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Landslides and debris flows of 19-21 July 1993 in the Agra Khola watershed of Central Nepal

P. B. Thapa and M. R. Dhital
Central Department of Geology, Tribhuvan University, Kirtipur, Kathmandu, Nepal

ABSTRACT

High intensity rainfall of 19-21 July 1993 triggered off a large number of mass movements in the Agra Khola watershed of Central Nepal. It caused a heavy loss of human lives and property. Landslides were distributed mainly in the upper part of the watershed, especially in the vicinity of Chisapani, Chaubas, Dandabas, and Chhap. Main types of mass movement were rockslides, soils slides, and complex failures. About 51% of them were soil slides and 18% were rockslides. Among the rockslides, 4% were deep-seated rotational slides. Large deep-seated rockslides were common on the north-facing dip slopes, whereas shallow slides were observed on the counter dip slopes and in the area occupied by granite. Soil slides occurred on slopes covered by 1-6 m deep colluvium and/or residual soils. The highest percentage of landslides was found in the Kulikhani Formation and on slopes of 25°-45°. The material from landslides contributed to a huge amount of debris, which was deposited on cultivated land. The debris formed up to 5 m high terraces along the rivers. The upper reaches of the Agra Khola and Chalti Khola are the main hazardous areas.

INTRODUCTION

The Agra Khola watershed lies in Central Nepal and occupies parts of the Makawanpur and Dhading districts. It is bounded by the latitudes 27°45' and 27°36' N, and the longitudes 84°58' and 85°7' E (Fig. 1). The Agra Khola is the main draining river in the study area, which joins with the Mahesh Khola at Mahadevbesi. The major tributaries of the Agra Khola are the Chalti Khola and Liti Khola. Altitude of the study area ranges from 600 m at the confluence of the Mahesh Khola and Agra Khola to 2509 m at the peak of Chisapani. The southern part of the area is dissected by many streams and gullies and has rugged topography whereas the northern portion is comparatively smooth. The streams form steep valleys and a few deep gorges.

During 19-21 July 1993, a severe rainstorm hit the Agra Khola watershed causing catastrophic landslides, floods, and debris flows. The incidence was responsible for heavy loss of human lives and property. Though often small-scale slides, flooding, and other natural disasters were not uncommon for that area, it was the greatest one in that region ever occurred before.

The rainfall pattern in the area is quite variable because of the intricate topography. The entire watershed received intense rainfall of 300-500 mm between 19 and 21 July of 1993 with the major cloudburst near the Tistung-Palung region (DPTC/TU 1994b). The maximum precipitation within 24 hours recorded at Tistung was 540 mm (DHM 1993). Rainfall distribution pattern caused almost coincidental

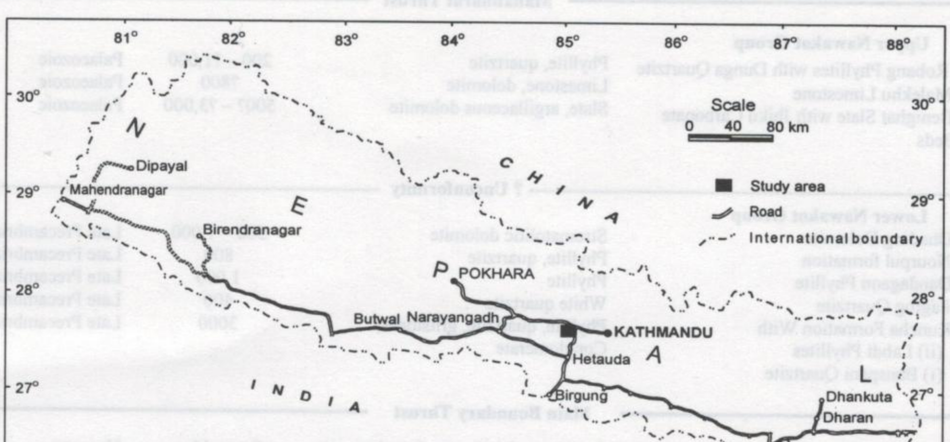

Fig. 1: Location map of the study area

arrival of floods from various tributaries to the main course (Dhital et al. 1993).

LAND USE

Owing to varied slopes and aspects, the land use pattern in the area is diverse. About 30% of the land is cultivated. The cultivated areas with many villages occupy the central and western portions of the watershed, whereas dry cultivated lands are situated in the southern parts. Farmers cultivate maize, millet, and vegetables. Wet cultivated lands appear mostly at lower altitudes where they are used for growing rice and vegetables. Other parts of north-facing slopes and rocky areas are covered by trees and bushes (Fig. 2).

GEOMORPHOLOGY

The area has varied topography. Sloping terraces predominate over the levelled ones. The southern part of the watershed is rocky hill slope and the northern one is gentle. Slopes in the watershed were divided into the following categories: less than 15°, 15°-25°, 25°-35°, 35°-45°, and greater than 45° (Fig. 3). Alluvial fans, talus deposits, river terraces, overbank deposits, point bars, and channel bars are the main geomorphological features observed along the river valleys.

ROCKS

The Agra Khola watershed lies in the Lesser Himalaya of Central Nepal. It is made up of low- to medium- grade metamorphic rocks of the Kathmandu Complex (Table 1; Fig. 4). The Kathmandu Complex is further divided into the Bhimphedi Group (Precambrian) and Phulchauki Group (Palaeozoic). The Bhimphedi Group is represented by marble (Markhu Formation), and quartzite and schist (Kulikhani Formation). Similarly, the Phulchauki Group is made up of metasandstone and phyllite (Tistung Formation), calcareous phyllite and slate (Sopyang Formation), and platy to blocky limestone (Chandragiri Limestone). Granite is found in the

Table 1: Stratigraphic subdivisions of south-central Nepal* (after Stöcklin and Bhattarai 1977; Stöcklin 1980)

