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Terrain Attributes and Drainage Texture As Indicators of Landslide Occurrence in a Part of Garhwal Himalaya, India

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ABSTRACT

Slope movement processes along with other terrain attributes influence surface morphology of an area. Correlation analysis of nineteen morphometric parameters and the landslide areal extent in 26 third order basins in a part of Garhwal region of the Lesser Himalaya, U.P. India, indicates that fraction of landslide area (Ls) in a basin has statistically significant correlation coefficient of about 0.86, 0.84, 0.68 and -0.55 (at 99% confidence level) with drainage texture (DT), stream frequency (SF), drainage density (DD) and basin circularity (BC) respectively. Drainage texture which is the product of stream frequency and drainage density, is one single morphometric parameter in a basin that has in it, the influence of many morphometric parameters which in turn, are reflection of the cumulative effect of elevation, slope, lithology, structural features, vegetation and hydrological condition. Higher the drainage texture, higher is the landslide areal extent. Based on regression analysis, a relationship between fraction of landslide area (Ls) and drainage texture (DT) of third order basin has been worked out which suggests that the third order basins always have some unstable slope faces. With a drainage texture of about 185, almost all the slopes are expected to be unstable. Relatively stable areas are associated with lower values of drainage texture. Circular basins with low relief have lower values of DT and therefore, their slopes are relatively more stable. This identified relationship is found to be useful within the error limit of 25 percent and is, therefore, recommended for use as a first step towards the landslide hazard zonation in similar terrains.

INTRODUCTION

The Himalayas is a young mountain range and owes its origin to the collision of the Indian plate with the Asian plate. It forms a geodynamically active terrain which witnesses frequent earthquakes, and widespread landslides every year during rainy seasons. Although, this terrain is highly landslide-prone, it appears that the slope failure phenomena are not observed everywhere. Slope instability is found to occur and recur in the areas characterised by unique combination of topographic, structural, lithologic, hydrologic, climatic and vegetational features. These factors act and interact in a given seismic zone to change the landscape. Thus the geomorphic parameters may have some relationship with the instability of the terrain. The present study aims at exploring this possibility, taking the landslide-prone sample area of the Garhwal region of the Lesser Himalaya, India (Fig. 1).

GEOLOGY OF THE AREA

Covering an area of about 102 sq. km. in the district of Garhwal (U.P), the terrain under study is girdled in the east, south and west by the river Ganga and bounded in the north by a prominent ridge R_1 (Fig.1). Ridge R_1 acts as a barrier to easterly moving monsoon clouds and thus, areas west of this ridge get more of precipitation than those on east.

Geologically the area lies in the Kumaon tectonic zone of the Lesser Himalaya in the Garhwal region, which is separated from the Garhwal tectonic zone by the North Almora thrust. The Main Boundary Thrust separates it from the Siwaliks (Mio-Pliocene) in the south.

The rocks exposed in the area belong two major lithostratigraphic successions separated by angular

