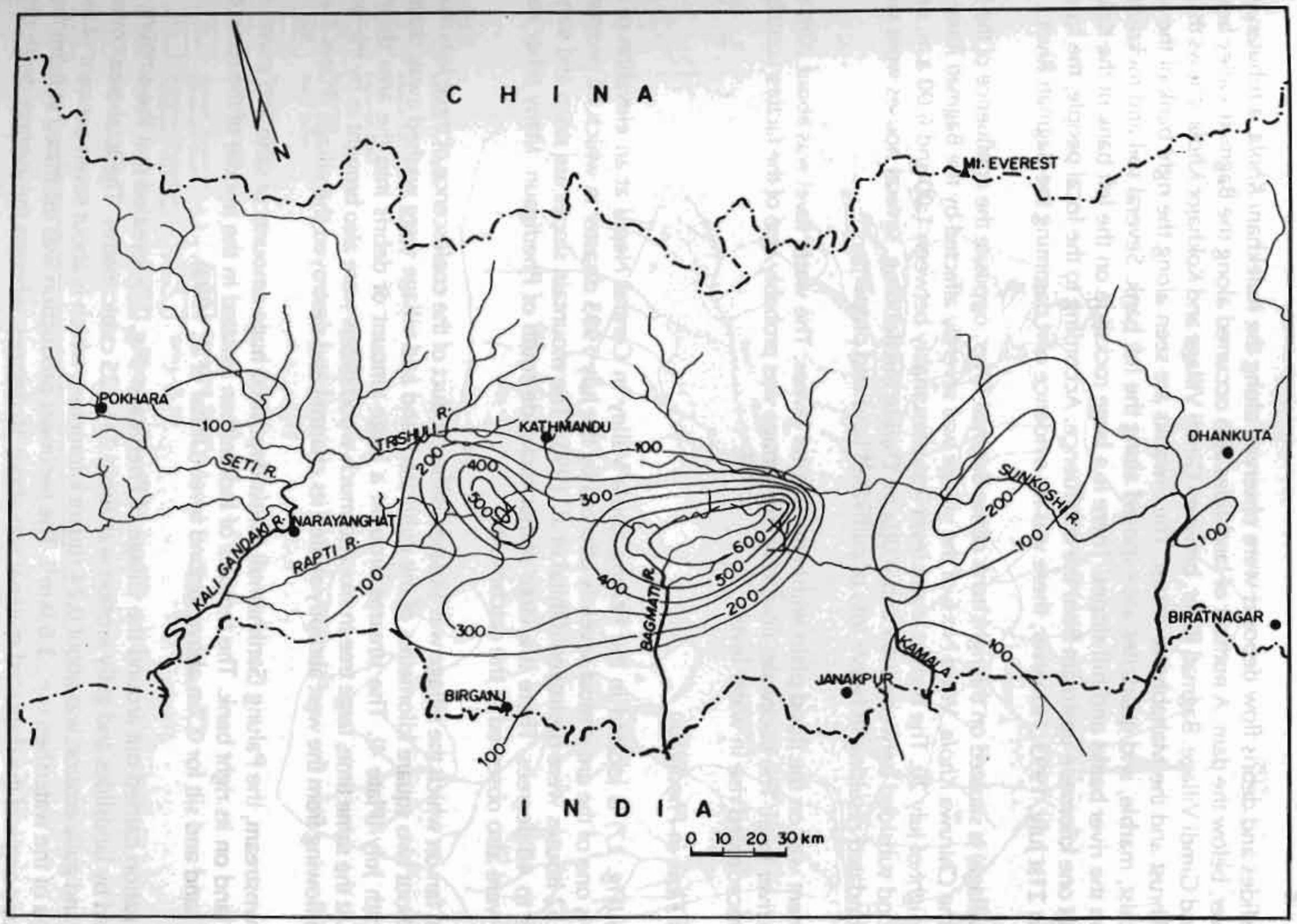


Rainfall at Simlang (Beside the Kulekhani Reservoir) from 19 to 23 July 1993

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.