Complex	Unit	Main lithology	Approximate thickness (m)	Age
A. KATHMANDU COMPLEX	**1. Phulchauki Group**			
	e) Godavari Limestone	Limestone, dolomite	3,000	Devonian
	d) Chitlang Formation	Slate	1,000	Silurian
	c) Chandragiri Limestone	Limestone	2,000	Cambro-Ordov.
	b) Sopyang Formation	Slate, calc. phyllite	200	?Cambrain
	a) Tistung Formation	Metasandstone, phyllite	3,000	Early Cambr. or late Paleaozoic
	---Transition---			
	1. Bhimphedi Group			
	f) Markhu Formation	Marble, schist	1,000	Precambrian
	e) Kulikhani Formation	Quartzite, schist	2,000	Precambrian
	d) Chisapani Quartzite	White quartzite	400	Precambrian
	c) Kalitar Formation with (iv) Jurikhet Conglomerate (iii) Pandrang Quartzite (ii) Bhimsen Dolomite (i) Lower Schist Member	Schist, quartzite partly garnetiferous	2,000	Precambrian
	b) Bhainsedobhan Marble	Marble	800	Precambrian
	a) Raduwa Formation	Garnetiferous schist	1,000	Precambrian
	Mahabharat Thrust			
B. NAWAKOT COMPLEX	**2. Upper Nawakot Group**			
	c) Robang Phyllites with Dunga Quartzite	Phyllite, quartzite	200 – ?1,000	Palaeozoic
	b) Malekhu Limestone	Limestone, dolomite	?800	Palaeozoic
	a) Benighat Slate with Jhiku Carbonate Beds	Slate, argillaceous dolomite	500? – ?3,000	Palaeozoic
	? Unconformity			
	1. Lower Nawakot Group			
	e) Dhading Dolomite	Stromatolitic dolomite	500 – 1,000	Late Precambrian
	d) Nourpul formation	Phyllite, quartzite	800	Late Precambrian
	c) Dandagaon Phyllite	Phyllite	1,000	Late Precambrian
	b) Fagfog Quartzite	White quartzite	400	Late Precambrian
	a) Kuncha Formation With (ii) Labdi Phyllites (i) Banspani Quartzite	Phyllite, quartzite, gritstones, Conglomerate	3000	Late Precambrian
	Main Boundary Thrust			
A. SIWALIK GROUP (Undifferentiated)		Sandstone, Mudstone, Conglomerate	Several km	Neogene

