Landslide Hazard Evaluation and Geostatistical Studies in Garhwal Himalaya, India

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ABSTRACT

The lower Himalaya region has been the target of intense development activities, particularly in last two decades. This sudden spurt of development activities has resulted in many direct and indirect adverse impacts on the stability of hill slopes. Hence there is a necessity to adopt systematic evaluation of instabilities of hill slopes prior to the execution of development schemes. This will help to minimise the adverse impacts associated with development project in the planning stage itself. Landslide Hazard Zonation (LHZ) mapping provides basic information about the status of stability of hill slopes in six different categories. In order to prepare LHZ map, six basic inherent causative factors have been considered.

Initially, the distribution of sub-categories of causative factors in various hazard zones has been deduced by preparing percent polygons. Spearman's rank correlation is used to obtain rank correlation coefficients between total estimated hazard (TEHD) and six causative factors and also among causative factors. In addition, relative order of influence of six causative factors has also been established for each hazard zone as well as for whole area of study by using Friedman Test and later verified by Page's Test. The study brings out the percent distribution of sub-categories of each causative factor in different hazard zones, relative behaviour of causative factors and their order in which they influenced the stability of the area. The result obtained from the analysis will help to identify the important causative factor(s) responsible for instability and will also help to workout suitable remedial measures before implementation of any development scheme in the region.

1.0 INTRODUCTION

Landslide hazard may be defined as the probability of occurrence of a potentially damaging natural phenomenon. A LHZ map provides information about various stability levels of hill slopes and is useful to Town Planners, Civil Engineers and Engineering Geologists for implementing development projects. A LHZ map depicts the division of land surface into zones of varying degree of instability based on the estimated significance of the causative factors in inducing instability (Anbalagan, 1992). The LHZ map has been prepared by using Landslide Hazard Evaluation Factor (LHEF) rating scheme (Anbalagan, 1992a and 1992b). This technique has already been accepted as Indian Standard (IS) Code by the Bureau of Indian Standards (IS: 14496; Part 2, 1998).

In the present work non-parametric statistical analysis has been carried out using information obtained on the six causative factors from LHZ mapping. Percent polygons of various sub-categories have been prepared to indicate relative trends of their percent distribution in different hazard zones. Spearmen's rank correlation has been used for establishing correlation among variables. The order of influence of causative factors in inducing instability has been studied using Friedman Test and later verified by Page's Test. The order of influence of six causative factors has been obtained for each hazard zone as well as for whole area of study. The correlation coefficient is useful to understand the relative behaviour of the causative factors in causing instabilities in hilly region. On the other hand, the order of importance of six causative factors will help to understand the major factor(s) responsible for instability of hill slopes. Based on that, appropriate remedial measures may be workout for stabilising the hill slopes.

The area under investigation is situated in the Lesser Himalaya of Garhwal region between 30^0 20' to 30^0 30' latitudes and 78^0 15' to $78^0$30' longitudes and falls within the administrative limits cf Tehri and Uttarkashi Districts (Fig.1).

2.0 GEOLOGY OF THE AREA

A number of investigators carried out geological studies in and around the study area. Kumar and Dhaundiyal (1976) worked on the stratigraphy and structure of 'Garhwal Synform' in the Garhwal and Tehri Garhwal regions of Uttar Pradesh. Saklani (1979) studied the lithology and structure of northern Tehri between the Bhilangna and Jalkur rivers, whereas Jain (1987) carried out structural, lithological and sedimentological studies of the area. Valdiya (1980) described the geology of both Kumaun and Garhwal Himalaya including the study area. The terminology used by Valdiya (1980) is followed in the present study.

The study area falls in both the inner and the outer regions of lesser Himalaya. The rocks of Rautgara Formation of Damtha Group, Deoban Formation of Tejam Group and Berinag Formation of Jaunsar Group represent the inner region od lesser Himalaya in the study area. The rocks exposed in the outer lesser Himalaya belong to the Chandpur and Nagthat Formations of Jaunsar Group and Blaini, Krol and Tal Formations of Mussoorie Group. The stratigraphy succession of the study area is shown in Table 1 and the distribution of different Formations belonging to the various Groups is shown in Fig. 2.

3.0 LANDSLIDE HAZARD ZONATION (LHZ) MAPPING OF STUDY AREA

The landslide hazard zonation (LHZ) maps have an important role in planning and implementation of development schemes in hilly regions. They are useful for the following purposes.

i) Identification and delineation of hazardous areas in the hilly region to avoid unstable zones during planning stage of projects.
ii) LHZ maps provide the input data for preparing risk maps which are useful in landslide hazard management.
iii) Ecologically sound mitigation measures can be adopted, depending on the nature of hazard of hill slopes.

In order to prepare LHZ map of the area, the Landslide Hazard Evaluation Factor (LHEF) rating scheme (Anbalagan, 1992a) has been used. This scheme uses six major inherent causative factors of hill slope, such as lithology, structure, slope

