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Landslide hazard mapping in the Nallu Khola watershed, Central Nepal

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ABSTRACT

This paper deals with landslide hazard mapping in the Nallu Khola watershed of Central Nepal. The study reveals that slope class 30°-40° is highly susceptible to sliding. The highest landslide density is seen on 35° slope with drainage frequency of 40-50 no./km². Similarly, the lowest landslide density is found associated with the lowest average slope gradient and lowest drainage density.

Landslide hazard map shows that the high, medium, and low hazard areas occupy respectively 20%, 45%, and 35% of the watershed. Similarly, the landslide density is the highest in the cells that are categorised as high hazard. The highest number of landslide containing cells in high hazard rank suggests that the forecasted hazard ranks nearly match with the present field conditions. But there are some areas, where forecasted hazard ranks do not match with the present field conditions.

INTRODUCTION

Stability of land is indispensable for the safety of human life and development of infrastructure. The inherent unstable nature of mountain areas is expressed in terms of soil erosion, landslides, and debris flows. Landslides are the most common natural hazards in Nepal, where more than 80% of the area is mountainous (DPTC 1998). In addition, soil fertility or land productivity deteriorates in the mountains, and flooding and sedimentation occurs in the lowlands. Landslides and floods alone claimed more than 4,200 human lives during the period from 1984 to 1993 (MOH 1994). Many villages in Nepal are situated on or adjacent to unstable slopes. A systematic study of landslides including hazard mapping and risk assessment on a larger scale has not been undertaken yet in Nepal (Upreti and Dhital 1996). Landslide hazard maps are useful for planning and implementing developmental schemes in mountain areas. In this background, landslide hazard mapping based on soil characteristics and geomorphological analysis was carried out in the Nallu Khola watershed of Central Nepal (Fig. 1). The Study was carried out in various phases from pre-fieldwork to processing and intergration of data to produce the landslide hazard map (Fig. 2).

STUDY AREA

The Nallu Khola watershed lies between 27°32' N and 27°34' N latitudes, and 85°19' E and 85°25' E longitudes. The watershed occupies an area of 16.04 km² in the Lalitpur District and is about 19 km south of Kathmandu (Fig. 1). The climate is subtropical (<2000 m) to lower temperate with mean annual rainfall of 1889 mm (DPTC 1993). Some physiographic and geomorphological characteristics of the watershed are given in Table 1.

The rocks of the Phulchauki Group of the Kathmandu Complex (i.e., the Tistung Formation, Sopyang Formation, Chitlang Formation, and Chandragiri Limestone) are present in the Nallu Khola watershed (Stöcklin and

Table 1: Physiographic and geomorphological characteristics of Nallu Khola watershed

Attribute	Unit	Dimension
Area	(km²)	16.04
Land use	(km²)	
Cultivated land		7.07 (44%)
Shrub land		2.34 (15%)
Forest		6.46 (40%)
Other		0.16 (1%)
Elevation	(m)	
Highest		2625
Lowest		1600
Relief	(m)	1025
Main stream length	(km)	9.8
Average slope	(degree)	26
Drainage density	(km/ km²)	4.6
Drainage frequency	(No./ km²)	
1st Order		7.1
2nd Order		2.2
3rd Order		0.4
4th Order		0.1