**Table reads upwards*

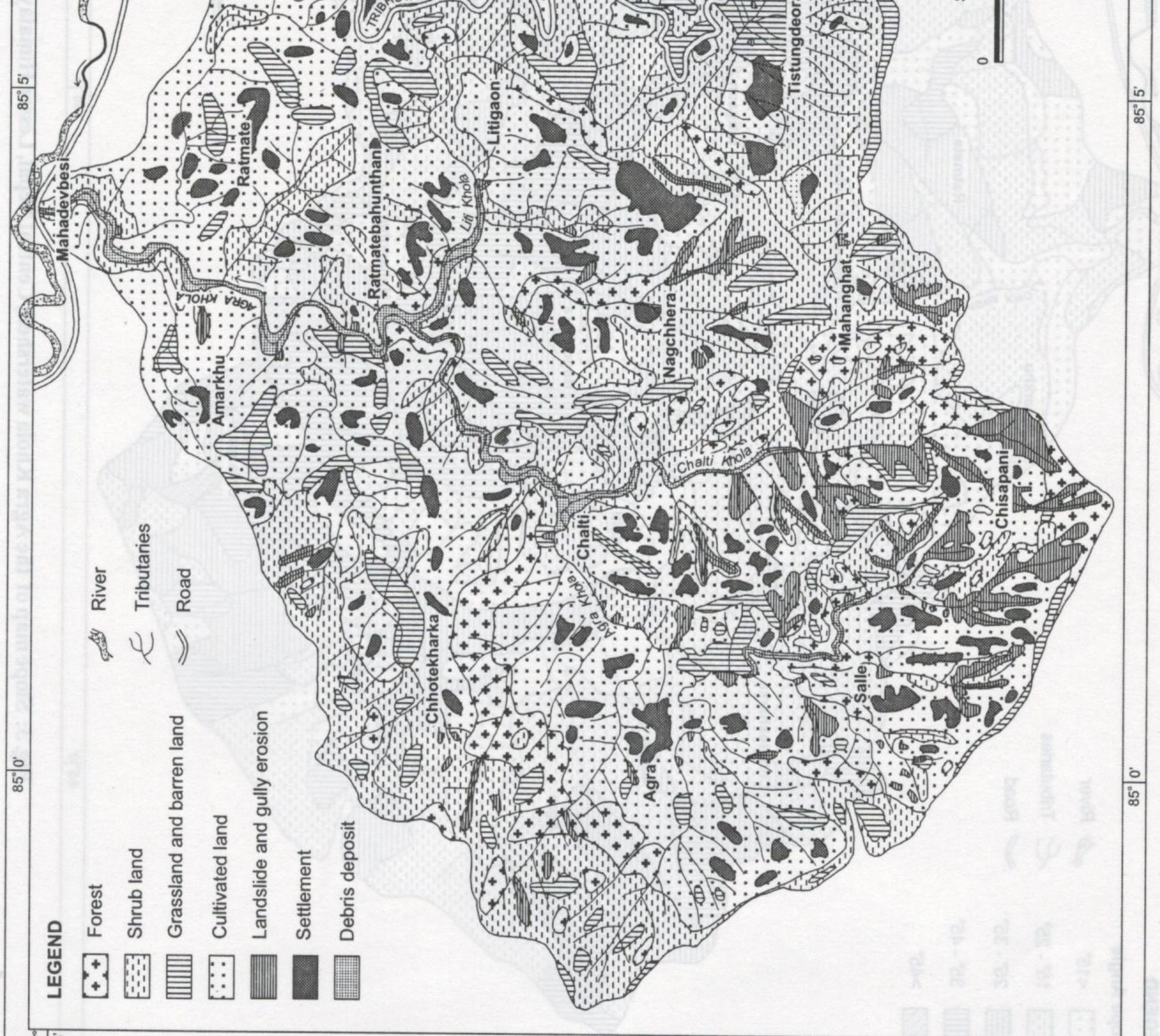

Fig. 2: Land use map of the Agra Khola watershed, Central Nepal, Lesser Himalaya

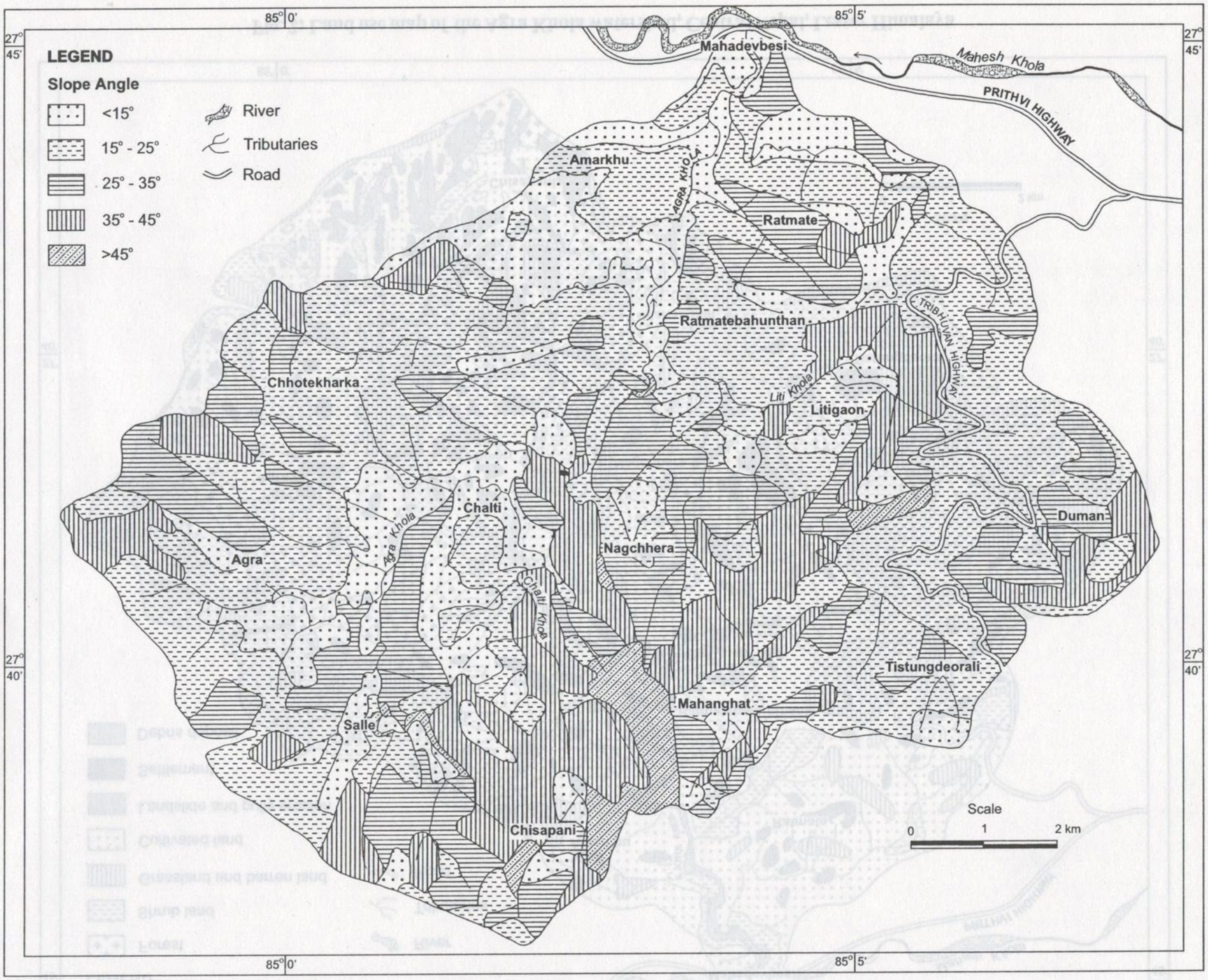

Fig. 3: Slope map of the Agra Khola watershed, Central Nepal, Lesser Himalaya

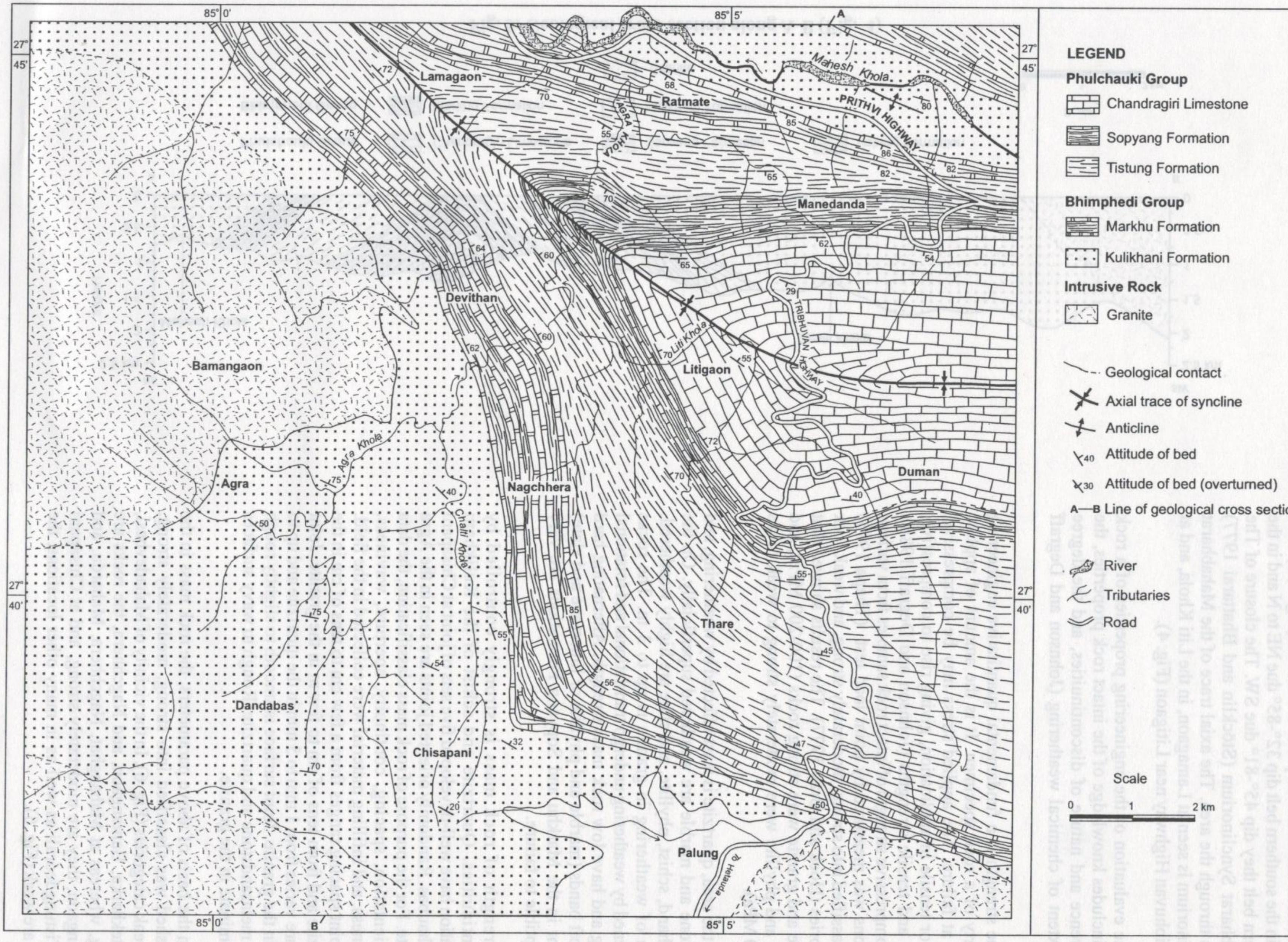

Fig. 4: Geological map of the Agra Khola area, Central Nepal, Lesser Himalaya (modified after Stöcklin and Bhattarai 1977)

northwestern and southern parts of the area (Fig. 4, 5). The rocks in the southern belt dip 32°-85° due NE to N and in the northern belt they dip 45°-81° due SW. The closure of The Mahabharat Synclinorium (Stöcklin and Bhattarai 1977) passes through the area. The axial trace of the Mahabharat Synclinorium is seen at Lamagaon, in the Liti Khola, and at the Tribhuvan Highway near Litigaon (Fig. 4).

The evaluation of the engineering properties of a rock mass includes knowledge of the intact rock properties, the occurrence and nature of discontinuities, and the degree and extent of chemical weathering (Johnson and Degraff 1988).

The strength is a fundamental quantitative engineering property of a rock specimen. It is the amount of applied stress at failure. The applied stress may be compressive, shear or tensile in application, giving rise to compressive, shear, and tensile strengths (Johnson and Degraff 1988). The compressive strength of intact rock samples from various locations was measured by point load test (Thapa 1995) and classified into strong, moderately strong, and weak rock categories (Hoek and Bray 1977). The results showed that marble and granite were strong rocks (100-200 MPa), and schist and phyllite were moderately strong to weak rocks (25-50 MPa).