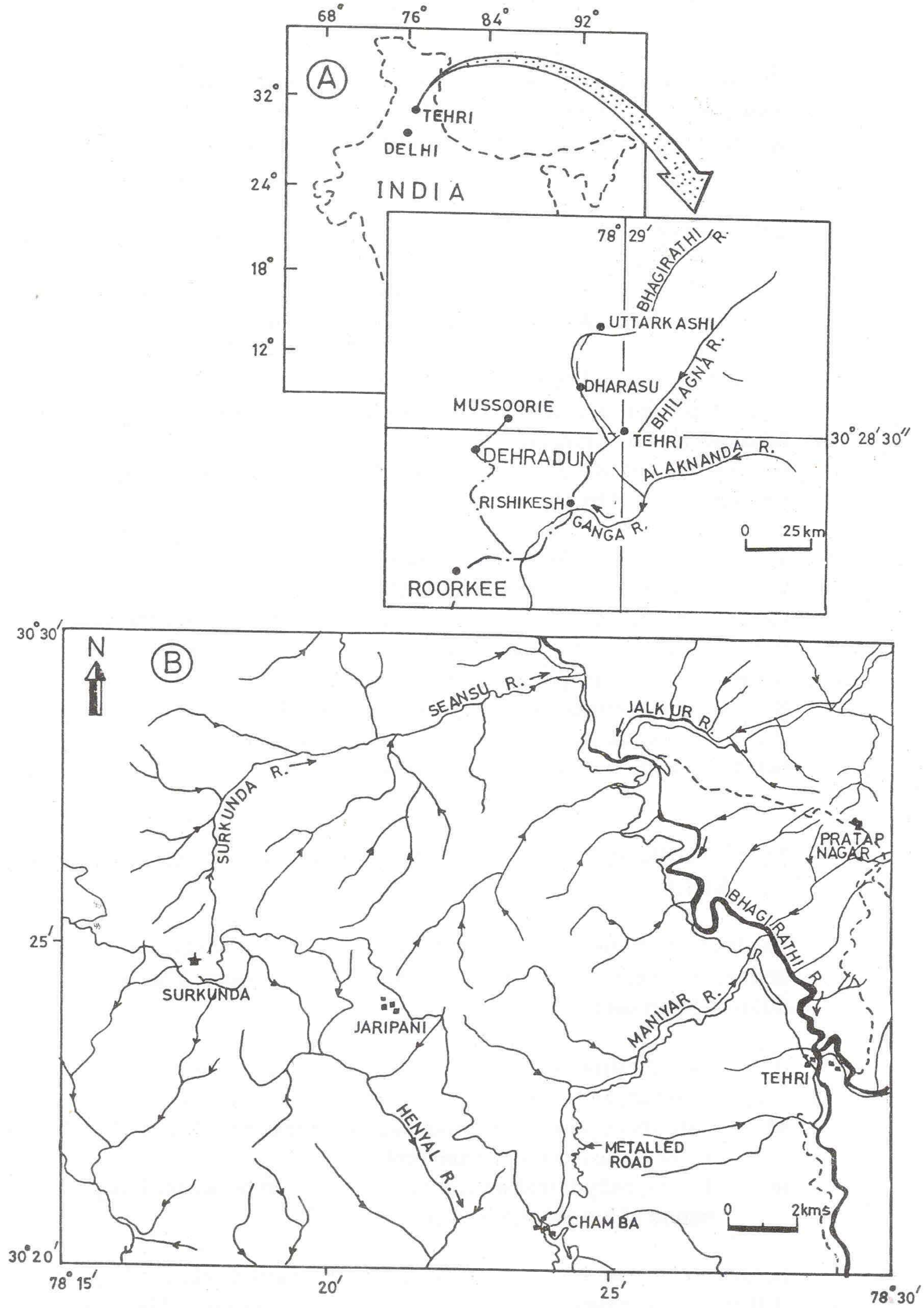

Fig. 1. A - Location of Tehri area
B - Area of study

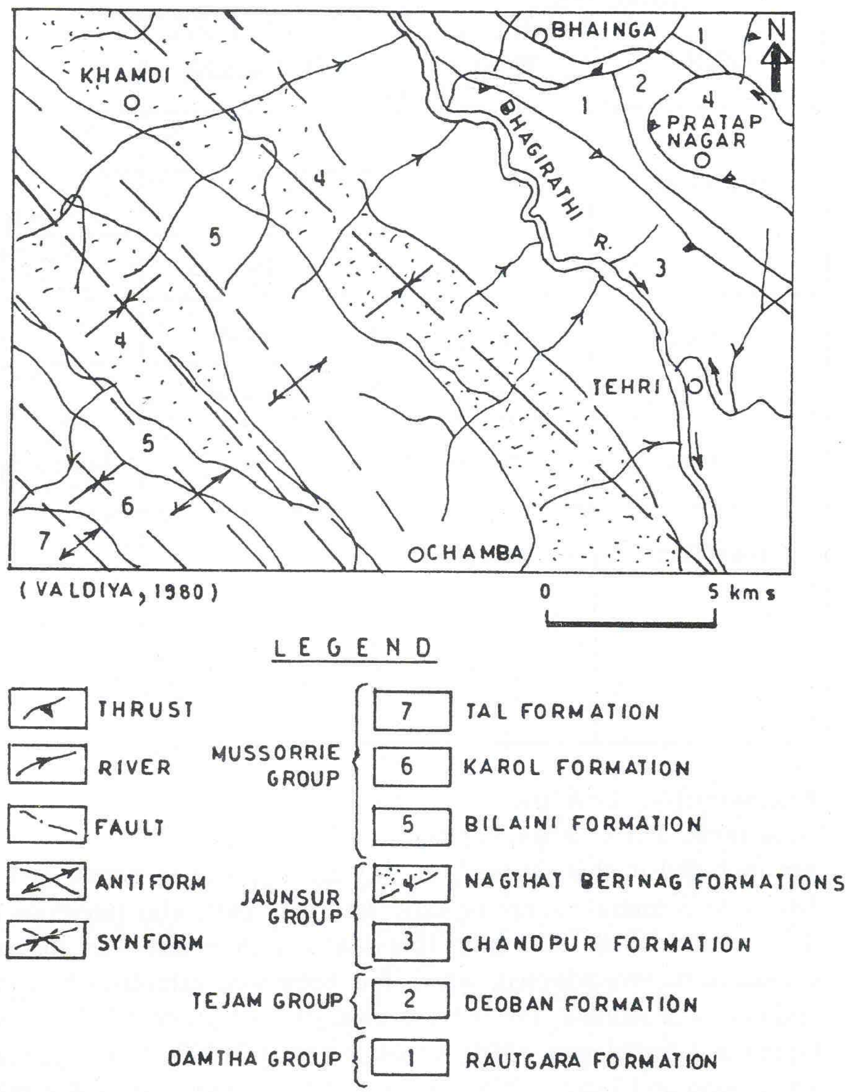

Fig. 2. Geological map of the study area

Table 1 - Stratigraphic succession of the study area (Valdiya, 1980 and Azmi & Joshi, 1983)