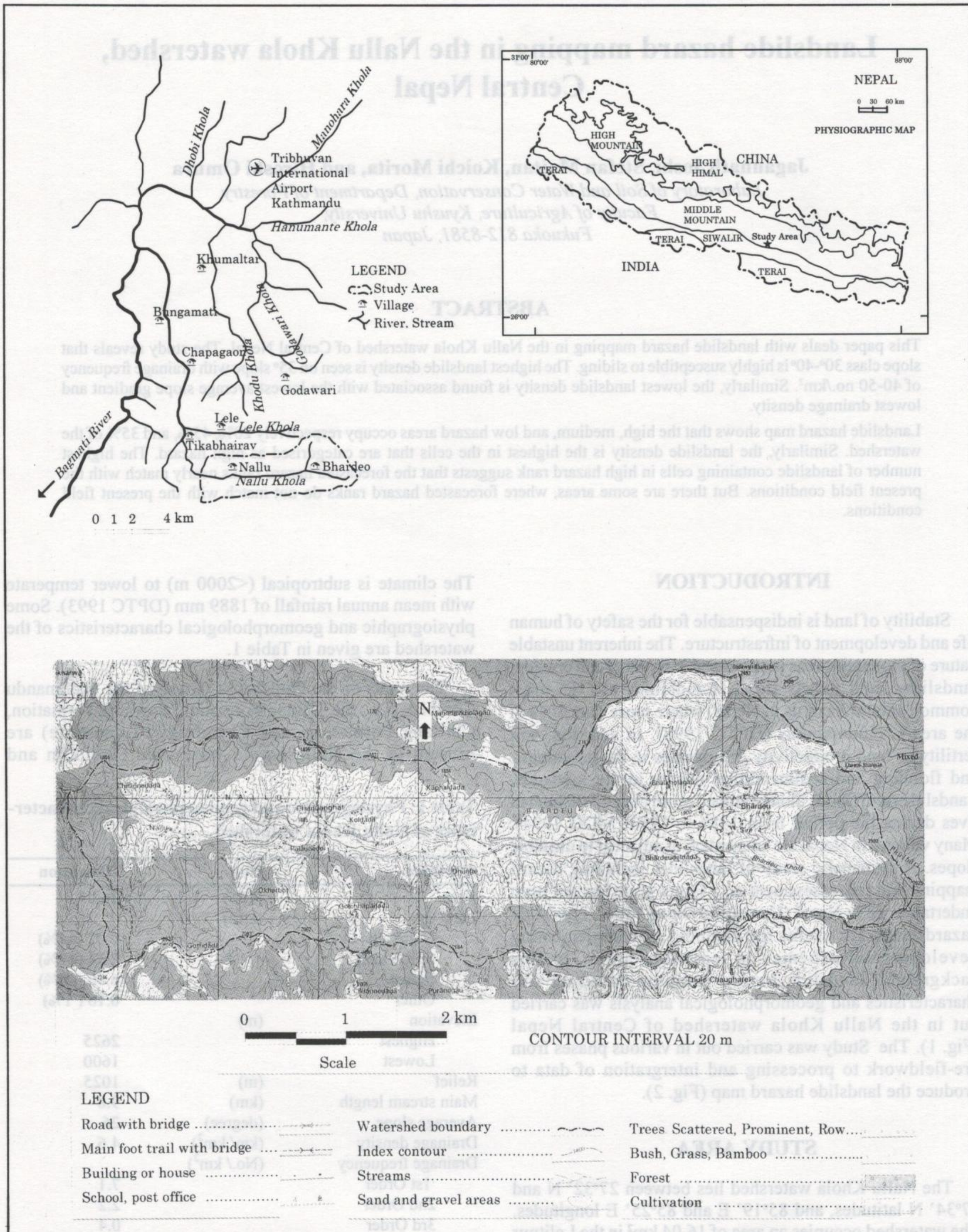

Fig. 1: Location map of the study area

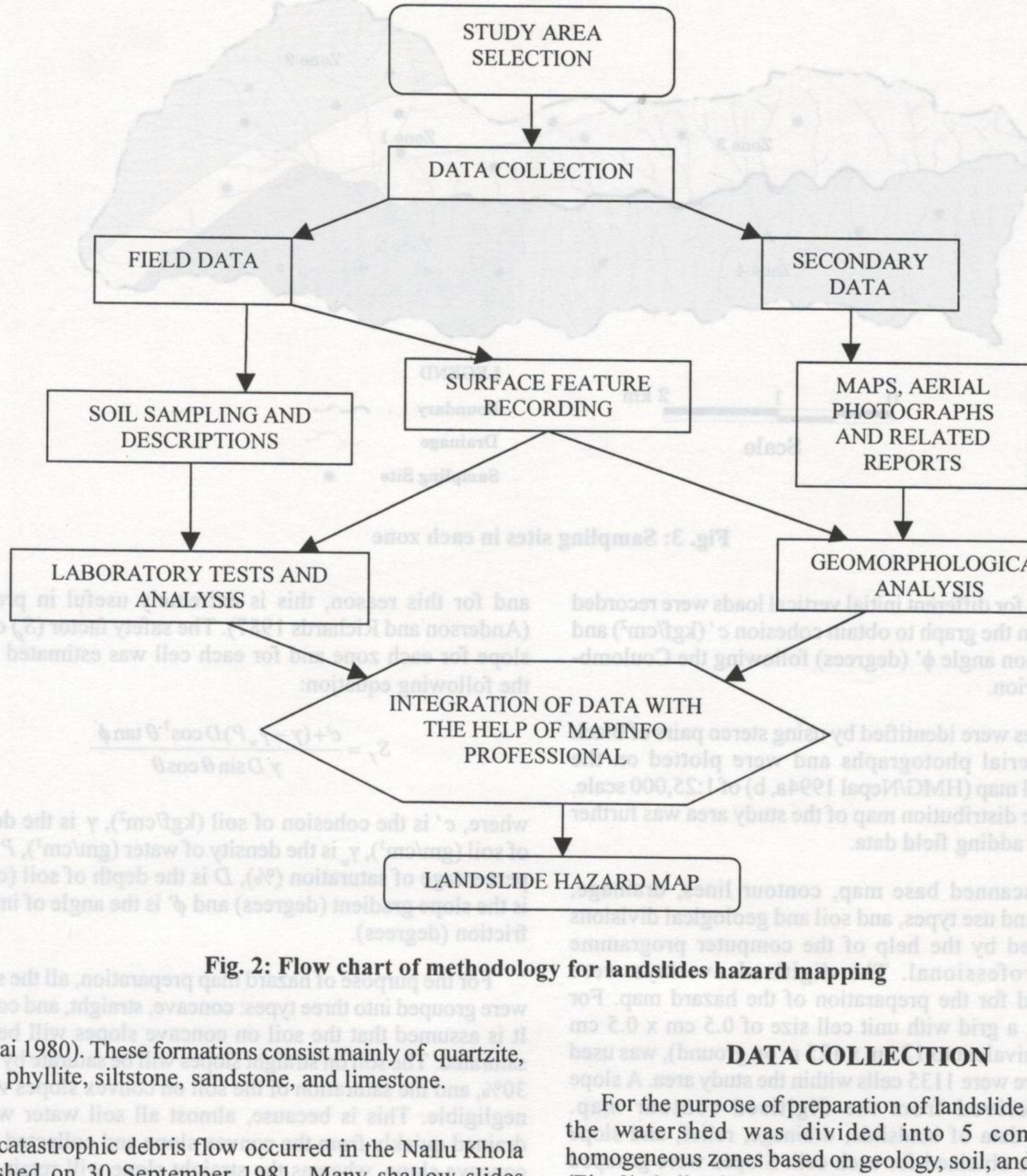

Fig. 2: Flow chart of methodology for landslides hazard mapping

Bhattrai 1980). These formations consist mainly of quartzite, slates, phyllite, siltstone, sandstone, and limestone.

A catastrophic debris flow occurred in the Nallu Khola watershed on 30 September 1981. Many shallow slides occurred on the upper reaches of the streams and gullies, and the sediments derived from them gave rise to debris flows while moving downstream. The disaster killed 55 people, destroyed many houses and temples, damaged large stretches of road and irrigation canal, and washed away valuable cultivated land. The disaster occurred after a continuous rainfall for 5 days, from 25 to 30 September. A total rainfall of 266.7 mm was recorded during that period. The rainfall on 30 September was particularly intense for about 3 hours, just before the occurrence of the debris flows, and its maximum intensity was 56.1 mm/hour. The return period of this rainfall is estimated at 20 years (DPTC 1993).

DATA COLLECTION

For the purpose of preparation of landslide hazard map, the watershed was divided into 5 comparatively homogeneous zones based on geology, soil, and topography (Fig. 3). Soil colours were distinguished by comparing with Revised Standard Soil Colour Charts (Research Council for Agriculture, Forestry and Fisheries, Japan 1989). Four soil samples were collected from each zone and the following physical and mechanical properties were determined in the laboratory.

Particle size analysis of soil samples was carried out by the hydrometer method (Scott 1963). Liquid limit tests were carried out by Casagrande's technique (Soil Mechanics Engineering Society, Japan 1979). Direct shear tests of air dry as well as saturated soil samples were carried out in fully drained conditions. The dry weight, void ratio, and water content of soils were also determined. Normal and