In the area, quartzite is least affected by weathering, and limestone and marble are weathered superficially. On the other hand, schist, phyllite, and slate are highly weathered. Depth of weathering in granite is up to 3 m. The rocks weakened by weathering undergo translational and rotational sliding and have low rock mass strength. Alternating hard and soft bands (marble and phyllite or limestone and slate) present in the Markhu and Sopyang Formations are very susceptible to failure.

Strength of rock mass is strongly controlled by discontinuities. Quartzite and schist of the Kulikhani Formation have well-developed five sets of joint at Chisapani and Chaubas. Randomly oriented joints are seen in the Agra Granite. For the purpose of rock mass classification, the data on orientation, spacing, continuity, aperture, waviness, roughness, and infilling material were collected in the field. The joint spacing ranges from a few cm to tens of cm in the quartzite and from tens of cm to few m in the granite. Joint aperture varies from 1 mm to 5 mm in the quartzite and up to 5 cm in the granite. Joint surface is smooth to slightly rough in the metasandstone and quartzite. Rough to wavy surfaces predominate in the granite.

On the basis of above parameters, the rock mass in the watershed was classified into strong, moderately strong, and weak categories (Fig. 6). In the vicinity of Mahadevbesi, Chhotekharka, Bamangaon, and Nagchhera, the rocks are strong, whereas at Mahanghat, Nagchhera, Mahardu, and Bamangaon, they are moderately strong, and at Chisapani and Tistungdeorali as well as in many other locations, the rocks are weak (Fig. 6).

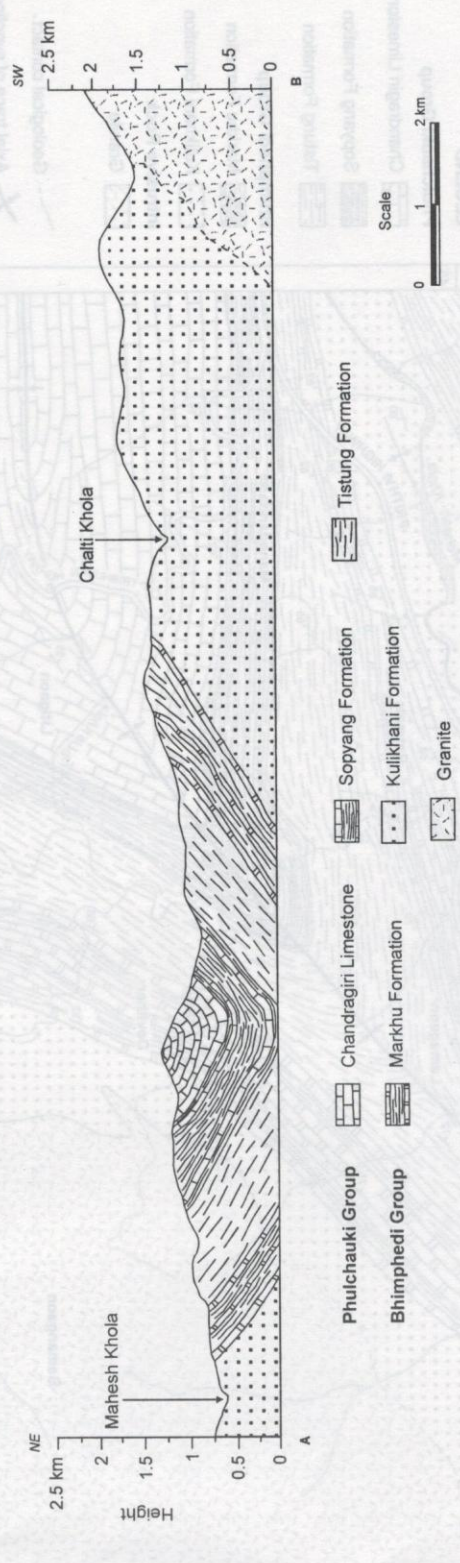

Fig. 5: Geological cross-section along A-B (Fig. 4)