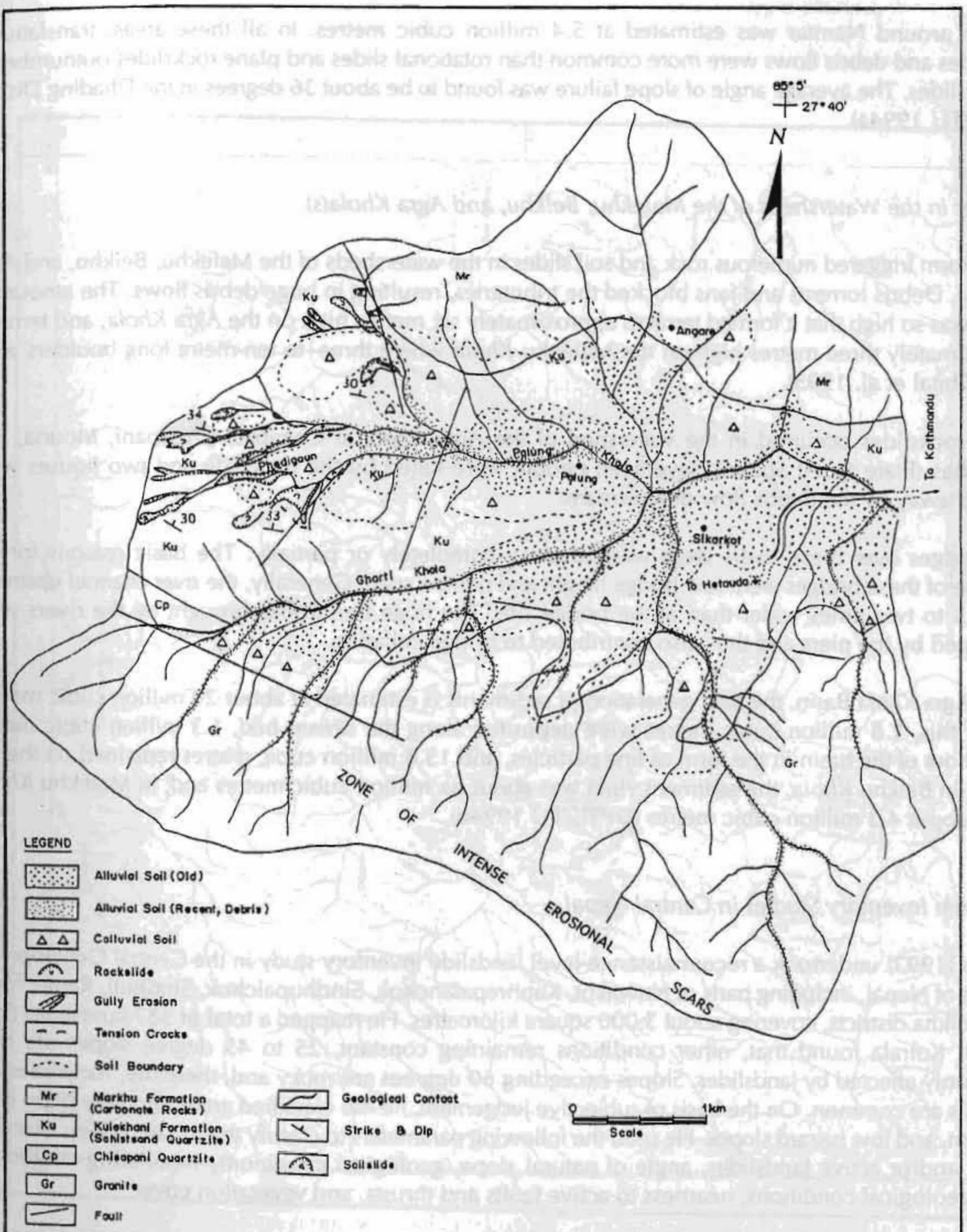
The alluvial fan on which the village was situated is the product of the coalescence of three fans from the streams. About two square kilometres of the cultivated land and village were washed away during the night of 19th July (Plate 4). The streams brought a huge amount of debris into the area during 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 $0.4X10^6m^3$, 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)