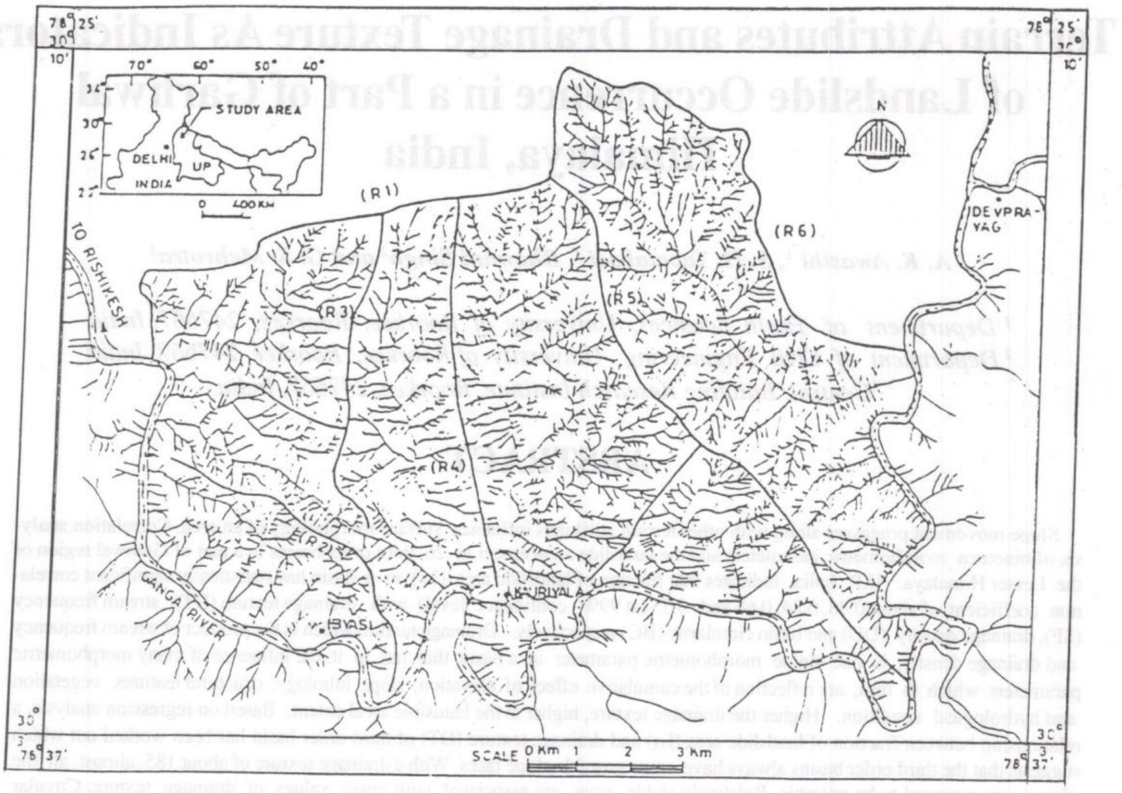

Fig. 1 : Location of the Area with Drainage Pattern.

unconformity. The lower succession, known as Lansdowne Formation (Precambrian), consists dominantly of quartzite of the Bijni Member and phyllite of the Amri-Pauri Member (Fig. 2). The younger succession comprises the Blaini Formation (mainly boulder beds, purple, green shales and siltstones), the Krol Formation (mainly limestones and dolomites with calcareous shales), the Tal Formation (mainly quartzites, slates, shales and shell limestones) and the overlying Subathu Formation (Eocene) consisting mainly of greenish shales (Fig 2). Though controversial, of late, the Blaini and Krol Formations have been dated as Late Precambrian to Cambrian by Azmi et al. (1981) and Precambrian by Prasad et al. (1990). The Lower Tal is dated as Cambro-Ordovician by Azmi et al. (1981). However Prasad et al. (1990) assign Cambrian age to the Tal Formation. In the south- western part of the area, Bijni Quartzite overlies the Subathu Formation (Eocene) due to a major reverse fault known as Singtali Fault (Kumar and Dhaundial 1979) or Garhwal Thrust (Auden 1937), which trends in general, WNW-ESE with steep southerly dips varying between 70^0 to 80^0. These rocks, in general, have four sets of joints dipping in NE, SSW, ESE and NW directions, at varying angle.

LANDSLIDES

Landslide distribution map (Fig. 3) prepared on the basis of aerial photographs and topographic map coupled with field investigations, revealed that 13.42 sq. km. of the terrain forming about 13% of the total area, has been affected by landslide activities. It is observed that, in general, the landslide density is high in the higher hill slopes near the upper parts of the ridges. Various types of slope movements such as rock slides, debris slides, avalanches and rotational slides and