GROUP	INNER LESSER HIMALAYA	OUTER LESSER HIMALAYA	AGE	
	FORMATIONS			
MUSSOORIE		Tal	Ordovician (?)-Devonian (500-350M Yr)	
		Krol	Cambrian (570-500M Yr)	
		Blaini	Eocambrian (650-570M Yr)	LATE PRECAMBRIAN
JAUNSAR	Berinag	Nagthat	-	
		Chandpur	-	
TEJAM	Deoban	-	Middle Riphean	
DAMTHA	Rautgara	-	>1300M Yr	

morphometry, land use and land cover, relative relief and hydrogeological conditions. The external contributory factors, such as rainfall and seismicity are not included in this scheme, as they are regional in nature and their impact on landslide potential cannot be estimated with particular reference to a slope facet. The reliability of LHZ map is essentially dependent on the rating system of causative factors adopted, which has been well established in parts of Kumaun and Garhwal Himalaya of India (Anbalagan, 1992 a and 1992b; Gupta et al. 1993; Gupta and Anbalagan, 1995; Anbalagan et al., 1992; Anbalagan and Singh, 1996; Anbalagan and Tyagi, 1996; Gupta and Anbalagan, 1997). For more details about LHZ mapping technique, appropriate literature as indicated above may be referred.

Initially, a slope facet map (Fig. 3) of the area on 1:50,000 scale has been prepared by assessing the topography of the area. Facet is a part of hill slope which has more or less uniform characters within the facet, showing consistent slope direction and inclination (Gupta, 1997). Hill slopes are divided into a number of facets by ridges, spurs, gullies and rivers. In case such features are absent, arbitrary lines are used as a slope facet boundary, where a significant change in the attitude of slope is observed. An individual facet is the smallest unit for LHZ mapping.

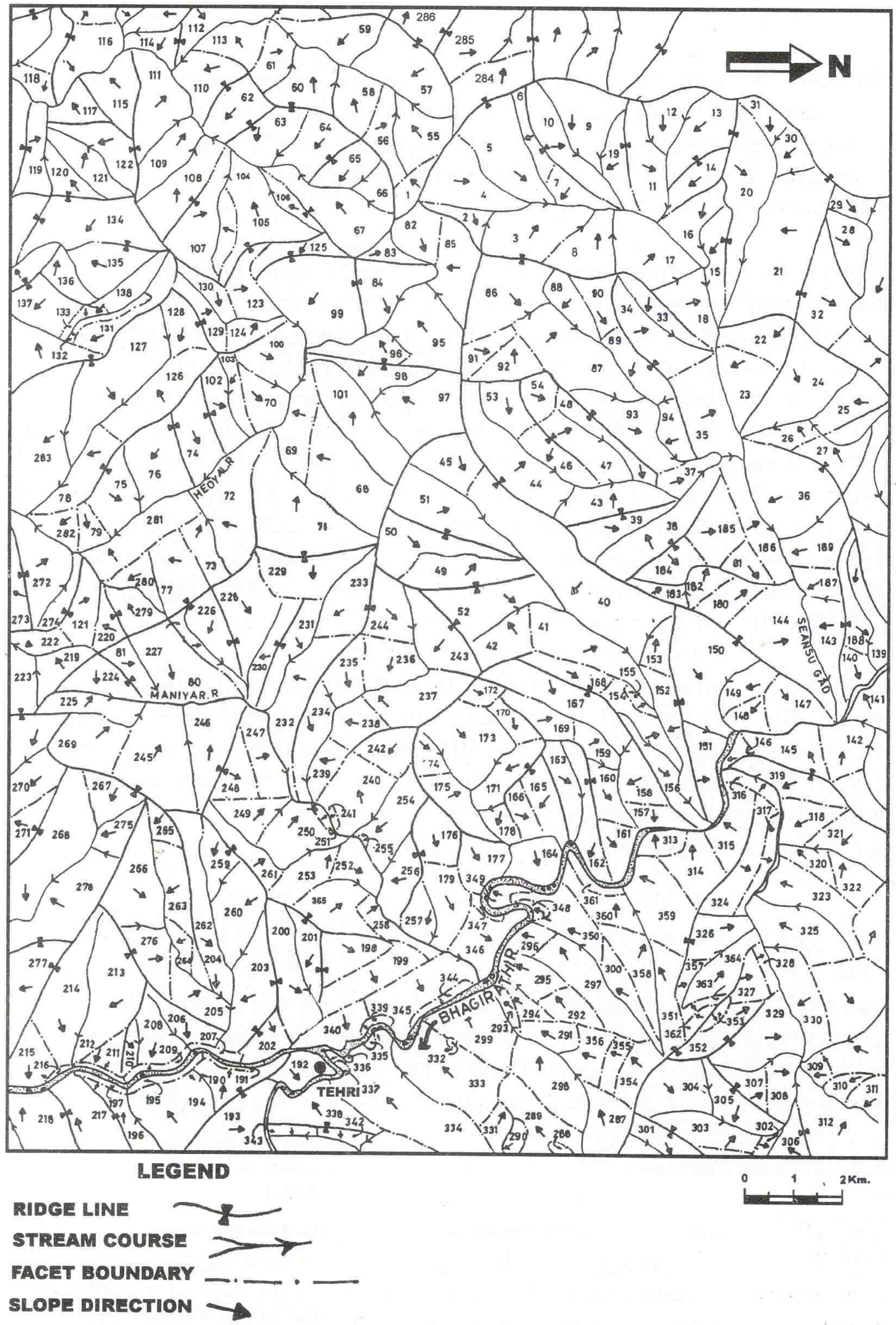

Fig. 3. Slope facet map of the study area

A slope facet map is used as a base map for preparing the thematic maps corresponding to each causative factor with the help of LHEF rating scheme. Finally, total estimated hazard (TEHD) values for study area are calculated by adding the ratings of all causative factors for individual facets, which is shown as LHZ map of the area (Fig.4).