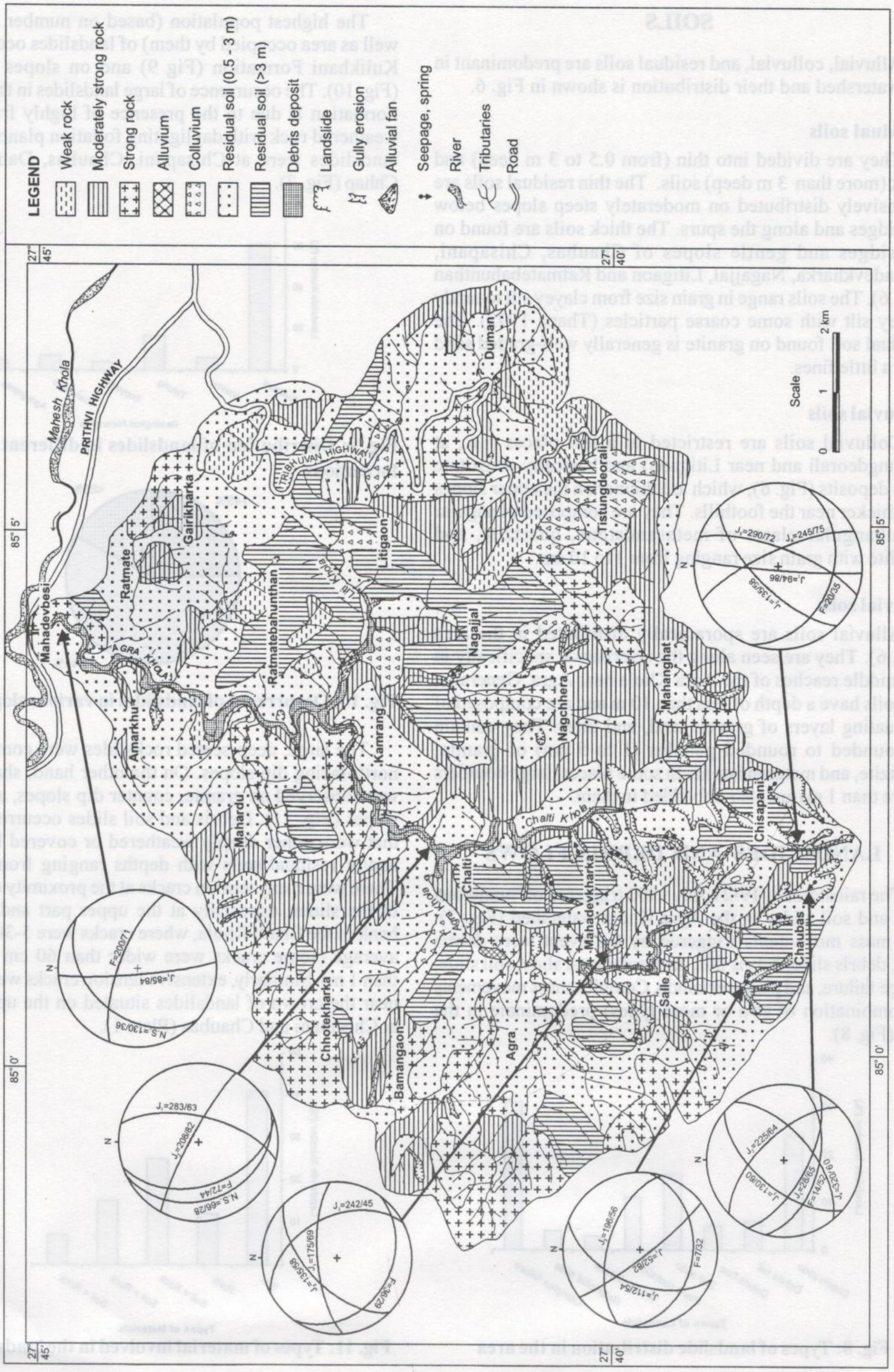

Fig. 6: Engineering geological map of the Agra Khola watershed, Central Nepal, Lesser Himalaya

SOILS

Alluvial, colluvial, and residual soils are predominant in the watershed and their distribution is shown in Fig. 6.

Residual soils

They are divided into thin (from 0.5 to 3 m deep) and thick (more than 3 m deep) soils. The thin residual soils are extensively distributed on moderately steep slopes below the ridges and along the spurs. The thick soils are found on the ridges and gentle slopes of Chaubas, Chisapani, Mahadevkharka, Nagajjal, Litigaon and Ratmatebahunthan (Fig. 6). The soils range in grain size from clayey silt to sandy clayey silt with some coarse particles (Thapa 1995). The residual soil found on granite is generally well-graded sand with a little fines.

Colluvial soils

Colluvial soils are restricted to a few places (i.e., at Tistungdeorali and near Litigaon) and basically constitute talus deposits (Fig. 6), which are thinner on the upper slopes and thicker near the foothills. They are composed of angular to subangular clasts of metasandstone, quartzite, and phyllite with grain size ranging from 1 to 10 cm.

Alluvial soils

Alluvial soils are sporadically distributed in the area (Fig. 6). They are seen along the riverbanks, specifically in the middle reaches of the Agra Khola near Agra. Generally, the soils have a depth of less than 10 m and are composed of alternating layers of gravel, sand, and fines. They contain subrounded to rounded pebbles (1 to 5 cm) of granite, quartzite, and metasandstone. In some places, large boulders (more than 1 m) are also imbedded in them.

LANDSLIDES AND DEBRIS FLOWS

The rainstorm of 19-21 July 1993 triggered off numerous rock and soil slides in the Agra Khola watershed (Fig. 7). The mass movements triggered by the event were debris flow, debris slide, debris fall, deep rotational slide, soil slide, wedge failure, and plane rockslide. Complex mass movements (a combination of two or more types) predominate in the area (Fig. 8).

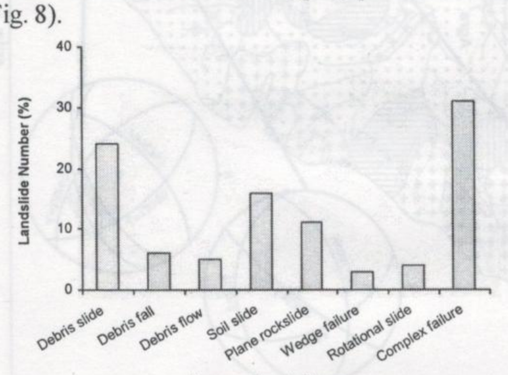

Fig. 8: Types of landslide distribution in the area

The highest population (based on number of slides as well as area occupied by them) of landslides occurred in the Kulikhani Formation (Fig 9) and on slopes of 25°-45° (Fig. 10). The occurrence of large landslides in the Kulikhani Formation is due to the presence of highly fractured and weathered rock with daylighting foliation plane. The major landslides were at Chisapani, Chaubas, Dandabas, and Chhap (Fig. 7).