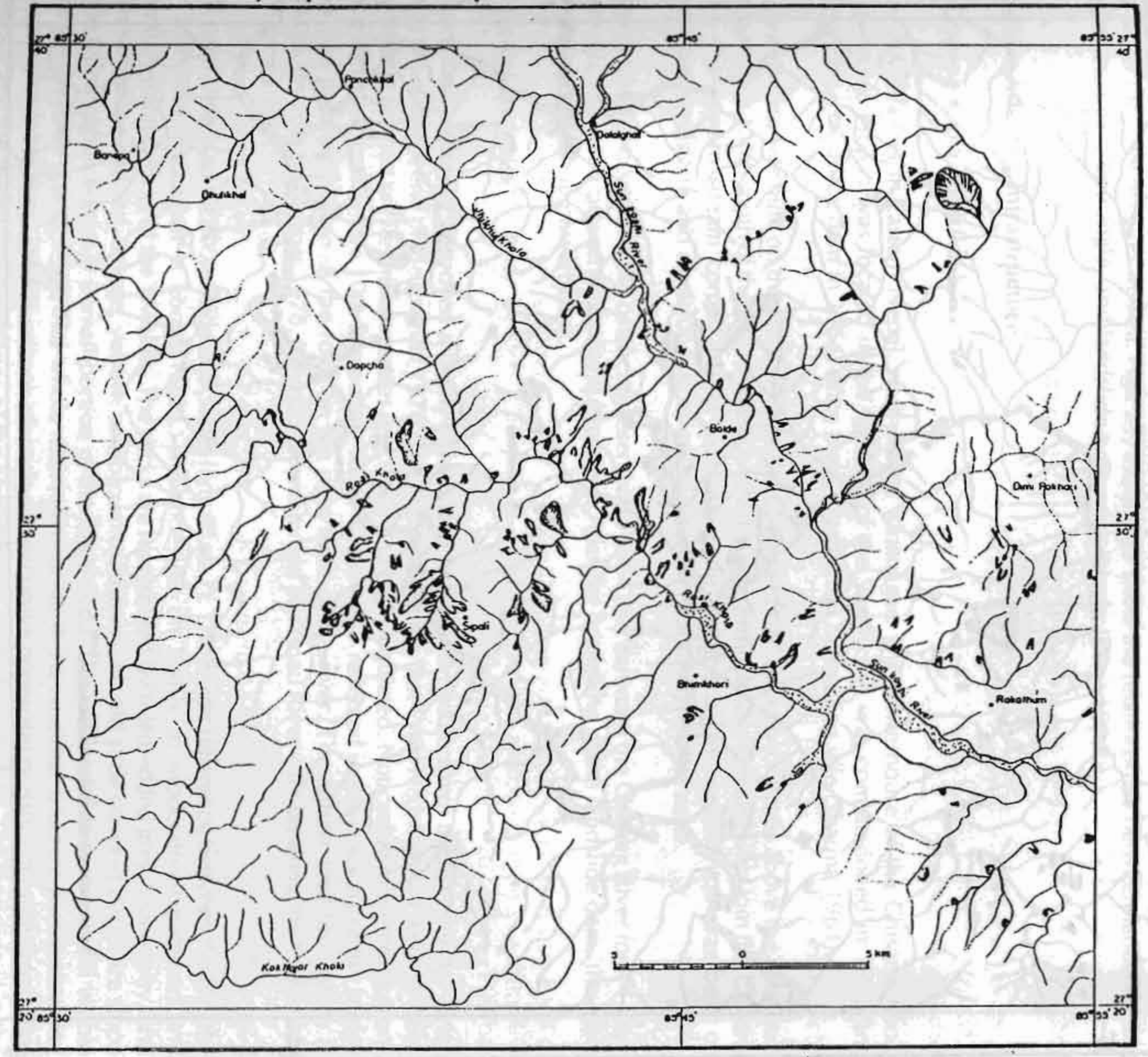


Figure 19: Landslide inventory map of Central Nepal between the Sunkoshi and Tamakoshi rivers (Koirala 1993, redrawn)

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)