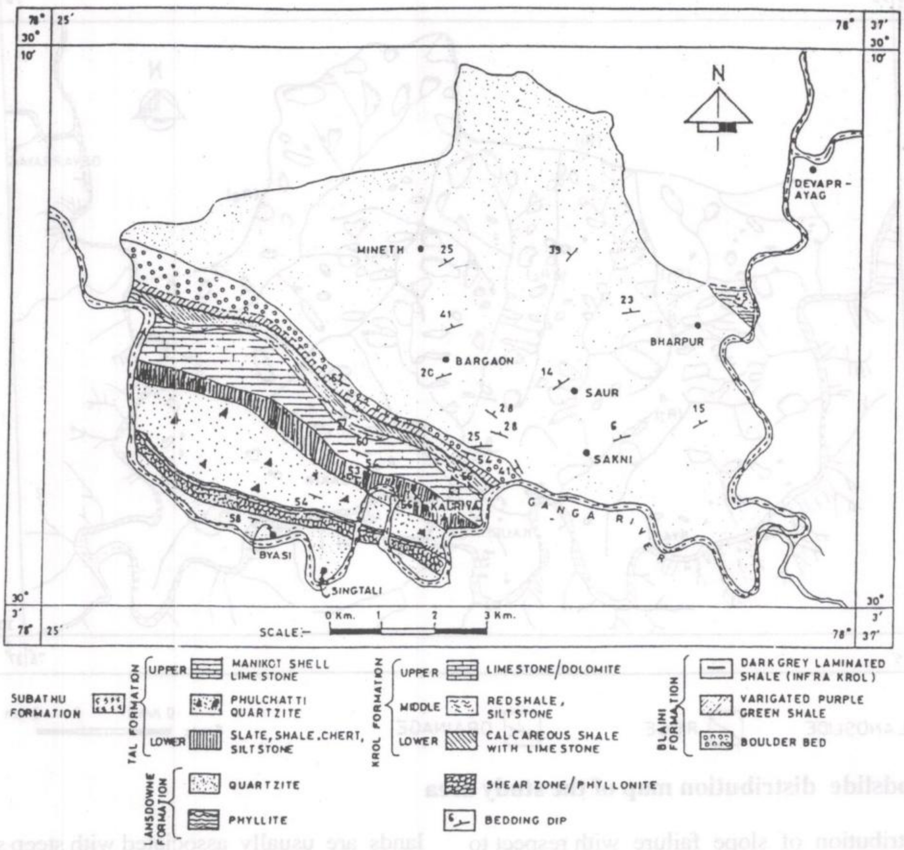

Fig. 2 Geological Map of the Area (Modified after Kumar and Dhaundiyal 1979)

cree were recognized in the field. Transnational slides are most common in the area.

LANDSLIDE AND TERRAIN ATTRIBUTES

Landslides are found to be intimately linked with the terrain attributes such as elevation, slope, vegetation cover, lithology and structure, and climatic conditions. The distribution of landslide affected areas in relation to elevation shows four modes (Fig. 4). The primary mode indicates that the maximum percentage of landslide area is found at elevations above 1800 m east of Ridge R5 (Fig. 1). Such regions are of very small areal extent (about 1.5% of the total area of the terrain). They are found on hillslopes close to the upper part of the ridges. These landslide prone areas are poor or devoid of vegetation. The second, third and fourth modes are found at elevation ranges of 1500 - 1600 m, 1100 - 1300 m, and 500 - 600 m with areal extents of about 4%, 17% and 7% respectively of the area. The areas to the west of ridge R5 (Fig. 1) have maximum elevation of 1500 m. The vegetation cover near the ridge at elevations 1100 - 1300 m and 1500 - 1600 m are moderately dense and in general, sparse. Field observations indicated that with increase of elevation, growth of secondary vegetation decreases. Also, slopes, in general, are steeper near the upper parts of ridges. Slope failures at elevations of 500 - 600 m are mainly due to road cuttings along the Ganga river.