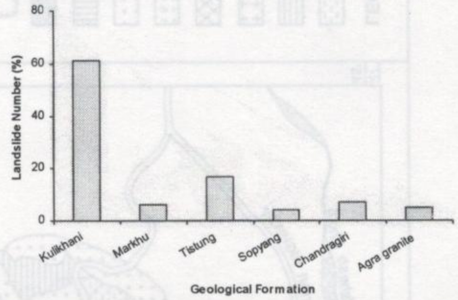

Fig. 9: Distribution of landslides in different geological formations

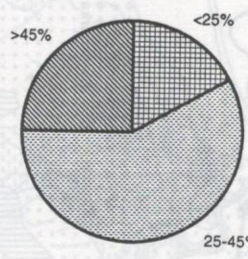

Fig. 10: Occurrence of landslides in various slopes (degree)

The large, deep-seated rockslides were common on the north-facing dip slopes. On the other hand, shallow slides were observed on granite, counter dip slopes, and thin soil slopes (Fig. 11). Debris and soil slides occurred on slopes that were either deeply weathered or covered by colluvial and/or residual soils with depths ranging from 1 to 6 m. There were many tension cracks at the proximity of the crown of the slides, especially at the upper part and on the left bank of the Chalti Khola, where cracks were 5-30 cm deep in average (some cracks were wider than 60 cm and deeper than 1 m). Similarly, extensive tension cracks were observed near the crown of landslides situated on the upper portion at Chisapani and Chaubas (Plate 1).

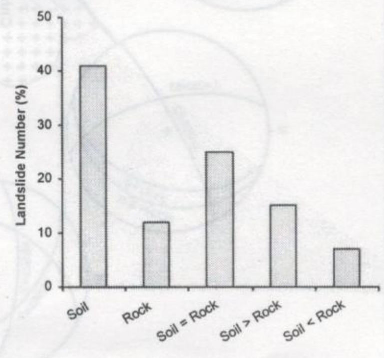

Fig. 11: Types of material involved in the landslides

Fig. 7: Landslide inventory map of the Agra Khola watersed, Cenral Nepal, Lesser Himalaya

Some landslides occurred in deforested areas and others occurred in forested areas making it difficult to conclude that deforestation caused the sliding although there was a tendency to occur more slides in agricultural areas, shrub lands, and barren lands (Fig. 12).

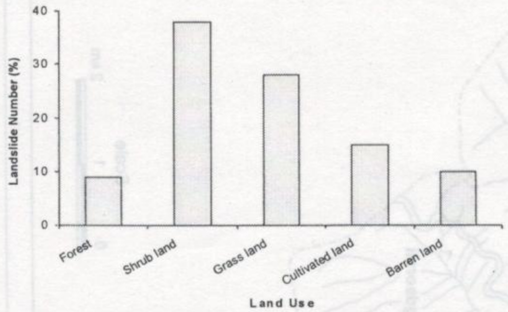

Fig. 12: Land use pattern in landslides

The material from landslides contributed a huge amount of debris. During the high flood, toe cutting accelerated the landslide along the banks and also contributed to debris. The old deposits in the upper reaches of the streams were also transported during the flood and increased the sediment outflow. The severe rainfall and high flood also caused sheet erosion, rill erosion, and contributed substantial amounts of sediment to the streams.

Debris torrents and fans seem to have blocked the tributaries resulting in huge debris flows in them. The debris flows occurred mainly in the upper reaches of the Chalti Khola, and also in the Agra Khola and Liti Khola (Fig. 2, 6). Most of the rivers deposited a huge amount of debris on the cultivated land (Plate 2). The amount of debris was great and it formed about 5 m high terraces in the Agra Khola. The grain size of the sediments was usually very coarse (several m in diameter).

A drastic change took place in riverbeds and their banks during the severe flood. After the flood, the bed levels were raised (as reported by the villagers). During the recession of flood, the river courses shifted to new locations by scouring the recently deposited debris. However, their levels were still higher than the earlier ones.

The sediment balance in the watershed is shown in Table 2. The volume of sediment produced from the landslides in the Agra Khola watershed was estimated at 20 million m^3 (DPTC/TU 1994b).

Table 2: Sediment balance (production, deposition, and transport) in the Agra Khola watershed (DPTC/TU 1994b)

Sediment production	Volume, milliom m^3	Sediment deposition	Volume, milliom m^3
By landslides	19.900	The material remaining on hill slopes (at the toe of landslides)	15.873
By erosion	0.082	In the form of suspended load	1.117
		In the form of bed load	0.222
Total	19.982	Total	17.212
Total sediment transported out of the watershed			**2.770**

ASSESSMENT OF DAMAGE

During the disaster, the upper and middle reaches of the Agra Khola, and the Chalti Khola were severely damaged by landslides (Fig. 7). A great destruction was seen at Chisapani, Chhap, and Mahadevkharka (Plate 3). Three houses were completely destroyed at Chaubas. One house situated very near to the landslide was partially damaged where extensive tension cracks were seen. However, the number of landslides was more in the middle reaches of the Agra Khola (Fig. 13). A record of damage at different places of the watershed is summarised in Table 3.

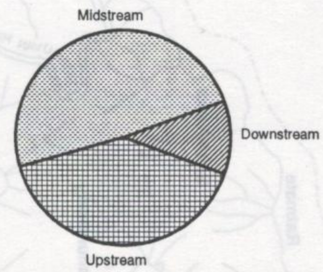

Fig. 13: Distribution of landslides in the Agra Khola watershed

Table 3: Assessment of damage in Agra Khola watershed

Types of damage or loss	Unit	Quantity
Lives	nos.	42
Completely destroyed houses	nos.	58
Partially destroyed houses	nos.	20
Animals	nos.	220
Water turbines	nos.	5
Water mills	nos.	65
Bridges	nos.	1
School	nos.	1
Land	*Ropanies*	776

The damage caused by landslides was comparatively less than that by debris flows. A large debris fan was seen at the confluence of the Agra Khola and Liti Khola (Plate 4). A debris fan was also observed at the confluence of the Agra Khola and Chalti Khola. In that area, a cemetery and several temples were washed away owing to very high (i.e., 3 m above the base level) flood. Three houses of Kaprechhap were completely destroyed. Aiselukharka is another pitiful place after the Chhap village. At Aiselukharka, 17 persons were killed and two houses were washed away. Similar event happened in the upper part of the Agra village where 11 persons were killed.