The TEHD values have been used to categories the slope facet into hazard zones such as very low hazard (VLH), low hazard (LH), moderate hazard (MH), high hazard (HH) and very high hazard (VHH). The distribution of hazard zones in the study area is shown as landslide hazard zonation (LHZ) map (Fig. 4). Here, the hazard zones indicate the probability of failure in terms of relative time, as absolute time for landslide events has no rationale. For example, a moderate hazard slope may fail earlier compared to a low hazard slope but a high hazard slope may fail early than a moderate hazard slope. The present study of LHZ mapping covered 365 slope facets and covering an area about 400 sq km. The distribution of categorised hazard zones in terms of numbers is 6, 118, 166, 70 and 5, which corresponds to 1.12%, 32.46%, 53.56%, 12.5% and 0.35% for VLH, LH, MH, HH and VHH respectively.

Part of river terraces, which form the most stable part of the area, fall in VLH zones. The LH and MH slope facets are more dominant ones and are well distributed throughout the area. The HH zones are mainly confined in the north-eastern region close to Bhagirathi River and in parts of south-western area of study. The most potentially hazardous zones namely VHH covers only half percent and are seen mainly on isolated slope facets.

4.0 STATISTICAL ANALYSIS

The LHEF rating scheme used in this research work fall in the ordinal scale of measurement. Thus, the non-parametric statistical methods have been used to calculate the rank correlation coefficients and order of influence. Percent polygons of sub-categories for individual causative factors have also been plotted.

4.1 Percent Polygons

Six sets of percent polygons have been prepared for each causative factor. Individual set represents clubbed polygons of sub-categories of their corresponding causative factor. It is to be noted that percentage of hazard zones is calculated with respect to total area covered in 356 slope facets, whereas the percentage of sub-categories of each causative factors is calculated with respect to the area covered by corresponding hazard zones.

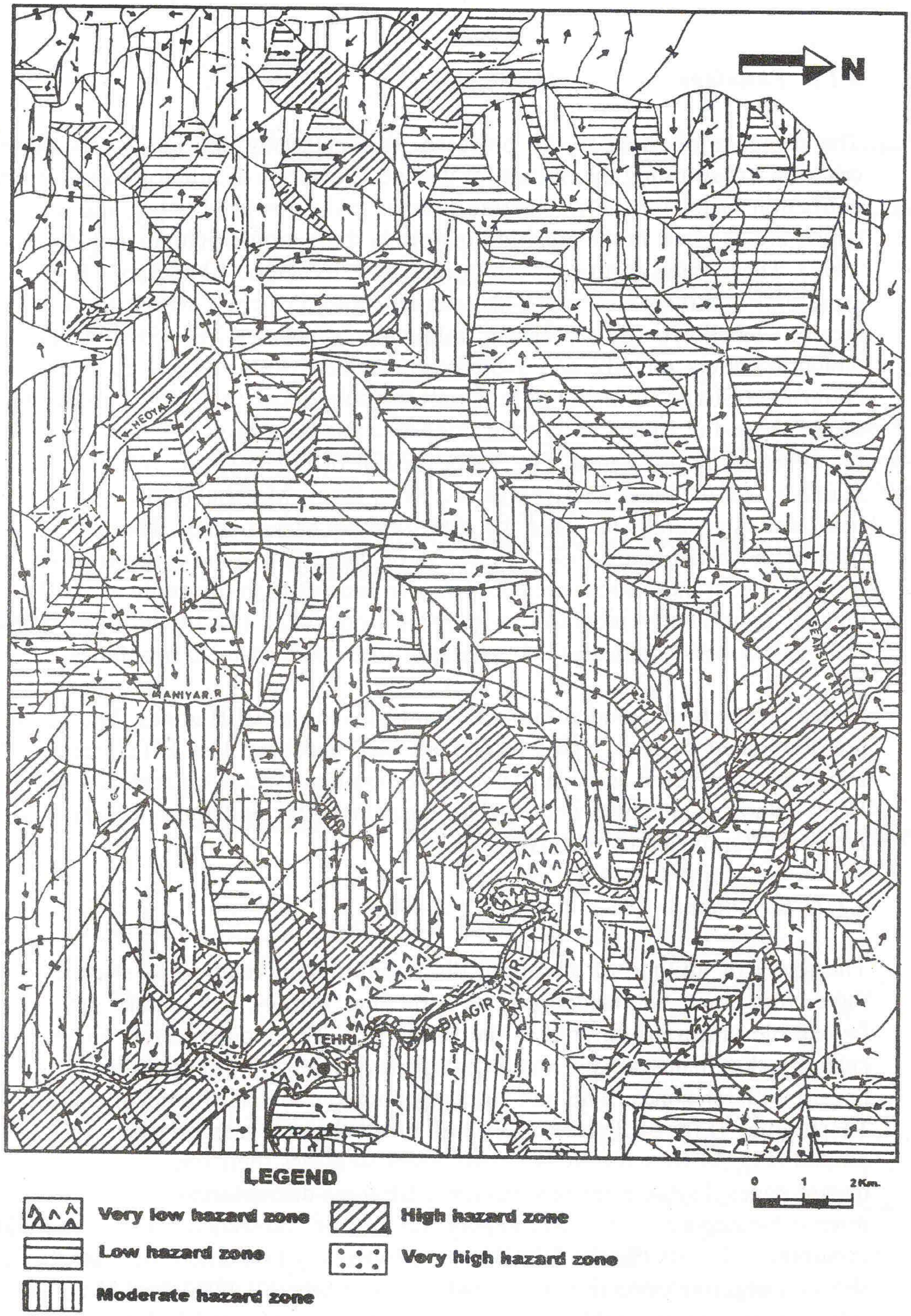

Fig. 4. Landslide hazard zonation map of the study area

4.1.1 Lithology

The response of rocks to the processes of weathering and erosion is the main criterion for awarding the ratings for the sub-categories of lithology and includes a correction factor for the weathering state of rocks observed. Rock and soil types, which are exposed in the area, fall mainly in three groups (Gupta and Anbalagan, 1995). These three groups namely rock type-I, rock type-III and soil. Rock type-I represents relatively hard rocks like quartzite and limestone, which are resistant to erosion. Rock type-III represents, relatively soft rocks like phyllite and slate, which weathers quickly and promote instability. Soils include the older well-compacted fluvial fill material (alluvial) to young loose material. The distribution of rock type-I & III and soil in the study area has been shown as percent polygons for different hazard zones (Fig. 5). A perusal of Fig. 5 shows VLH slope facets mainly cover the older well-compacted River Borne Material (RBM). On the other hand, soil is generally less than the 10% for other hazard zones. The rock type-I, is maximum for LH zones (68.17%) and show decreasing trend towards VHH zones indicating that these rocks are less prone to instability in the study area. The rock type-III consistently increases in percent from VLH (12.13%) zones to VHH (87.21%) zones. It indicates that rock type-III is more prone to instability.