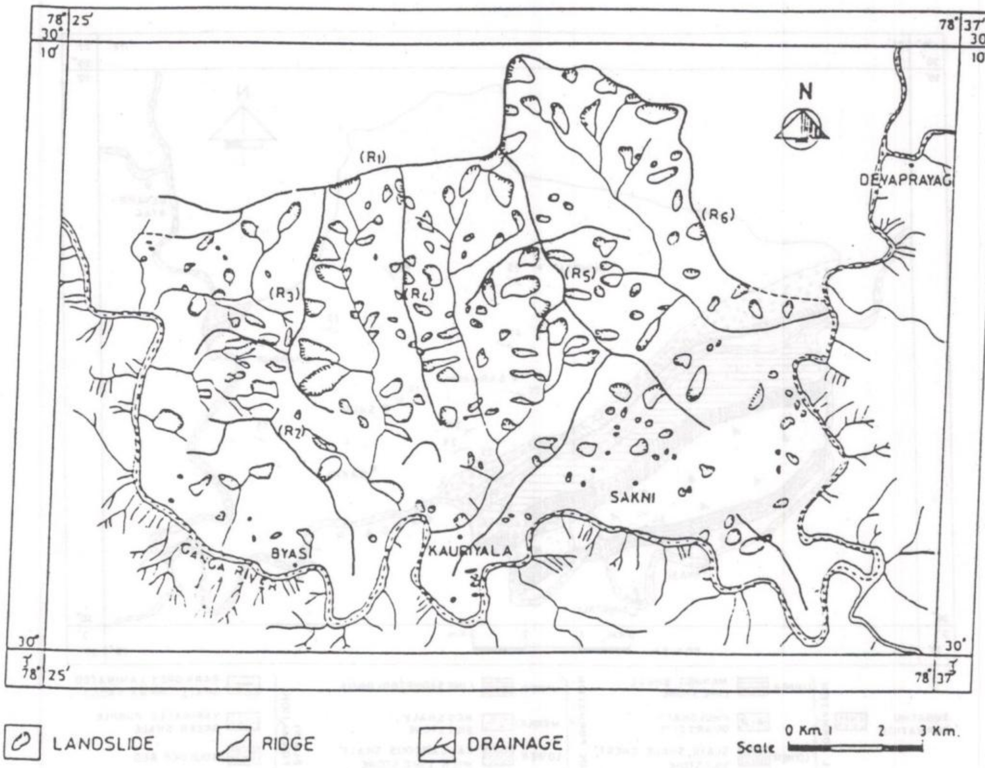

Fig. 3 Landslide distribution map of the study area

The distribution of slope failure with respect to slope angle shows a bimodal pattern (Fig. 5). The primary mode reveals that the maximum slope failure is found in the areas having slope angle between 30 to 35x. This appears to be due to proximity of this hillface, in general, to the upper part of slopes which are characterised by moderate to sparse vegetation cover. The land failure activities are also conspicuous in areas characterised by steeper slope angle between 40 - 45x. These areas are in the western part of the ridge R_5 where the amount of precipitation is relatively high.

The distribution of landslide with vegetation cover indicates that as the density of natural vegetation decreases, the landslide increases (Fig. 6). Although the barren areas have relatively low areal extent of about 3.6% of the total area, they are affected most by slope failure. It is observed that the barren lands are usually associated with steep slopes in the upper part of ridge slopes.

Slope movement has affected each and every stratigraphic units (Fig. 7). The Lower Krol Member consisting mainly of limestones, dolomites and calcareous shales has been affected the most, followed by the quartzitic Bijni member of the Lansdowne Formation. The Lower Krol Member is entirely exposed in western part of ridge R_5 where rainfall is comparatively high. The slope movements of this member is, thus, not only due to physical processes but also due to chemical processes. The Bijni quartzite of Lansdowne Formation has an areal extent of 72.16 sq. km, forming 70.7 % of the total area. Thus, most of land failures are found associated with it.

The major structural feature present in the area is the Singtali Fault. In general, areas affected by