The bridge of the Prithvi Highway at Mahadevbesi was washed away early in the morning of 20 July 1993. The basic reason for bridge collapse was the low bridge height and narrow span. Generally, the river channel upstream was from 1.5 to 3 times wider than the full bridge span. Huge logs brought by river were entrapped by the piers and thus also contributed to the bridge collapse.

Plate 1: Extensive tension cracks observed near the crown of landslide at Chaubas. View towards north.

Plate 2: Debris deposited along the course of the Agra Khola, northwest of Kaprechhap, where three houses were destroyed. At this place, cultivated land was also washed away. View towards southwest.

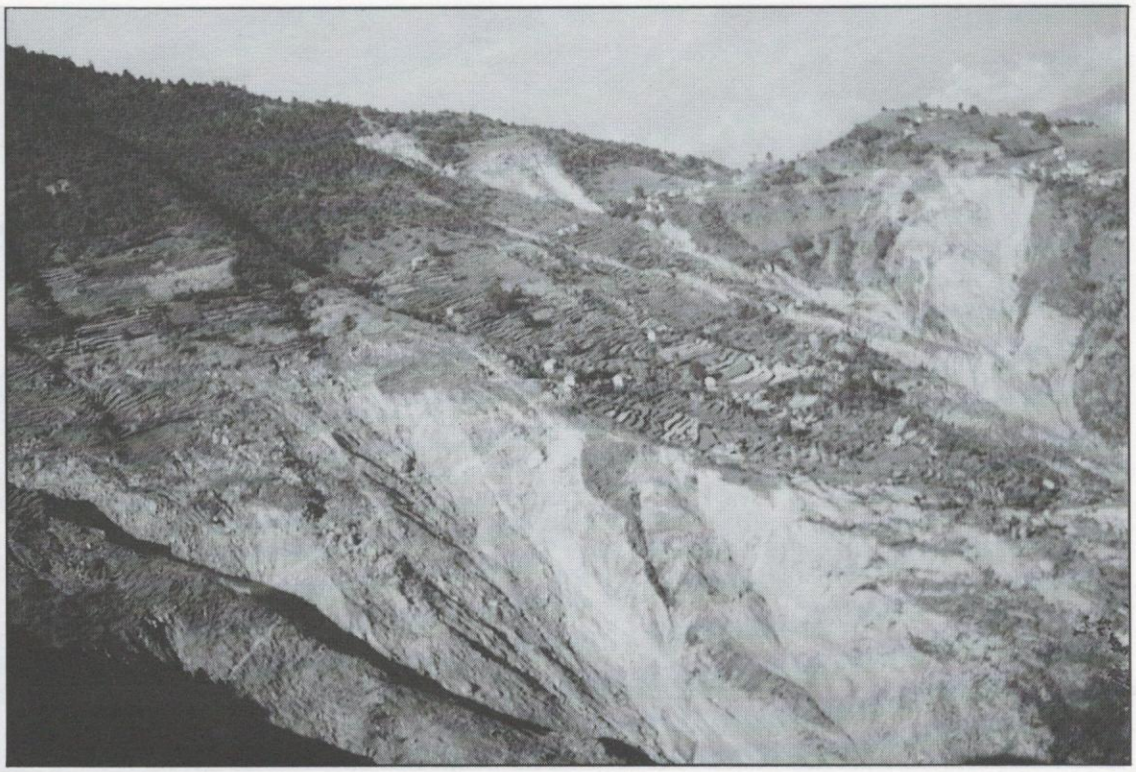

Plate 3: Vulnerable position of the village of Chisapani, situated between two large landslides. The entire village area is creeping. View towards southwest.

Plate 4: A large debris fan at the confluence of the Liti Khola and the Agra Khola. View towards southwest.

Part of the Tribhuvan Highway (38 km to 65 km from Kathmandu), which lies in the Agra Khola watershed, also suffered from rock and soil slides. The road below the Duman village was severely damaged and transportation was also obstructed for a few days.

HAZARD ASSESSMENT

Hazard is probability of occurrence within a specified period of time and within given areas of a potentially damaging phenomenon (Varnes 1984). It is the source of risk that may cause damage to or loss of life and property. Hazard may be classified as relative hazard, absolute hazard, and monitored hazard (Hartlen and Viberg 1988). Relative hazard is assessed by assigning ratings to different factors contributing to hazard. Absolute hazard is expressed deterministically, e.g. factor safety, or probabilistically. Monitored hazard is assessed by the actual measurement of the effects, e.g. deformations (Hartlen and Viberg 1988).

The relative hazard map was prepared by adding ratings for various hazard components. For this purpose, the areas covered by soil and rock were rated separately (Tables 4, 5; Fig. 14) and many overlays were used (Fig. 2,3,4,6,7). The rock and soil hazard levels were classified into low, medium, and high (Table 6). Examples of rock and soil slope ratings are presented in Tables 7 and 8.

Table 4: Soil slope hazard rating (modified after Deoja et al. 1991)

S. N.	Attributes	Characteristics		Rating
		Types of soil	Slope angle in degrees	
1	Soil type/slope angle	Alluvium	<15	0.05
			15 – 25	0.06
			26 – 35	0.12
			36 – 45	0.08
			>45	0.10
		Residual	<15	0.06
			15 – 25	0.07
			26 – 35	0.14
			36 – 45	0.10
			>45	0.12
		Colluvium	<15	0.07
			15 – 25	0.08
			26 – 35	0.15
			36 – 45	0.13
			>45	0.14
2	Soil thickness	0.5 m–3 m		0.07
		>3 m		0.10
3	Land use	Forest		0.00
		Shrub land		0.05
		Grassland		0.07
		Cultivated land		0.10
		Barren land		0.12
4	Drainage	Dry tributaries		0.07
		Stream		0.09
		River		0.13
5	Hydrogeology	No seeps, no springs		0.00
		Dry and rain induced springs and seeps		0.08
		Permanent springs and seeps		0.14
6	Landslide and gully erosion	Small landslide and gully erosion		0.18
		Large landslide and gully erosion		0.27
7	Sign of instability	Tilted trees		0.15
		Tension cracks		0.21
		Tension cracks and tilted trees		0.25
8	Tectonics	Major synclinal axis		0.06
		Minor faults		0.09