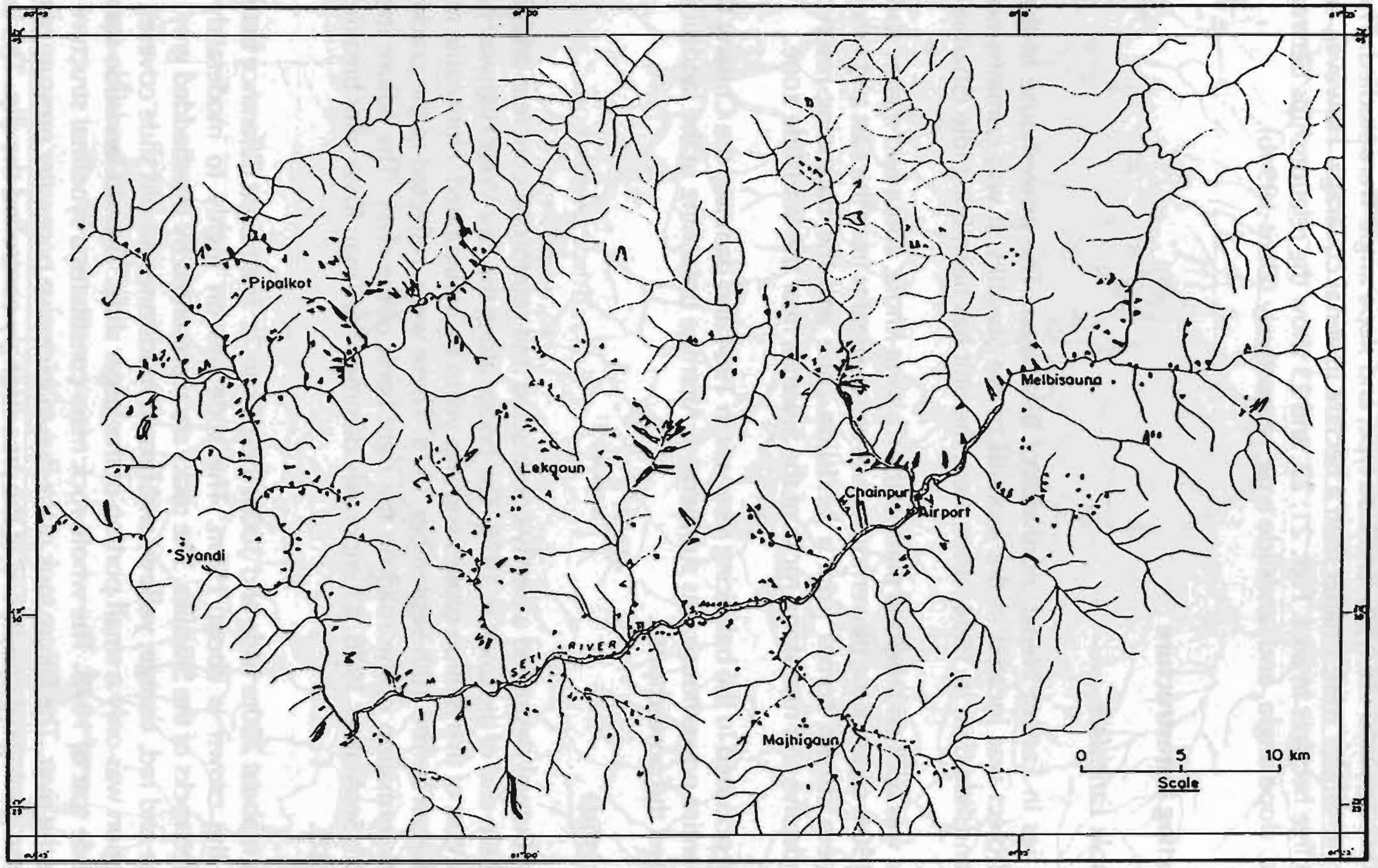


Figure 21: The relationship between the area covered by landslides and the landslide population, Bajhang District, Far-western Nepal (Dixit 1994b, redrawn)