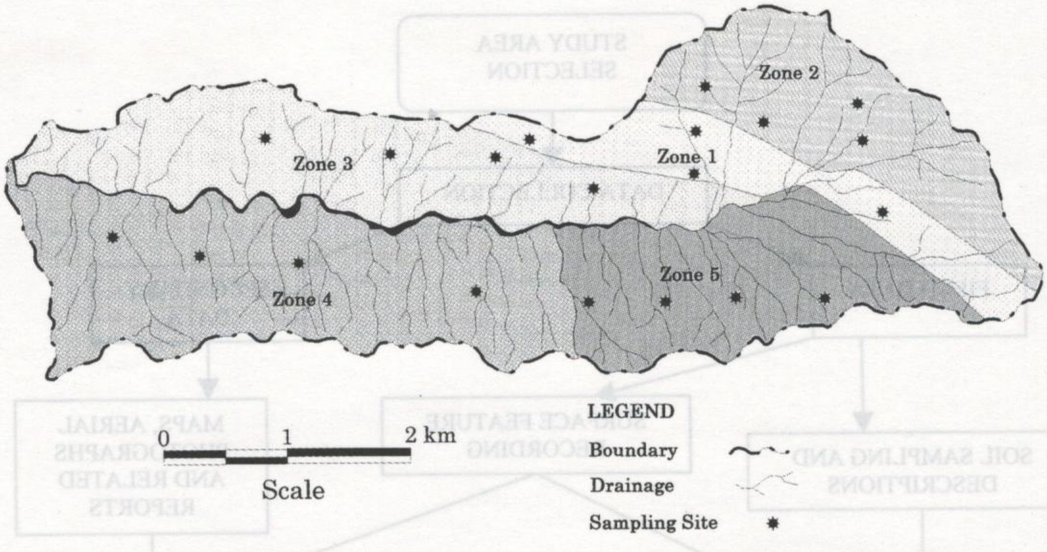

Fig. 3: Sampling sites in each zone

shear stresses for different initial vertical loads were recorded and plotted on the graph to obtain cohesion c' (kgf/cm^2) and internal friction angle ϕ' (degrees) following the Coulomb-Mohr's criterion.

Landslides were identified by using stereo pairs of black and white aerial photographs and were plotted on the topographical map (HMG/Nepal 1994a, b) of 1:25,000 scale. The landslide distribution map of the study area was further improved by adding field data.

From a scanned base map, contour lines, drainage, landslides, land use types, and soil and geological divisions were digitised by the help of the computer programme MapInfo Professional. The digitised overlays were superimposed for the preparation of the hazard map. For this purpose, a grid with unit cell size of 0.5 cm x 0.5 cm (which is equivalent to 125 m x 125 m on ground), was used (Fig. 4). There were 1135 cells within the study area. A slope map was derived from the digitised contour map. Quantitative data of landslide, drainage, relief, and slope gradient were obtained for each cell. Slopes were grouped into the following classes: up to 10°, 10° to 20°, 20° to 30°, 30° to 40°, 40° to 50°, and more than 50°. The area covered by each slope class was computed. Drainage frequency (f) or landslide density (d) in each slope class were estimated using the equation:

$$f \text{ or } d = \frac{\sum n}{\sum a}$$

where, n is the number of drainage (or landslide) within a cell, and a is the area of the cell.

The infinite slope analysis method was employed for the calculation of safety factor of slopes. This method is simple to use since there is a linear equation for the factor of safety, and for this reason, this is extremely useful in practice (Anderson and Richards 1987). The safety factor (S_f) of soil slope for each zone and for each cell was estimated using the following equation:

$$S_f = \frac{c' + (\gamma - \gamma_w P) D \cos^2\theta \tan\phi'}{\gamma D \sin\theta \cos\theta}$$

where, c' is the cohesion of soil (kgf/cm^2), γ is the density of soil (gm/cm^3), γ_w is the density of water (gm/cm^3), P is the percentage of saturation (%), D is the depth of soil (cm), θ is the slope gradient (degrees) and ϕ' is the angle of internal friction (degrees).

For the purpose of hazard map preparation, all the slopes were grouped into three types: concave, straight, and convex. It is assumed that the soil on concave slopes will be fully saturated. The soil on straight slopes will be saturate by about 30%, and the saturation of the soil on convex slopes will be negligible. This is because, almost all soil water will be drained quickly from the convex slope and collected in the concave slope, whereas the straight slope will retain some water making the soil moist. On the basis of these assumptions, the safety factor was computed for each cell and the values were grouped into the following three categories for hazard ranking: $S_f < 1$: high hazard; $S_f = 1\text{-}4$: medium hazard; and $S_f > 4$: low hazard.

RESULTS AND DISCUSSION

The Nallu Khola watershed is dissected by north-, west- and south-facing drainage systems with average density of 4.6 km/km^2. About 70 per cent of the area is steeper than 20° (Fig. 5). Generally, the drainage frequency decreases with increasing slope angle, whereas the landslide density