Table 5: Rock slope hazard rating (modified after Deoja et al. 1991)

S. N.	Attributes	Characteristics				Rating
		Central wedge (Number)	Lateral wedge (Number)	Plane failure	Topple failure	
1	Expected types of failure	0	0	0	0	0.00
		0	0	0	0 or 1	0.02
		0	1	0	0 or 1	0.03
		0	>1	0	0 or 1	0.05
		0	0	1	0 or 1	0.04
		0	1	1	0 or 1	0.08
		0	>1	1	0 or 1	0.10
		1	0	0	0 or 1	0.06
		1	1	0	0 or 1	0.09
		1	>1	0	0 cr 1	0.13
		1	0	1	0 or 1	0.11
		1	1	1	0 or 1	0.15
		1	>1	1	0 or 1	0.20
		>1	0	0	0 or 1	0.09
		>1	1	0	0 or 1	0.13
		>1	>1	0	0 or 1	0.19
		>1	0	1	0 or 1	0.16
		>1	1	1	0 or 1	0.20
		>1	>1	1	0 or 1	0.25
		Possible unknown type of failure				0.20
2	Hydrogeology	No seeps, no springs				0.00
		Dry and rain induced springs and seeps				0.04
		Permanent springs and seeps				0.07
3	Drainage	Dry tributaries				0.01
		Seasonal perennial streams (<2 m deep)				0.03
		Seasonal perennial streams (>2 m deep)				0.05
		River				0.07
4	Rock type	Quartzite, marble and limestone				0.02
		Calcareous phyllite and slate				0.05
		Phyllite and schist				0.09
		Alternating/interbedded hard and soft rock				0.10
5	Discontinuity spacing	Wide (>1 m wide)				0.00
		Moderate (1 m–30 cm)				0.02
		Close (30 cm–5 cm)				0.04
		Very tight (<5 cm)				0.06
6	Discontinuity width	<0.1 mm				0.01
		0.1 mm–1 mm				0.02
		1 mm–5 mm				0.03
		> 5 mm				0.04
7	Rock weathering	Fresh				0.00
		Slightly weathered				0.01
		Moderately weathered				0.03
		Highly weathered				0.05
		Completely weathered				0.07
8	Tectonics	Major synclinal axis				0.02
		Minor fault				0.05
9	Land use	Forest				0.00
		Shrub land				0.03
		Barren land				0.05
10	Slope angle	Gentle (<15°)				0.00
		Slightly steep (16°–25°)				0.01
		Moderately steep (26°–35°)				0.07
		Steep (36°–45°)				0.04
		Very steep (>45°)				0.05
11	Rockslide	Small rockslide				0.10
		Large rockslide				0.17
12	Sign of instability	Tilted trees				0.08
		Tension cracks				0.10
		Tension cracks with tilted trees				0.13

Table 6: Hazard level classification

Hazard level	Total rating
Low	<0.40
Medium	0.40–0.70
High	>0.70

Fig. 14: Hazard map of the Agra Khola watershed, Central Nepal, Lesser Himalaya

Table 7: Examples soil slope hazard rating (location numbers in Fig. 14)

Location No.	Hazard parameters (see Table 4) 1	2	3	4	5	6	7	8	Total rating	Hazard level
1	0.14	0.10	0.10	0.09	0.08	-	0.21	0.09	0.81	High
2	0.14	0.07	0.07	0.09	0.14	0.27	-	0.09	0.87	High
3	0.14	0.07	0.10	0.13	0.00	0.27	-	-	0.71	High
4	0.07	0.10	0.10	0.13	0.14	0.27	-	-	0.81	High
5	0.07	0.07	0.10	0.00	0.08	0.18	-	-	0.50	Medium
6	0.06	0.10	0.10	0.09	0.08	0.18	-	-	0.61	Medium
7	0.10	0.07	0.05	0.09	0.00	0.00	-	-	0.31	Low
8	0.07	0.10	0.10	0.07	-	-	-	-	0.34	Low

Table 8: Examples of rock slope hazard rating (location numbers in Fig. 14)

Location No.	Hazard parameters (see Table 5) 1	2	3	4	5	6	7	8	9	10	11	12	Total rating	Hazard level
9	0.19	0.07	0.05	0.10	0.04	0.03	0.03	0.05	0.00	0.07	0.17	-	0.80	High
10	0.20	0.04	0.05	0.10	0.04	0.03	0.03	-	0.03	0.04	0.17	-	0.73	High
11	0.10	-	0.07	0.10	0.06	0.02	0.01	-	0.03	0.01	0.10	-	0.50	Medium
12	-	0.04	0.03	0.10	0.04	0.03	0.03	-	0.03	0.04	-	0.13	0.47	Medium
13	0.05	0.00	0.07	0.05	0.02	0.03	0.01	0.02	0.01	-	-	-	0.26	Low
14	-	0.04	0.03	0.09	0.02	0.04	0.05	0.05	0.05	-	-	-	0.37	Low

Various types of hazard and their categories are shown in Fig. 14. High hazard areas are confined in the vicinity of Chisapani, Chaubas, Salle, Tistungdeorali, Duman, and Amarkhu. The upper reaches, especially after the confluence of the Agra Khola and the Chalti Khola are highly hazardous. Medium and low hazard areas are found in the middle reaches and northern part of the watershed (at Agra, Chhotekharka, Nagchhera, Litigaon, Ratmate, and Ratmatebahunthan) with some high hazard zones in between.

CONCLUSIONS

The number of landslides and the extent of inundation during the rainstorm of July 19-21, 1993 were extraordinarily high in the Agra Khola watershed. There were more than 107 landslides within the watershed. Mass movements were mainly deep rotational slides, shallow soil slides, rockslides and debris flows. The upper reaches of the watershed are severely damaged especially around Chisapani, Chaubas, and Chhap. Maximum per cent of landslides was found in the Kulikhani Formation and on natural slopes with angles of 25°-45°. The occurrence of large landslides in the Kulikhani Formation is due to the presence of highly fractured and weathered rock with daylighting foliation planes.

In this region, similar disaster may recur if the same type of heavy rainfall occurs again. Debris flows may occur in the middle reaches of the Agra Khola, whereas, severe gully erosion, landslides, and debris flows may happen in the upper reaches of the Liti Khola. The areas of low hazard are considered to be safe, the medium hazard zones can be made stable with some mitigation measures, but the high hazard zones are not suitable for construction and agricultural use.

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