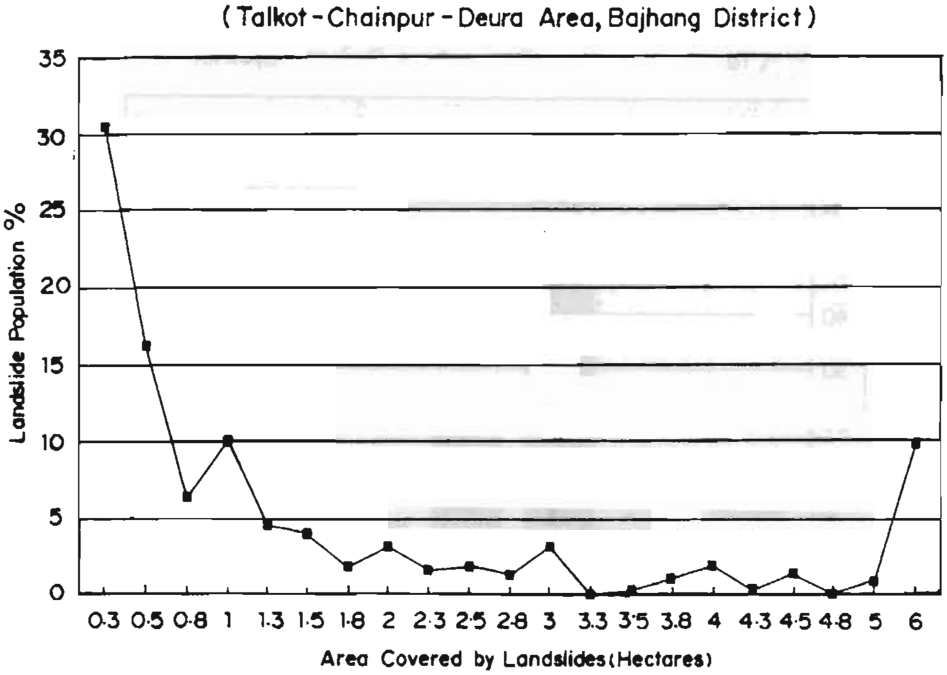


Figure 22: The relationship between the slope and the landslide population, Bajhang District, Far-western Nepal (Dixit 1994b, redrawn)

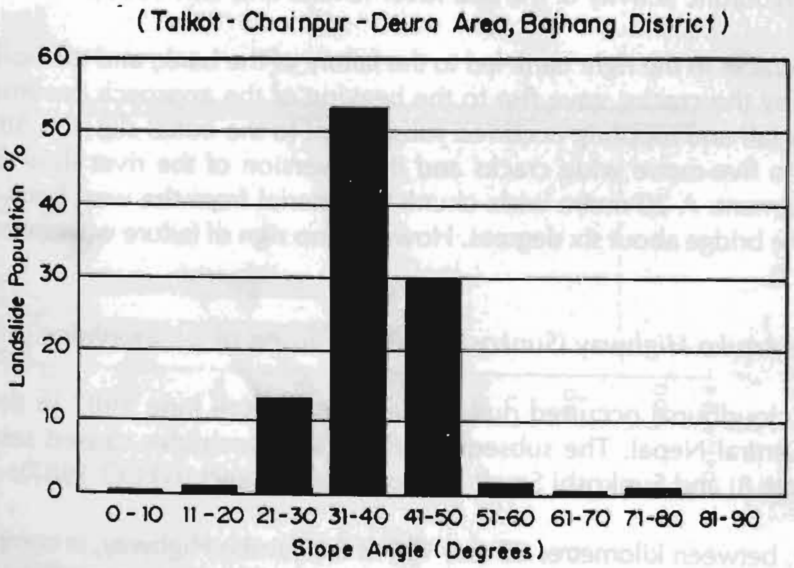
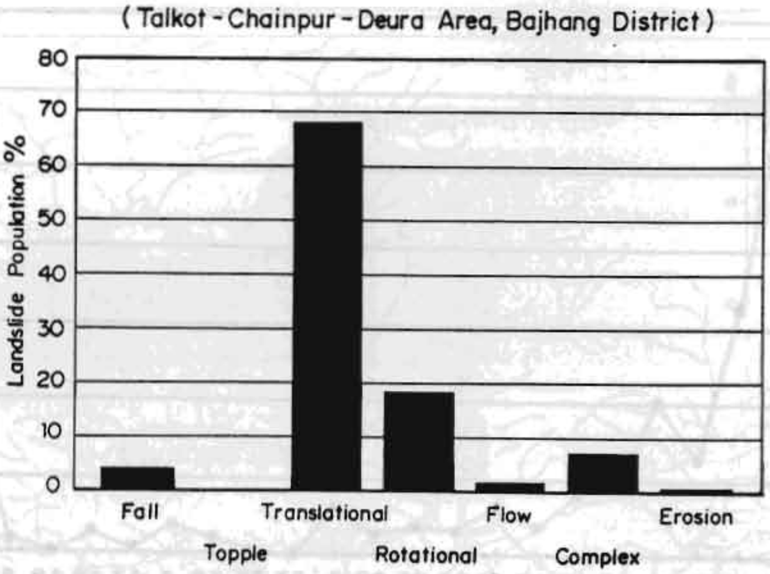


Figure 23: The relationship between landslide types and landslide population (Dixit 1994b, redrawn)



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).