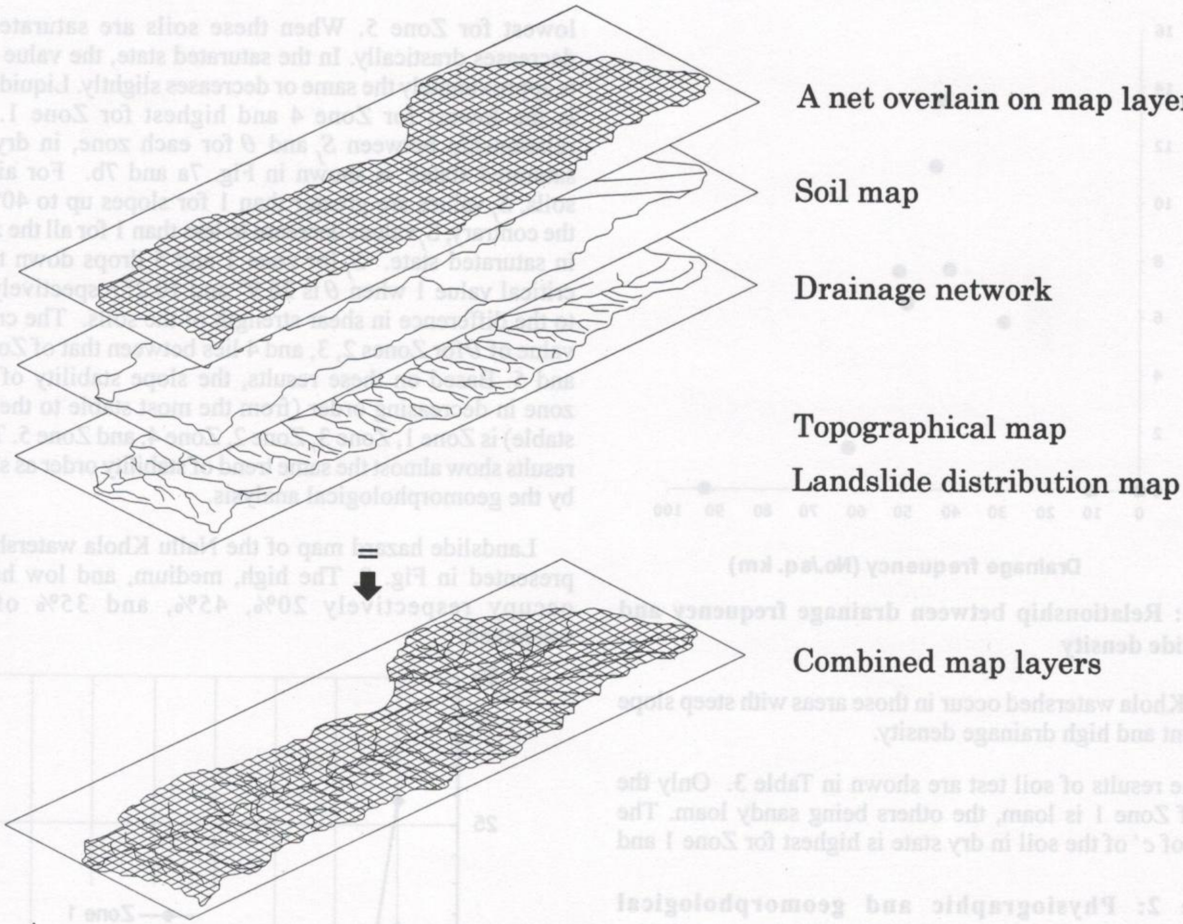

Fig. 4: A net overlaid on different thematic map layers

shows the reverse trend up to 35°, it is constant between 35° and 45°, and then gradually decreases. The trend of landslide density curve shows a maximum near 40°. It is related to the fact that the slope steeper than 40° contains thin soil cover. This result supports an earlier study (Dikshit 1994) that the natural hill slopes with gradient between 30° and 40° are found to be most critical for failure in Nepal. A study of landslides in Japan by Koide (1955) revealed similar results, where he found that the 35° slope was the most susceptible to sliding. Fig. 6 shows that the highest landslide density (13.5 no./km^2) lies between the drainage frequencies of 40 and 50 no./km^2.

The geomorphological characteristics and soil properties in the 5 zones differ considerably (Table 2, 3). Consequently, the distribution of landslides in them is also not uniform. The highest density of recent landslide scarps is observed in Zone 5, which corresponds to the highest drainage density in the same zone. On the other hand, the low density of recent landslides in Zones 3 and 1 is related to their lower values of average slope gradient and drainage density. The highest density of old landslide scarps is observed in Zone 2, where the average slope is the steepest among the 5 zones. Based on these results, it can be stated that the landslides in the