Hence it may be concluded that soil dominates in the VLH zones. The LH zones are dominated by rock type-I, which are hard and have less LHEF ratings. MH zones are considered as fairly stable slopes mainly covered by rocks of type-I and III in almost equal percentages. The unstable (HH) and most unstable (VHH) zones are dominated by rock type–III.

4.1.2 Structure

The study of attitude of structural discontinuities in relation to slope indicates three important sub-categories of structure namely favourable, moderately favourable and unfavourable in the study area. The moderately favourable sub-category dominates all the major categories of hazard zones except very high hazard (VHH) zones. The sub-category unfavourable is dominantly present in VHH zones (Fig. 6). Percent polygons of all the sub-categories have also been plotted (Fig. 6) over different hazard zones to assess their importance in various hazard zones. Figure 6 reveals that there are three distinct trends corresponding to three sub-categories. The sub-category 'favourable' shows a negative trend with a minimum value (0.0%) for VHH zones. Moderately favourable sub-category also shows a negative trend in general with a peak value (89.42%) for LH zones. The sub-category 'unfavourable' shows an increasing trend from VLH zones (0.0%) to VHH zones (70.93%).

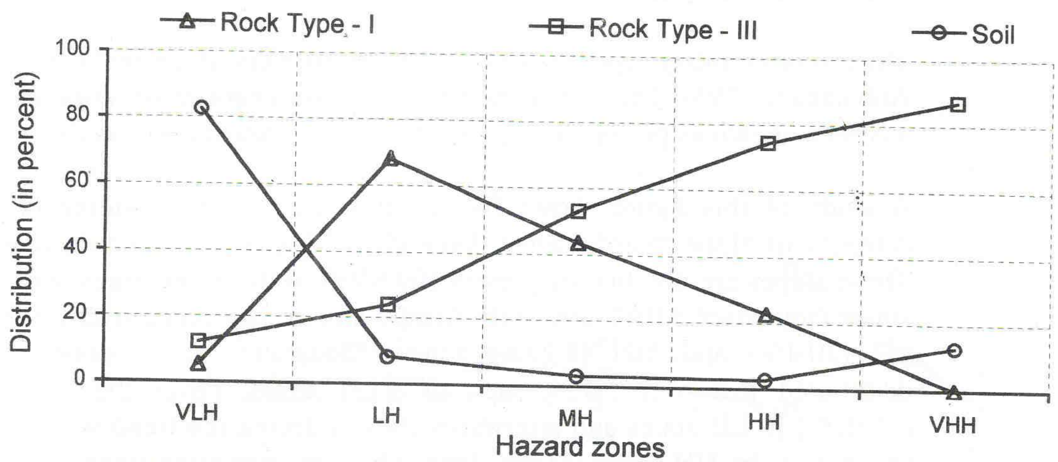

Fig. 5. Distribution of sub-categories of Rock/Soil type in various hazard zones

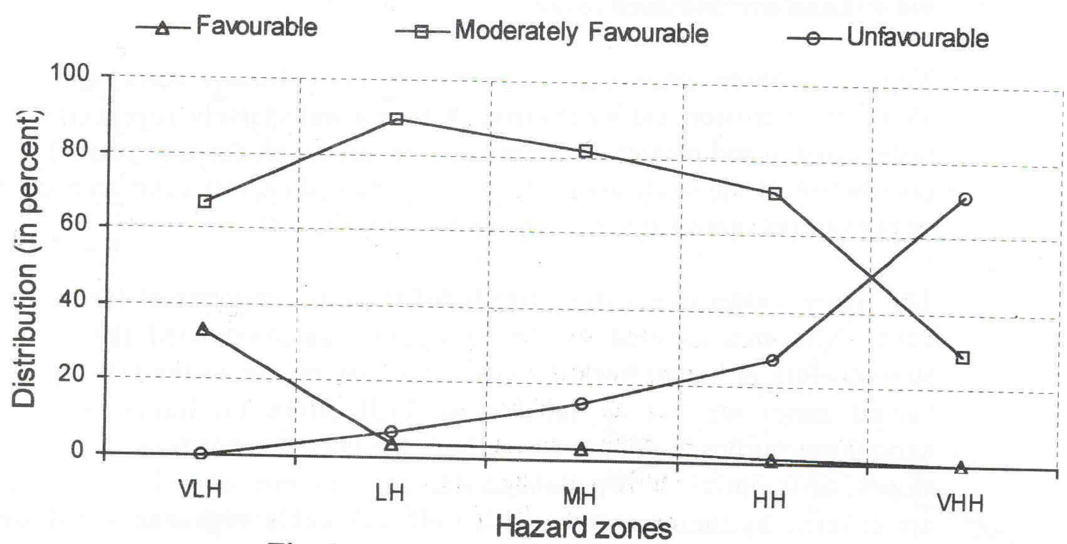

Fig. 6. Distribution of sub-categories of structure in various hazard zones

4.1.3 Slope morphometry

Slope morphometry represents the zones of different slope inclination (Gupta & Anbalagan, 1995). The distribution of five sub-categories of slope morphometry has been shown as percent polygons for different hazard zones in Fig. 7.