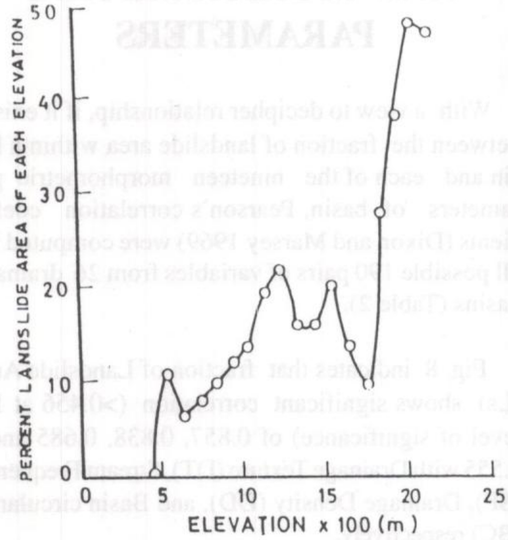

Fig. 4 Distribution of Landslide Area vs. Elevation

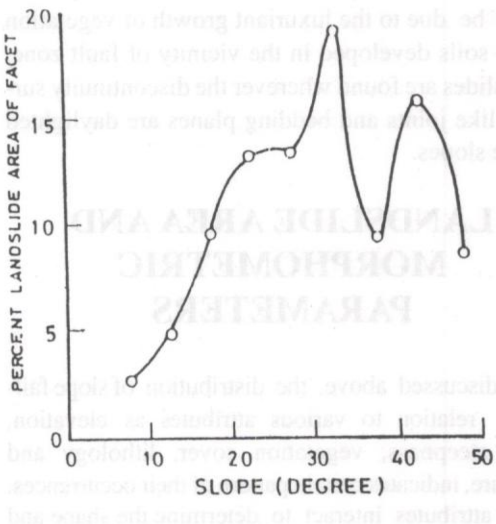

Fig. 5 Distribution of Landslide Area vs. Slope

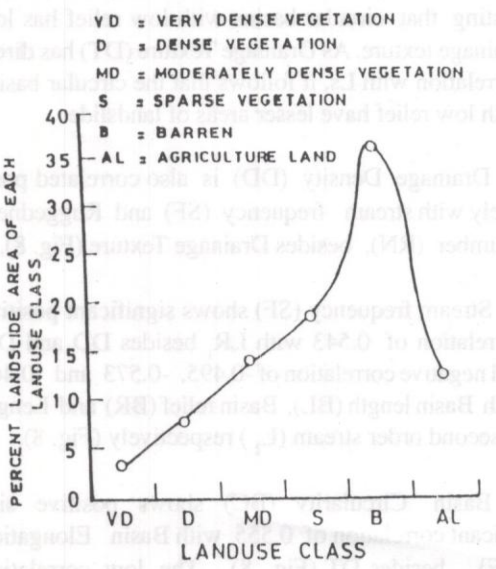

Fig. 6 Distribution of Landslide Area vs. landuse (vegetation)

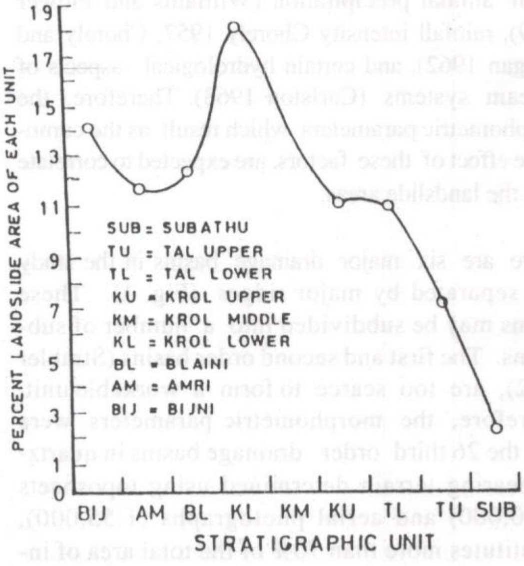

Fig. 7 Distribution of Landslide Area vs. Stratigraphic Units

major fault or thrust are considered highly susceptible to slope movements. Although this major fault in the southwestern part of the area has caused intense fracturing of the quartzites, the slope failure is not a common phenomenon in its vicinity. This could be due to the luxuriant growth of vegetation in the soils developed in the vicinity of fault zone. Landslides are found wherever the discontinuity surfaces like joints and bedding planes are daylighted on the slopes.

LANDSLIDE AREA AND MORPHOMETRIC PARAMETERS

As discussed above, the distribution of slope failure in relation to various attributes as elevation, slope steepness, vegetation cover, lithology and structure, indicates certain pattern of their occurrences. These attributes interact to determine the shape and the geomorphic features of the terrain. Geomorphic studies by various workers indicate the sensitivity of morphometric parameters to lithology (Horton 1945 Yatsu 1965 and Burden 1966), structure (Beaty 1962), slope inclination, vegetation cover (Strahler 1964), mean annual precipitation (Williams and Flower 1969), rainfall intensity Chorely 1957; Chorely and Morgan 1962), and certain hydrological aspects of stream systems (Carlston 1963). Therefore, the morphometric parameters which result as the cumulative effect of these factors, are expected to correlate with the landslide areas.

There are six major drainage basins in the study area separated by major ridges (Fig. 1). These basins may be subdivided into a number of sub-basins. The first and second order basins (Strahler 1952), are too scarce to form a workable unit. Therefore, the morphometric parameters were for the 26 third order drainage basins in quartzite bearing terrain determined using toposheets (1:50,000) and aerial photographs (1:55,000), constitutes more than 70% of the total area of investigation. The morphometric parameters are presented in Table 1.

CORRELATION BETWEEN LANDSLIDE AREA AND MORPHOMETRIC PARAMETERS

With a view to decipher relationship, if it exists, between the fraction of landslide area within a basin and each of the nineteen morphometric parameters of basin, Pearson's correlation coefficients (Dixon and Marsey 1969) were computed for all possible 190 pairs of variables from 26 drainage basins (Table 2).

Fig. 8 indicates that fraction of Landslide Area (Ls) shows significant correlation (>0.456 at 1% level of significance) of 0.857, 0.838, 0.685 and -0.555 with Drainage Texture (DT), Stream Frequency (SF), Drainage Density (DD), and Basin circularity (BC) respectively.

Drainage Texture (DT) shows very high positive correlation coefficient of 0.952 and 0.948 with Drainage Density (DD) and Stream Frequency (SF) respectively (Fig. 8). It also shows negative correlation with Basin Relief (BR) and Basin Circularity (BC), suggesting that circular basins with low relief has low drainage texture. As Drainage Texture (DT) has direct correlation with Ls, it follows that the circular basins with low relief have lesser areas of landslide.