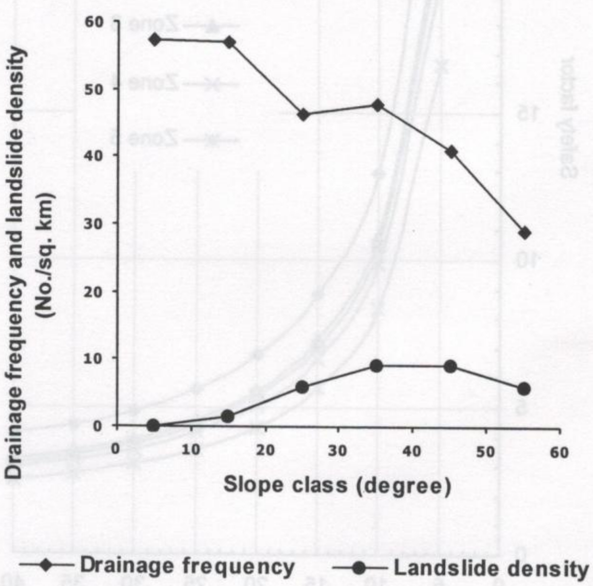

Fig. 5: Relationship between slope gradient, drainage frequency, and landslide density

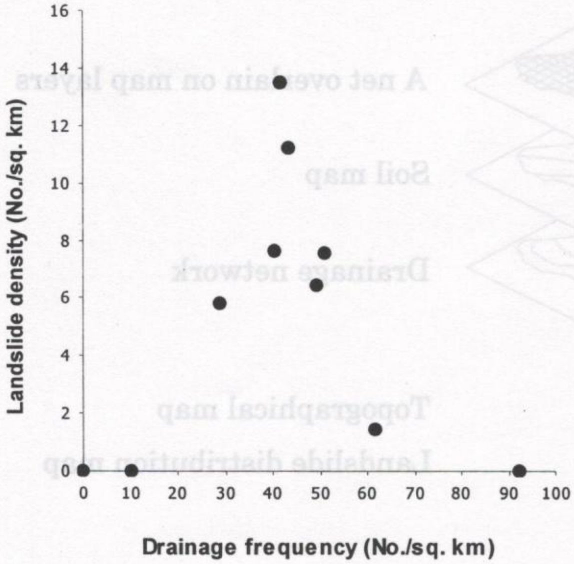

Fig. 6: Relationship between drainage frequency and landslide density

Nallu Khola watershed occur in those areas with steep slope gradient and high drainage density.

The results of soil test are shown in Table 3. Only the soil of Zone 1 is loam, the others being sandy loam. The value of *c'* of the soil in dry state is highest for Zone 1 and lowest for Zone 5. When these soils are saturated, *c'* decreases drastically. In the saturated state, the value of ϕ' is approximately the same or decreases slightly. Liquid limit is the lowest for Zone 4 and highest for Zone 1. The relationship between S_f and θ for each zone, in dry and saturated states, is shown in Fig. 7a and 7b. For air dry soils, S_f values are greater than 1 for slopes up to 40°. On the contrary, S_f values decrease to less than 1 for all the zones in saturated state. S_f for zone 1 and 5 drops down to the critical value 1 when θ is 26.9° and 10.2° respectively due to the difference in shear strength of the soils. The critical value of θ for Zones 2, 3, and 4 lies between that of Zones 1 and 5. Based on these results, the slope stability of each zone in decreasing order (from the most stable to the least stable) is Zone 1, Zone 3, Zone 2, Zone 4, and Zone 5. These results show almost the same trend of stability order as shown by the geomorphological analysis.

Table 2: Physiographic and geomorphological characteristics of five zones of Nallu Khola watershed

Characteristics	Zones				
	1	2	3	4	5
Area (km^2)	1.69	2.66	3.84	4.93	2.92
Soil color	10R 6/8	2.5YR 7/1	2.5YR 7/4	7.5YR 8/3	5YR 7/6
Rock type	A	B	C	D	E
Soil depth (m)	3.0±1.2	1.9±0.9	3.4±2.8	2.5±1.2	1.9±1.3
Average Elevation (m)	2080	2250	1840	1890	2010
Average slope (degrees)	30.73	37.77	24.82	30.21	28.09
Drainage density (km/km^2)	5.14	7.47	6.98	8.23	10.99
Landslide density (No./km^2)					
Recent landslide scars	4.73	7.89	3.39	8.72	14.38
Old landslide scars	5.92	17.67	11.72	2.23	5.48
Total	10.65	25.56	15.10	10.95	19.86

10R6/8 : Reddish orange, 2.5YR7/1 : Light reddish gray,
2.5YR7/4 : Pale reddish orange, 7.5YR8/3 : Light yellow orange,
5YR7/6 : Orange, A: Argillaceous and marly slate, thin limestone;
B : Light, fine-crystalline limestone, partly siliceous; C : Sandstone, siltstone, sandy limestone; D : Siltstone, sandstone, phyllite; E : Phyllite, sandstone, siltstone.