A study of this figure shows five distinct trends corresponding to each sub-category of slope morphometry. Very gentle slopes show the decreasing trend. These slopes are dominantly present (94.85%) in the VLH zones, whereas in LH zones they cover 3.08% area only. Gentle slopes distributed over a small part of LH (20.4%) and MH (8.27%) zones. Moderately steep slopes, which are distributed just over 5.15% area of VLH zones, cover the maximum area (71.02%) in LH zones and afterwards show a decreasing trend with 39.65% area covered in the HH zones. Steep slopes show an increasing trend from LH zones (4.86%) to HH zones (36.08%). Cliffs/Escarpments also show the increasing trend from LH zones to VHH zones. Cliffs/ escarpments cover 0.63% area of the LH zones, whereas 100% area of the VHH zones. Thus, it may be concluded that sub-categories of slope morphometry, which are less prone to instability, are mainly distributed in stable zones. On the other hand, sub- categories, which are more prone to instability, are mainly distributed in unstable zones such as HH & VHH zones.

4.1.4 Land use and land cover

Vegetation cover commonly checks the action of climatic agents and protects the slopes from erosion and weathering. A barren and sparsely vegetated slope shows faster erosion and greater instability as compared with dense vegetated slopes. The distribution in the study area of all the five sub-categories have been shown again as percent polygons for various hazards zones (Fig. 8).

The figure shows five distinct trends for the sub-categories of land use and land cover. The area covered by the agricultural land/populated flat land decrease subsequently in higher hazard zones. This may be due to the fact that the higher hazard zones are not as suitable as VLH zones for human settlement and agriculture purposes. Since, agriculture practices are not possible on very steep slopes, agricultural lands/populated flat lands are not seen in VHH zones, which are covered by the escarpment/cliff (>45^0). Thickly vegetated forest area is not found on VLH zones, mainly due to the human interference, as these zones are mainly used for agriculture practice. The second major part (28.67%) of LH zones is covered by thickly vegetated forest land, commonly observed in the higher reaches. In general, percentage of thick forest cover decreases as the hazard category increases. Moderately vegetated forests have been observed in LH, MH

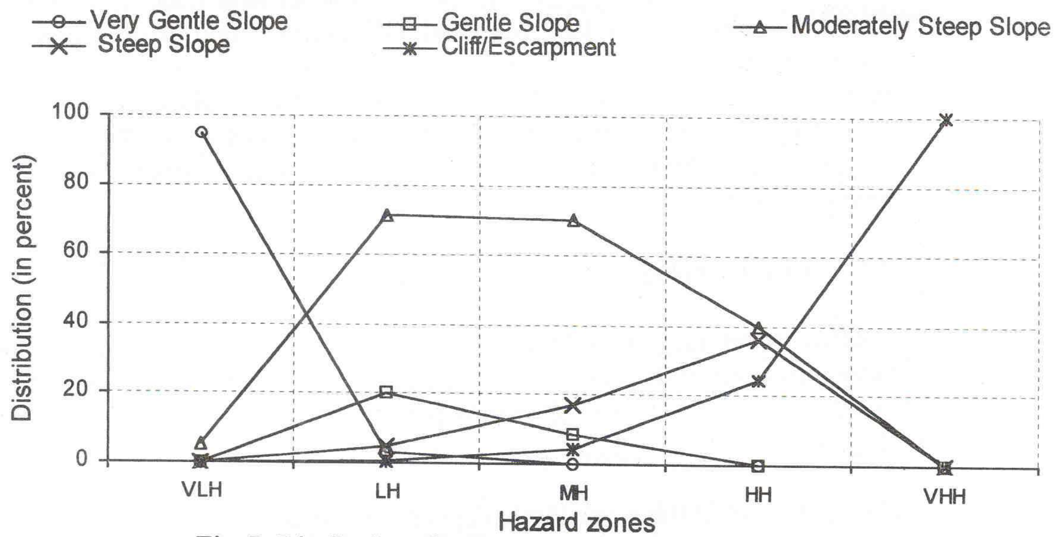

Fig. 7. Distribution of sub-categories of slope morphometry in various hazard zones

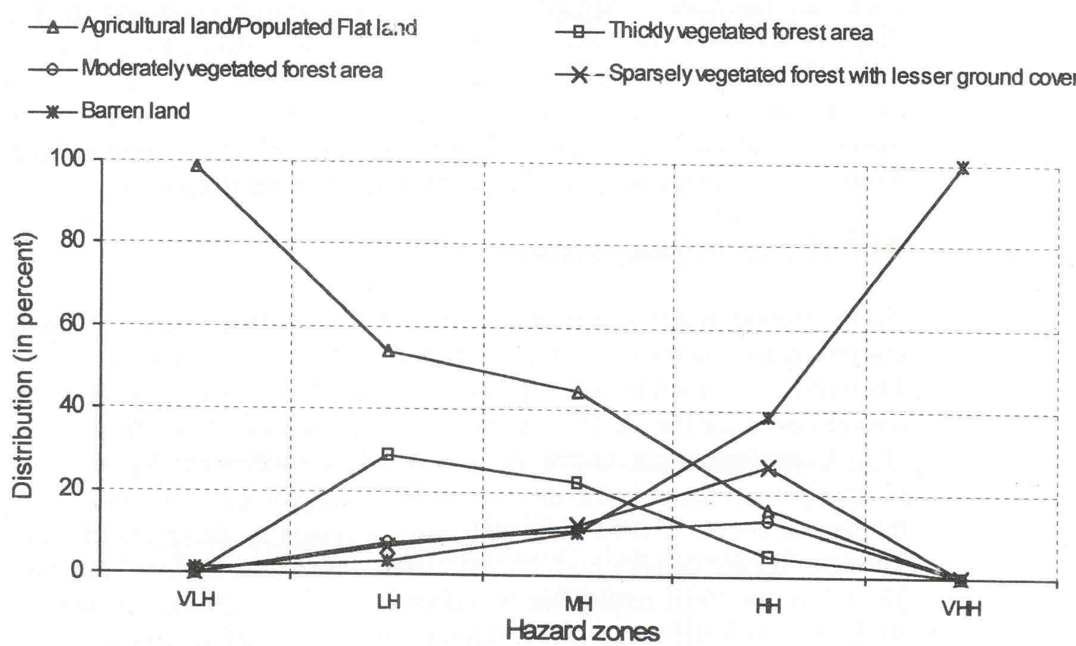

Fig. 8. Distribution of sub-categories of land use and land cover in various hazard zones

and HH zones. Similarly, sparsely vegetated areas with lesser ground cover have also been observed in LH, MH and HH zones. Their distribution shows an increasing trend towards higher hazard zones. Barren land shows a consistent increasing trend towards higher hazard zones. These lands cover the minimum area (1.47%) of the VLH zones and 100% area of VHH zones. Therefore, the sub-categories contribute more towards instability are well distributed in higher hazard zones and vice versa.