Drainage Density (DD) is also correlated positively with stream frequency (SF) and Ruggedness Number (RN), besides Drainage Texture (Fig. 8).

Stream frequency (SF) shows significant positive correlation of 0.543 with LR_1 besides DD and DT, and negative correlation of -0.495, -0.573 and -0.467 with Basin length (BL), Basin relief (BR) and Length of second order stream (L_2) respectively (Fig. 8).

Basin Circularity (BC) shows positive significant correlation of 0.555 with Basin Elongation (BE), besides DT (Fig. 8). The low correlation between BC and BE probably indicates that there is some structural control which helps in the development of basin circularity which is in conformity with

Table 1 Morphometric parameters used

Sl. No.	Parameters	Symbols	Formula
1.	Fraction of Landslide area	Ls	LA/BA
2.	Basin slope	B.SL	BR/BL
3.	Bifurcation ratio	BF_1	F_1/F_2
4.	Bifurcation ratio	BF_2	F_2/F_3
5.	Length ratio	LR_1	L_1/L_2
6.	Length ratio	LR_2	L_2/L_3
7.	Stream frequency	SF	$F_1+F_2+F_3/BA$
8.	Drainage density	DD	$L_1+L_2+L_3/BA$
9.	Drainage Texture	DT	SF x DD
10.	Ruggedness number	RN	DD x BR
11.	Basin Elongation	BE	$\frac{ND}{BL}$
12.	Basin circulaity	BC	BA/p2X 4π

LA, BA, BL, BR and ND are Landslide Area, Basin Area, Basin Length and Basin Relief, and Diameter of circle whose area is equal to that of the basin, respectively.
L_1, L_2, L_3 and P are Lengths of first order, second order and third order stream, and the basin perimeter respectively.

the findings of Chorely (1964). Basin area (BA) shows a high positive correlation of 0.883, 0.953, 0.929, 0.963, 0.911, 0.959, 0.576 and 0.957 with Bifurcation ratio (BF_2), F_1, F_2, lengths of first order, second order and third order (L_1, L_2, L_3), BR and BL respectively (Table 2). Basin relief (BR) has significant positive correlation of 0.485, 0.459, 0.672, 0.489, 0.576 and 0.712 with F_1, L_1, L_2, L_3, BA and BL respectively, implying thereby that as relief increases the frequency of first order streams, length of first, second and third order streams, basin area and basin length also increase. The relief has a maximum effect on basin length and the length of second order streams. Its correlation with BL suggests its tendency to erode. It is important to note that the area is characterised by retreating slopes which are usually dominated by rill and channel erosion. Hence, it appears that the present topography is the result of accelerated erosion of slopes toward ridges.

From the discussion above and Figure 8, it becomes apparent that DT is directly related to DD, SF, RN, BC, BR and Ls. Stream frequency (SF) is directly related to BL, L_2, BR LR and Ls and the Drainage Density (DD) is directly related with DT, SF, RN and Ls. Therefore, the drainage texture (DT) which is a product of drainage density (DD) and stream frequency (SF), is one single parameter which influences most of the morphometric parameters both directly and indirectly. Also, it is the parameter which shows the highest significant correlation coefficient (0.86) with fraction of landslide area (Ls) and, hence, this parameter appears to be of great importance in investigating the slope instability in such terrain.

RELATIONSHIP BETWEEN LANDSLIDE AREA AND DRAINAGE TEXTURE

The landslide area has a significantly high positive linear correlation coefficient of about 0.86 (Table 2)

Table 2 Correlation matrix of all possible correlation coefficient among morphometric parameters