Table 3: Geotechenical characteristics of soils

Soil Characteristics	Zones				
	1	2	3	4	5
Textural class	Loam	Sandy Loam	Sandy Loam	Sandy Loam	Sandy Loam
Particle size distribution					
Sand (%)	52.90	60.90	56.90	52.90	58.90
Silt (%)	32.80	34.80	30.80	34.80	34.80
Clay (%)	14.30	4.30	12.30	12.30	6.30
Cohesion (kgf/cm^2)					
Air dry	0.623	0.251	0.506	0.311	0.193
Saturated	0.084	0.001	0.066	0.003	0.010
ϕ (degree)					
Air dry	28.19	35.75	33.62	32.62	25.55
Liquid limit (%)	47.50	47.00	45.50	39.00	46.00
Bulk density (gm/cm^3)	1.22 ±0.03	1.20 ±0.05	1.23 ±0.04	1.17 ±0.04	1.10 ±0.06

Landslide hazard map of the Nallu Khola watershed is presented in Fig. 8. The high, medium, and low hazard occupy respectively 20%, 45%, and 35% of the watershed.

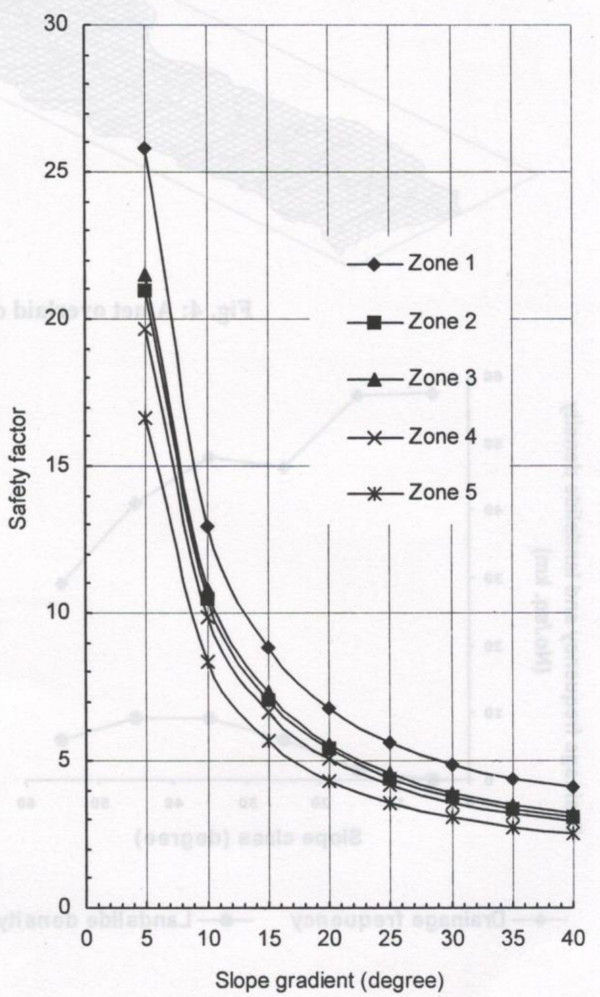

Fig. 7(a): Relationship between safety factor and slope gradient in air dry state