4.1.5 Relative relief

Relative relief may be defined as the elevation difference within an individual facet measured in the slope direction of the facet (Gupta, 1997). The distribution of relative relief has been shown as percent polygons for different hazard zones (Fig. 9).

Relative relief of the slope facets depends on the size of the individual slope facet angle, to some extent. Generally, large slope facets have high relief. Very low hazard (VLH) areas are completely covered by the low relief, as these zones are nearly flat. Distribution of low relative relief is small in case of low hazard (2.63%), moderate hazard (0.60%) and high hazard (2.52%) zones, as the size of slope facet is comparatively large in general. Since, very high hazard (VHH) slope facets are generally very small in size, distribution of low relief in very hazard zones are noticeable. Medium relief shows a similar trend and its distribution drops in MH zones in comparison to LH zones, as most of the zones are large in size in MH zones. Medium relief is again well distributed in HH and VHH zones as slopes of these zones are steep. High relief covers maximum area in MH zones mainly due to the large slope facet size. Similar trends have been noticed in high hazard and very high hazard zones as these zones have steep slopes.

4.1.6 Hydrogeological conditions

Since ground water in the hilly terrain is channelled mainly along structural discontinuities within the rocks, it does not have a uniform flow pattern. Therefore, the groundwater expression on the slope surface has been taken into consideration for the study. A perusal of Fig.10 shows, all the five sub-categories of hydrogeological conditions are present in the study area. As such, there is no distinct pattern found in the distribution of hydrogeological conditions. In most of the hazard zones, 95% of the area is always shared by damp and dry conditions. Though, in case of very high hazard zones 'flowing conditions' are contributing 12.79% of the VHH zones. But, this does not represent the actual condition of the study area, as VHH zones itself represent less than a half percent of the total study area.

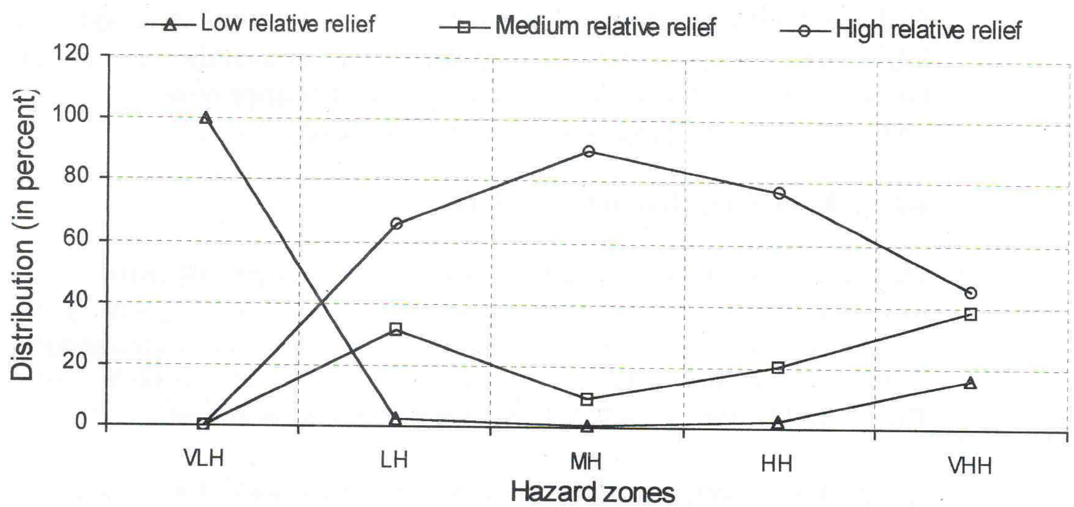

Fig. 9. Distribution of sub-categories of relative relief in various hazard zones

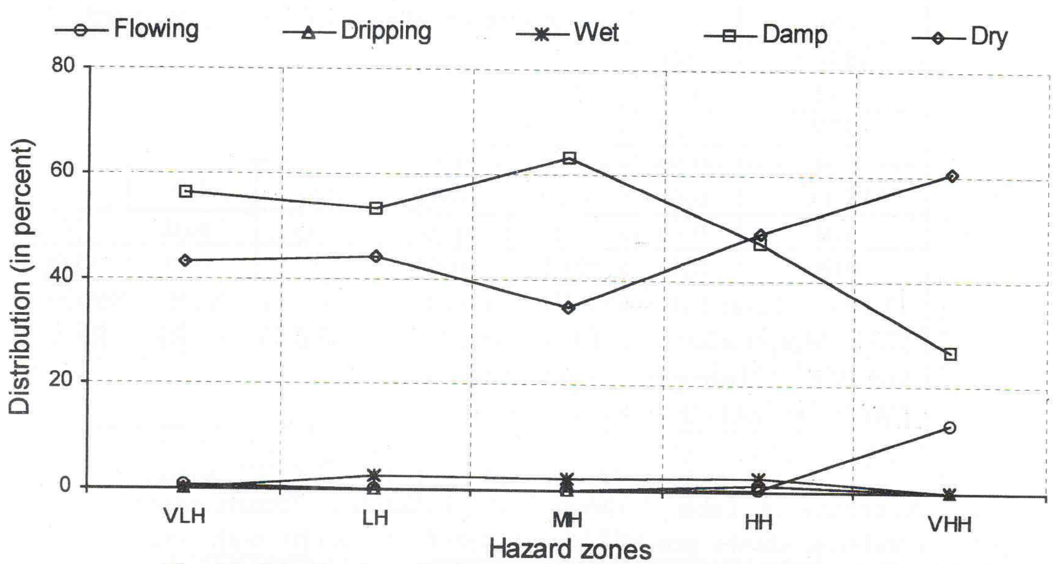

Fig. 10. Distribution of sub-categories of Hydrogeological condition in various hazard zones

Hydrogeological conditions indicated by surface moisture condition does not follow any trend. Two conditions, dry and damp are mainly persisting throughout the study area over the different hazard zones. Presence of other three conditions such as wet, dripping and flowing are negligible.

