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RESEARCH ARTICLE

GIS-based Morphometric Analysis of Five Major Sub-watersheds of Song River, Dehradun District, Uttarakhand with Special Reference to Landslide Incidences

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Abstract Evaluation of the morphometric parameters requires preparation of drainage map, contour map, ordering of the various streams and measurements of catchment area, perimeter, relative relief, relief ratio, length of drainage channels, drainage density, drainage frequency, bifurcation ratio, texture ratio, circulatory ratio and constant channel maintenance, which help to understand the nature of the drainage basin. The present study involves the Geographic Information System (GIS) analysis techniques to evaluate and compare linear, relief and aerial morphometry of the five sub-watersheds of Song River (tributary of the Ganga River) with special reference to landslide incidences, for future development and planning of the watershed. Jakhan Rao, Song River, Bandal Nadi, Baldi Nadi and Suswa Nadi are the five major sub-watersheds of the Song River basin. All the sub-watersheds are basically of 5th to 6th order. Drainage patterns are mainly dendritic to sub dendritic. The drainage pattern of the Song River basin is mainly structurally controlled and the area is characterized by high to moderate relief. The asymmetric factor indicates that the tectonic rotation of the four sub-watersheds is upward on the right side of the drainage basin and only one sub-watershed is downward. The numbers of the landslide incidences are also more in the upward side, than the downward side of the Song River basin.

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Introduction

The study area (Fig. 1) is located in the sub-tropical, humid and temperate type of climate between 30°00′ to 30°30′ North latitude and 77°45′ to 78°15′ East longitude, Dehradun District, Uttarakhand. The rock exposed in the area ranges from Neo-Proterozoic to Quaternary.

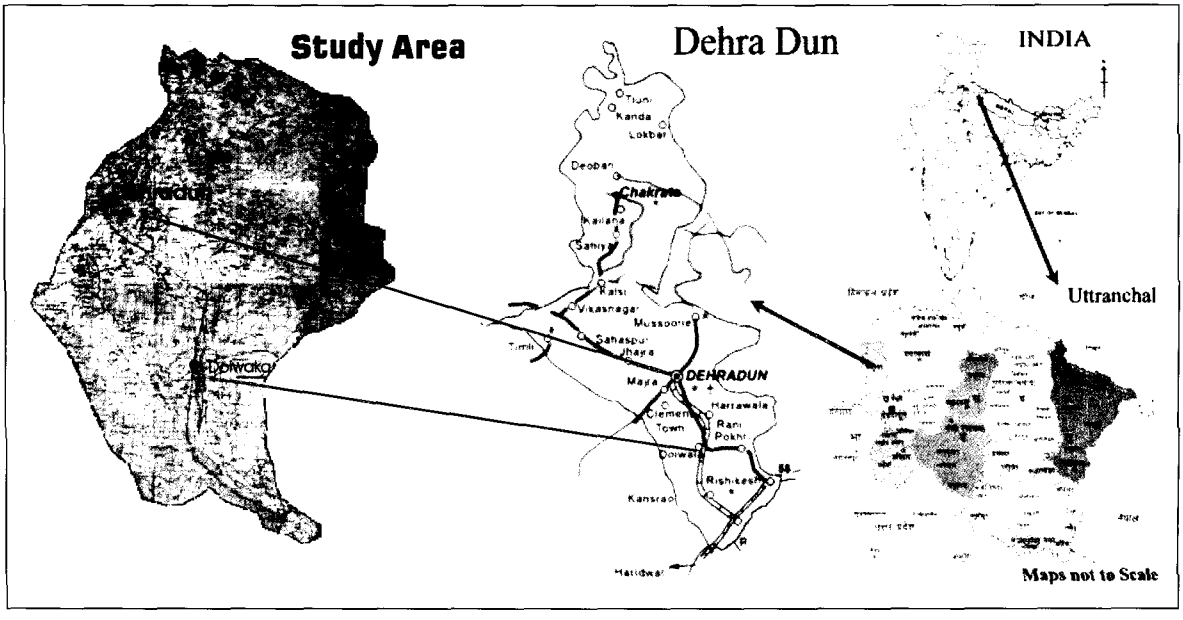

Fig. 1 Location of the Song River watershed.

Lithologically Jakhan Rao sub-watershed comprises loose material of gravel, boulder bed, dolomite, limestone, calcareous shale, slate, phyllite, shaly slate, tilloids and quartzite. The Song River, Bandal Nadi and Baldi Nadi sub-watersheds comprise, quartzite with limestone, shale, chert with phosphorite, carbonaceous shale, calcareous shale, slate, phyllite, shaly slate, tilloids, marl and olive green carbonaceous shale. Suswa Nadi sub-watershed consists of fan alluvium, Doon gravel, coarse sandstone, boulder bed, conglomerate, clay and grit of Upper Siwalik rocks, quartzite with limestone, occasionally conglomerate, dolomite, limestone, calcareous shale, shale with limestone intercalation, carbonaceous shale, slate and phyllite.