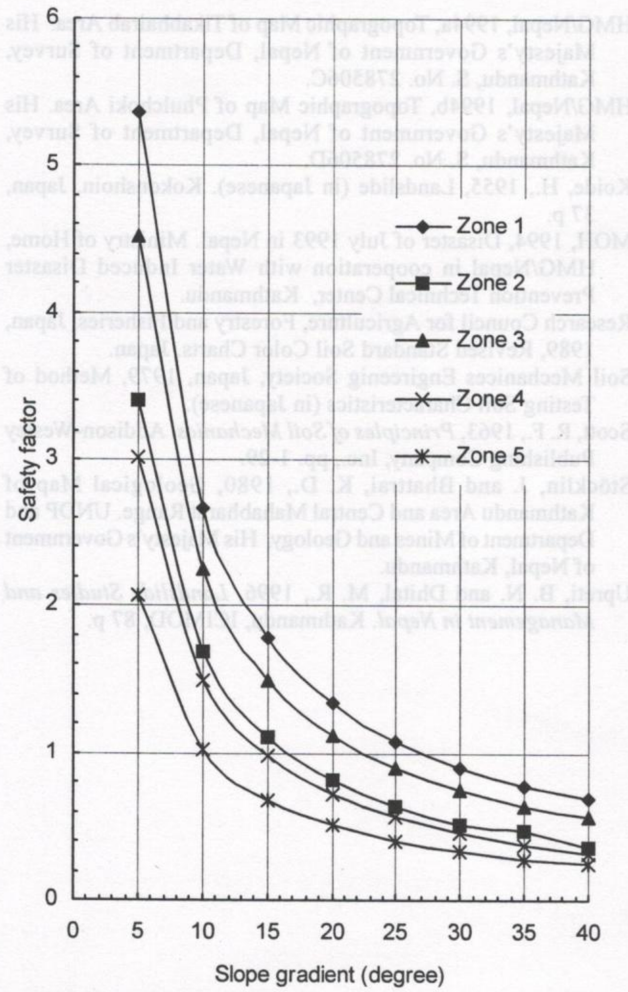

Fig. 7(b): Relationship between safety factor and slope gradient in saturated state

Table 4 shows the number of landslides falling in a unit cell for each hazard rank. The highest percentage of landslide-containing cells in the high hazard rank suggests that the forecasted hazard ranks nearly match with the existing field conditions. But the occurrence of some landslide-containing cells in low hazard areas suggests that still there are some errors in the methodology, which need to be corrected in order to achieve accurate results.

Table 4: Comparision of forecasted hazard rank and number of grid cells in which landslides exist.

Forcasted hazard	Total number of cells	Number of cells in which landslides exist (No.)	(%)	Number of cells in which landslides do not exist (No.)	(%)	Number of landslides (No.)
High	233	32	14	201	86	52
Medium	510	29	6	481	94	47
Low	392	27	7	365	93	28
Total	1135	88		1047		127

CONCLUSIONS

All the soils of the Nallu Khola watershed are almost similar in texture except for the soil of Zone 1. But, the shear strength of the soils varies greatly in dry and saturated states. Consequently, the safety factor of slopes also varies in the same way. Based on the safety factor, comparatively high, medium, and low landslide hazard areas are identified, which are further verified by comparing with landslide density and drainage frequency. The slope stability of each zone corresponds to the geomorphological characteristics. Soil characteristics and geomorphology of the watershed are interrelated and the combined effect of both plays a major role in the slope stability. The forecasted hazard ranks nearly match with the existing field conditions in most of the areas. But, still there are some areas where forecasted hazard ranks

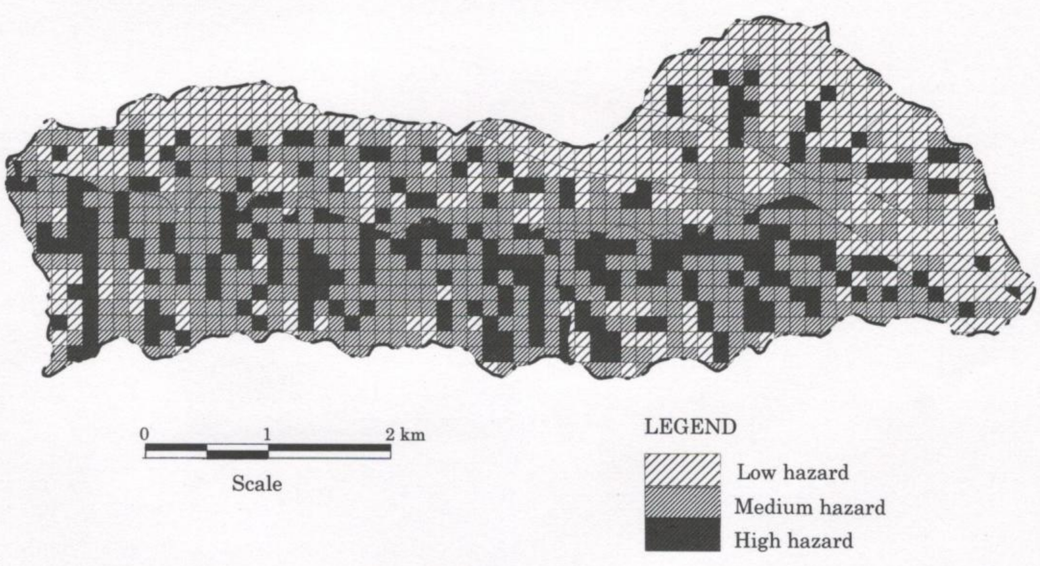

Fig. 8: Landslide hazard map of Nallu Khola watershed

do not match with the existing field conditions. Therefore, it is necessary to review and refine the methodology in order to achieve more accurate results.

ACKNOWLEDGEMENTS

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