	Ls	B.SL	BF_1	BF_2	LR_1	LR_2	SF	DD	DT	B.E	RN	F_1	F_2	L_1	L_2	L_3	BR	BA	BL	BC
Ls	1.00	0.3376	-0.3875	-0.0559	0.3423	-0.0840	0.8382	0.6847	0.8570	-0.3963	0.3567	-0.2440	-0.1456	-0.2064	-0.2990	-0.2603	-0.3855	-0.2662	-0.3312	-0.5547
B.SL		1.0000	-0.5461	-0.7268	-0.0334	0.2219	0.3795	0.1566	0.2896	0.1820	-0.1064	-0.8301	-0.7500	-0.8197	-0.6742	-0.8292	-0.3219	-0.7947	-0.8391	-0.0744
BF_1			1.0000	0.2509	0.2049	0.3632	-0.2349	-0.0290	-0.2309	-0.0013	0.3791	0.5541	0.2706	0.5085	0.4515	0.3652	0.4481	0.4388	0.5230	0.3625
BF_2				1.0000	-0.0193	-0.1715	-0.2404	-0.0935	-0.1690	-0.0246	0.1919	0.8585	0.9154	0.8941	0.7628	0.8855	0.3462	0.8833	0.3269	-0.0715
LR_1					1.0000	-0.3831	0.5432	0.3153	0.3749	-0.1925	0.0825	0.0039	-0.0439	-0.0091	-0.3875	-0.0304	-0.3521	-0.1519	-0.0154	-0.0760
LR_2						1.0000	-0.16[illegible]	0.0466	-0.0875	0.1410	0.3011	-0.0846	-0.2288	-0.0696	0.1769	-0.2978	0.2367	-0.0809	-0.0527	0.2990
SF							1.0000	0.8472	0.9484	-0.3600	0.3822	-0.3160	-0.2577	-0.3213	-0.4674	-0.3559	-0.5728	-0.4403	-0.4949	-0.4424
DD								1.0000	0.9516	-0.2885	0.6624	-0.1124	-0.1067	-0.1119	-0.2191	-0.1985	-0.4224	-0.2575	-0.2948	-0.4018
DT									1.0000	-0.3921	0.5508	-0.2410	-0.1959	-0.2394	-0.3405	-0.2764	-0.4758	-0.3502	-0.3934	-0.4952
B.E										1.0000	-0.4051	0.0205	0.0629	0.0486	0.0135	-0.0491	-0.1857	0.0293	-0.1630	0.5550
RN											1.0000	0.3100	0.2173	0.2860	0.3310	0.1880	0.3801	0.2057	0.2796	-0.3311
F_1												1.0000	0.9457	0.9894	0.8581	0.9338	0.4851	0.9529	0.9135	0.0763
F_2													1.0000	0.9570	0.8090	0.9362	0.3767	0.9288	0.9565	-0.0475
L_1														1.0000	0.8435	0.9299	0.4599	0.9626	0.9139	0.0458
L_2															1.0000	0.8315	0.6717	0.9110	0.8962	0.1054
L_3																1.0000	0.4893	0.9587	0.9281	-0.0071
BR																	1.0000	0.5760	0.7119	0.0159
BA																		1.0000	0.9570	0.0459
BL																			1.0000	0.0001
BC																				1.0000