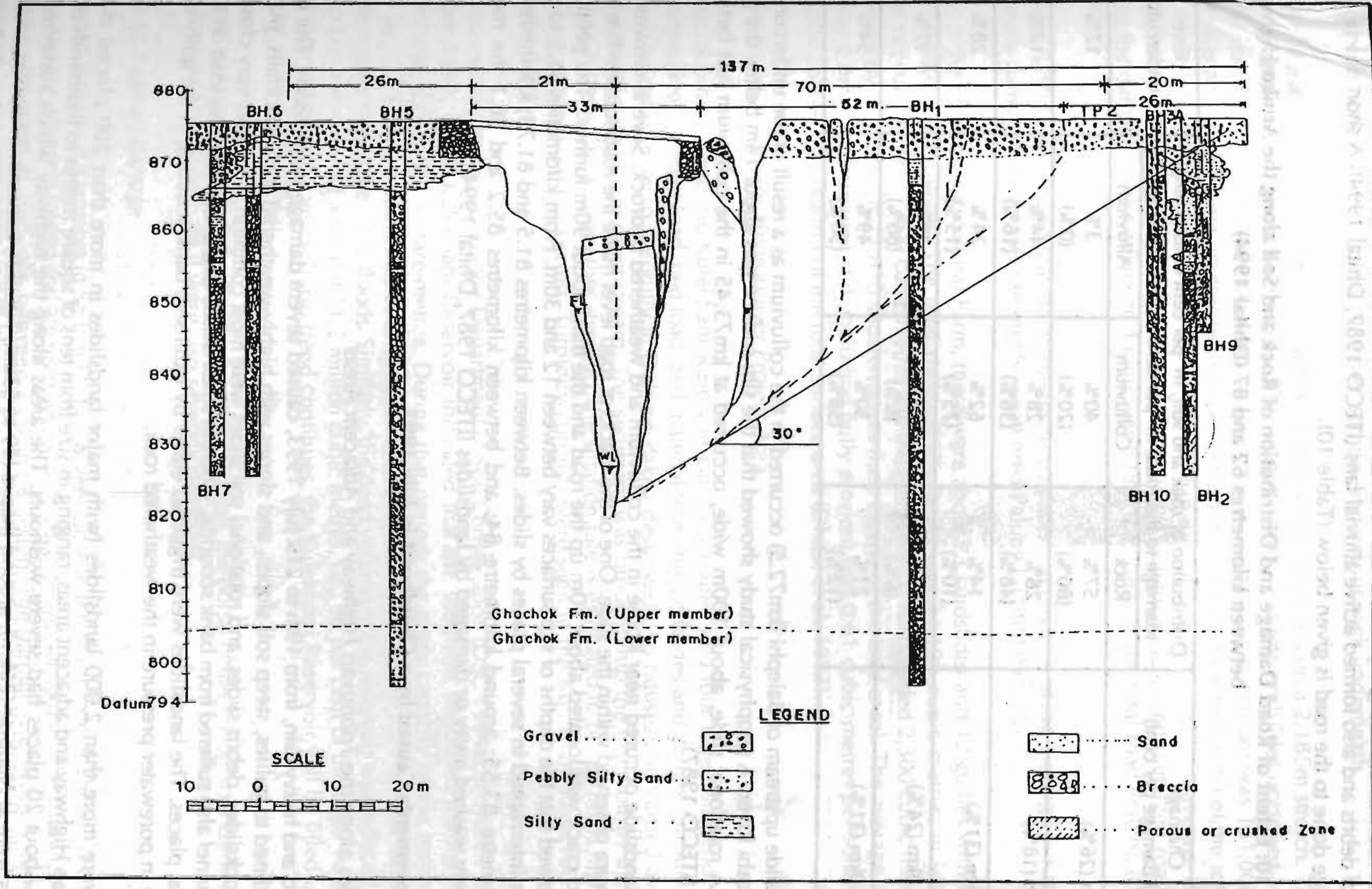
The development of cracks in the right bank led to the failure of the bank, and the horizontal component of the slip, induced by the cracks, gave rise to the heaving of the approach pavement adjacent to the bridge. The failure by fall and toppling occurred subsequent to the initial slip. On 5th September 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., $1,680 \times 0.54 = 907 kg/m^2$) 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., $1,680 \times 0.61 = 1,014 kg/m^2$) 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)