4.2 Rank Correlation Coefficient

The spearmen's rank correlation determines the degree of association between two random variables say X and Y. It provides a numerical value between –1 to +1 for the amount of linear dependence. If the values of X are randomly paired with the values of Y, the measure of correlation should be fairly close to zero. This should be the case when X and Y are independent (Conover, 1980).

The rank correlation coefficients have been calculated for all 21 pairs of six variables and total estimated hazard (TEHD) from 365 slope facets are presented in Table–2. These coefficients have been tested for statistical significance (5%, 2-Tail).

TABLE 2 - Correlation matrix of variables

VARIABLES	VARIABLES						
	TEHD	LIT	STR	SM	LULC	RR	HGC
	RANK CORRELATION COEFFICIENT						
TEHD	1.0						
LIT	0.47	1.0					
STR	0.27	-0.13	1.0				
SM	0.58	-0.05	0.10	1.0			
LULC	0.68	0.16	-0.02	0.38	1.0		
RR	0.18	-0.11	0.06	0.05	-0.03	1.0	
HGC	0.03	0.03	-0.03	-0.07	-0.13	-0.06	1.0

TEHD – Total Estimated Hazard, LIT – Lithology, STR – Structure, SM – Slope Morphometry, LULC – Land Use & Land Cover, RR – Relative Relief and HGC – Hydrogeological Conditions

CRITICAL VALUE (2-TAIL, 0.05) = ±0.103

A perusal of Table 2 shows that all causative factors except hydrogeological condition shows positive significant relationships with total estimated hazard (TEHD) at 5% level of significant. It indicates that as the total estimated hazard (TEHD) increases, there is a significant increase in causative factors except for HGC. In other words, as the landslide hazard potential increases contribution of causative factors towards slope instability increases. The mutual correlation or co-linearity among the causative factors is shown in Table 2.

Land use and land cover, Slope Morphometry and Lithology show a good positive correlation with TEHD. This indicates that landslide hazard potential increases mainly due to slope facets becoming more devoid of vegetation, steeper and also the distribution of vulnerable lithology becoming more prominent in the area of study. The correlation between TEHD and HGC does not appear to indicate any significant influence of surface moisture (water) conditions on the slope stability. Only, LULC and SM seem to have some significant association among causative factors. This indicates that as the slope facets are becoming steeper, they also become barren.

4.3 Order of Influence

Friedman's Test is used to obtain the order of influence and verified by the Page's Test. These are non-parametric statistics to arrange the variables in an ascending or descending order of their importance. The order of influence of six causative factors is established for all five - hazard zones as well as for whole area at 5% significance level (Table 3) by using Friedman's Test. Page's Test confirms the sequences of six causative factors, established by Friedman's Test for various hazard zones as well as for the whole area of study.

TABLE 3 - Order of influence of causative factor

HAZARD LEVEL	FRIEDMAN TEST					
	ORDER OF INFLUENCE					
	1	2	3	4	5	6
Very Low Hazard	STR	LIT & LULC	SM	RR	HGC	-
Low Hazard	SM & STR	LULC, RR & LIT	HGC	-	-	-
Moderate Hazard	SM	STR	LULC	LIT & RR	HGC	-
High Hazard	SM & LULC	STR & LIT	RR	HGC	-	-
Very High Hazard	LULC & SM	LIT & STR	RR & HGC	-	-	-
Whole Area	SM	STR	LULC	LIT	RR	HGC

LIT – Lithology, STR – Structure, LULC - Land Use and Land Cover, SM – Slope Morphometry, RR – Relative Relief and HGC - Hydro Geological Conditions

The MH zones fall at the middle among the five hazard zones and cover the largest part (53.56%) of the study area. These zones may have the properties of lower as well as the higher hazard zones. The order of influence of various causative factors in MH zones is more or less same, as that indicated for the whole area of study. Structure and land use and land cover are the second and the third most influencing causative factors of stability in MH slope facets, whereas hydrogeological condition shows a minimum influence on the slope stability. The order of influence of all causative factors is more or less same in HH and VHH zones. Slope morphometry and land use and land cover are the ones which play important role to influence the stability of hill slopes, whereas, structure and lithology are the second most important causative factors which influence stability.

5.0 CONCLUSIONS

Systematic planning is a pre-requisite for implementation of development schemes in hilly terrains. The LHZ mapping is the first step in this direction. Therefore, a landslide hazard zonation (LHZ) map of the study area has been prepared, which divides the area into zones of varying degrees of instability in terms of very low hazard (VLH), low hazard (LH), moderate hazard (MH), high hazard (HH) and very high hazard (VHH). The VLH and LH zones are generally considered safe for development schemes. Though, MH zones are also considered stable, but may contain some local vulnerable pockets. These pockets should be identified before implementation of any development scheme. However, HH and VHH zones should be avoided completely. If these zones are unavoidable under development compulsions, detailed investigations to understand the nature of instability should be carried out in order to find out sound remedial measures.

The LHZ mapping data has been used to plot percent polygons of sub-categories for individual causative factors, which indicate the relative behaviour of sub-categories within the hazard zones. This also shows the area in percent covered by each sub-category in the individual hazard zone. The data obtained from LHZ mapping has been effectively used for further statistical analysis using Spearman's correlation, as well as Friedman's and Page's tests for examining correlation and order of influence of causative factors respectively. The implementation of development projects on natural hill slopes such as roads, buildings may significantly change the existing status of causative factors. Thus, it is recommended that HH and VHH slope facets should be avoided, but if these slopes are unavoidable, suitable precautionary measures should be adopted considering the relation of sub-categories of each causative factors, correlation values and the order of importance of causative factors.

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