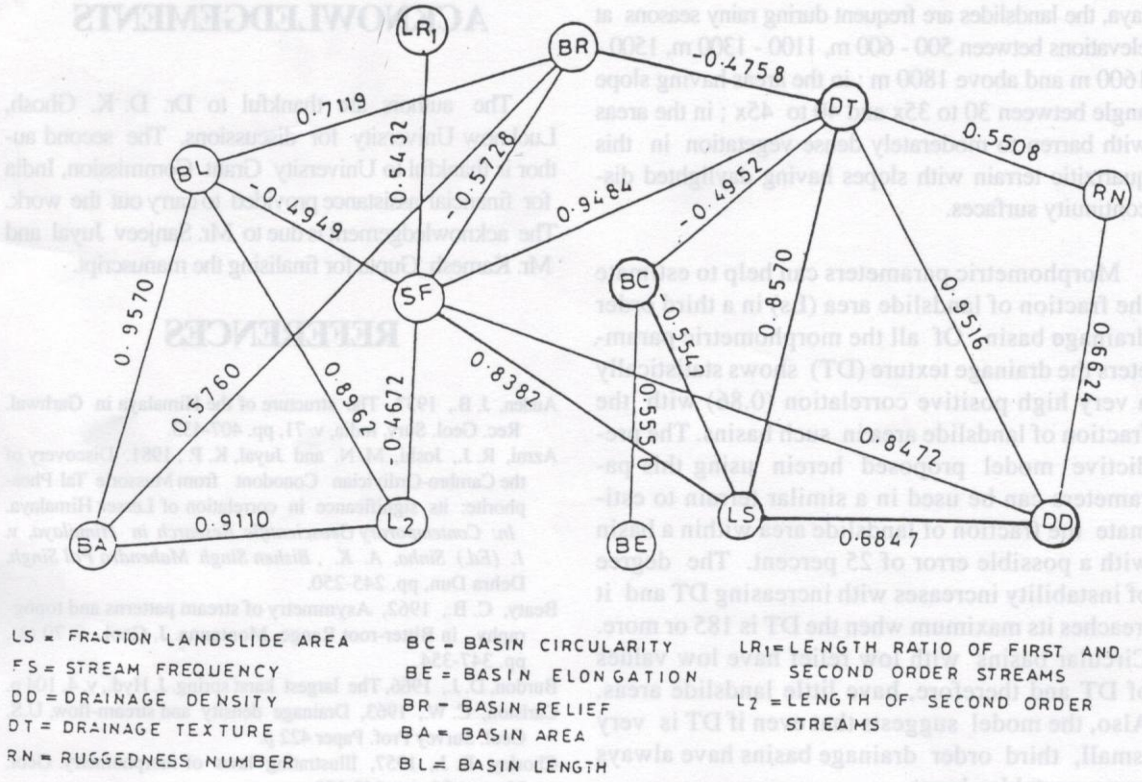

Fig. 8 Correlation Coefficients Between fraction of Landslide Area (Ls) and Morphometric Parameters (Figures Along the Lines Indicate Correlation Coefficients)

with Drainage Texture (DT). Therefore, the development of a quantitative relationship between these two parameters may provide a predictive model for the estimation of the fraction of landslide area from the Drainage Texture. Regression analysis was applied on 26 observations of fraction of Landslide area (Ls) and the Drainage Texture (DT) and the following regression model was worked out.

$$Ls = 0.0279 + 0.0052\, DT$$

This relationship indicates that as DT increases, L_s increases and under extreme condition when DT approaches to about 185, almost all slopes of the basin become critical and unstable. Circular basins of low relief have low values of DT and thus have little landslide areas and their slopes are relatively stable. The relationship also suggests that even if DT is very small, the third order basin will have some unstable slope faces.

With a view to test the efficacy of the regression model, four randomly selected test basins were subjected to this analysis. Under ideal condition, the estimated and observed landslide areas shall have matching values. Plots of the estimated and observed fraction landslide area for each of 26 third order drainage basins alongwith four sampled basins under test are shown in Fig 9. It indicates that the plots of all the four basins under test and most of the observed samples fall close to 45x line indicating the efficacy of this predictive model. It has a possible error of 25 percent.

CONCLUSIONS

The landslide distribution is found to relate with the terrain attributes such as topographic elevation, hill slope inclination, vegetation cover, lithology, structure in relation to climatic conditions. In the Garhwal region (Tehri district) of the Lesser Himalaya, the landslides are frequent during rainy seasons at elevations between 500 - 600 m, 1100 - 1300 m, 1500 - 1600 m and above 1800 m ; in the areas having slope angle between 30 to 35x and 40 to 45x ; in the areas with barren to moderately dense vegetation in this quartzitic terrain with slopes having daylighted discontinuity surfaces.

Morphometric parameters can help to estimate the fraction of landslide area (Ls) in a third order drainage basin. Of all the morphometric parameters the drainage texture (DT) shows statistically a very high positive correlation (0.86) with the fraction of landslide area in such basins. The predictive model proposed herein using this parameters can be used in a similar terrain to estimate the fraction of landslide area within a basin with a possible error of 25 percent. The degree of instability increases with increasing DT and it reaches its maximum when the DT is 185 or more. Circular basins with low relief have low values of DT and therefore, have little landslide areas. Also, the model suggests that even if DT is very small, third order drainage basins have always some unstable slopes.

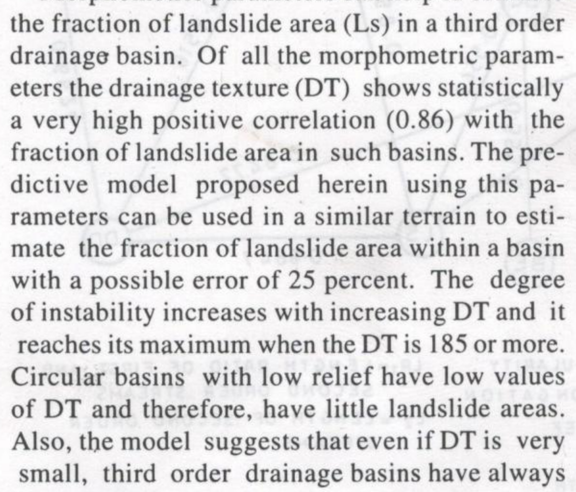

Fig. 9 Comparsion of Computed and Observed fraction of Landslide Area(Ls)

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