Physiographically, the area features piedmont fans and Doon Valley in the southern part and the elevated rugged mountainous terrain of lesser Himalaya in the north part having both peaks and 'U' & 'V' shaped valleys. Majority of the ridges (locally called as Dhar) in the area are structurally controlled. Longitudinal ridges, transverse ridges and intermittent deep dissected valleys are the normal features in this area. The area experiences temperature ranging from below freezing point in winter to as high as 36°C in summer. A large amount of precipitation occurs during the months of June to September due to monsoon whereas little rains occur during December–February due to western climate disturbance.

The general trend of the rocks except near the fold closure is NW–SE, with dips varying from 15° to 60° on either side. The Lesser Himalayan rocks show polyphase deformation with major axes running NW–SE direction. The refoldation of antiforms and synforms is manifested in the form of several structural culminations and depressions. The rocks of 'Mussoorie Syncline' are folded into doubly plunging syncline, with its axis trending in general NW–SE direction.

Morphometric analysis

Methodology

The five sub-watersheds drainage networks were delineated from rectified, mosaiced SOI topographic maps of 53J/03, 04, 07, 08 and 53F/11 (1:50,000 scale) on polyconic projection system with the help of GIS software.

With the help of the vector module of Erdas software 8.4, drainage was digitized. The stream order was calculated using the method proposed by Strahler's (1964). The methodology adopted for the computation of morphometric parameters are given below:-

All the above parameters of five sub-watersheds were calculated using GIS software.

Discussion

Jhakhan Rao, Song River, Bandal Nadi, Baldi Nadi and Suswa Nadi sub-watersheds are of 6th, 5th, 6th, 5th and 5th order, respectively. The number of streams in various orders is countered and the total length of each order stream is calculated at sub watershed level with the help of GIS software (vector module of ERDAS software). The mean stream length is characteristic property related to the drainage network and its associated surfaces (Vijith and Sathesh, 2006) (Table 1).

Table 1 Methodology adopted for the computation of morphometric analysis

Morphometric parameters	Symbol/Formula
Area (km^2)	A
Perimeter (km)	P
Stream order	(u) Hierarchical order
Stream length of all order	(Lu)
Total number of stream segments in all order	Nu
Mean stream length	(Lsm)=Lu/Nu
Bifurcation Ratio	Rb= Nu/Nu+1
Drainage density (km/km^2)	$Dd=L_u/A$
Stream frequency	$F_s=N_u/A$
Drainage texture	$R_t=N_u/P$
Circularity ratio	$R_c=4\ \Pi\ A/P^2$
Form factor	$R_f=A/L_b^2$
Constant channel maintenance	C=1/Dd
Basin relief	B_h
Elongation ratio	$R_e=2\{(\sqrt{A}/\Pi)/\ L_b$
Total number of first order	N_1
Texture ratio	$T=N_1/P$
Π	3.14

The *Bifurcation ratios* (Rb) of Jhakhan Rao, Song River and Suswa Nadi sub-watersheds are 2.644, 2.009 and 2.213, on the other hand Bandal Nadi and Baldi Nadi sub-watersheds are 1.839 and 1.813. High *Bifurcation Ratios* of Jhakhan Rao, Song River and Suswa Nadi sub-watersheds indicate structural complexity and low permeability of the terrain. Bandal Nadi and Baldi Nadi have a low value of *Bifurcation Ratio* (Rb), which indicates that the drainage of the basin is not affected by structural disturbance (Table 2). It is also suggested that the sub-watershed is highly permeable and covered by thick vegetation. The computed Rb value is given in Table 3. The *Bifurcation Ratio* is also an indicative tool of the shape of the basin. Elongated basins have low Rb value, while circular basins have high Rb value (Morisawa, 1985).

The *mean stream length (Lsm)* of Song watershed and its sub-watershed is given in Table 4. The plot (Fig. 2) of logarithm of stream length (ordinate) as a function of stream order (abscissa) yields a set of points lying essentially along a straight line fit following Horton's (1945) law of stream length. The straight line fit indicates that the ratio between Lu and u is constant throughout the successive order of a basin and suggests that geometrical similarity is preserved in basins of increasing order. It also indicates that all the sub-watershed homogeneous rock material is subjected to weathering-erosion characteristics of the watershed.

The important parameters describing the shape of the basin are *Form Factor (Rf), Circulatory Ratio (Rc)* and *Elongation Ratio (Re)*, which are computed

Table 2 Linear aspect of the drainage network of Jakhan Rao, Song River, Bandal Nadi, Baldi Nadi and Suswa Nadi sub-watershed

Sub watershed	Stream order	Number of streams N_u	Total length of streams in km L_u	Log N_u	Log L_u
Jakhan Rao	1	478	243.7858	2.6794	2.3870
	2	213	62.79	2.3284	1.7979
	3	125	27.0106	2.0969	1.4315
	4	52	14.3687	1.7160	1.1574
	5	60	28.1052	1.7782	1.4488
	6	10	44.1678	1.0000	1.6451
Song River	1	654	306.6672	2.8156	2.4867
	2	312	82.7787	2.4942	1.9179
	3	129	31.8959	2.1106	1.5037
	4	57	13.9175	1.7559	1.1436
	5	120	40.8019	2.0792	1.6107
Bandal Nadi	1	463	210.3721	2.6656	2.3230
	2	223	54.4947	2.3483	1.7364
	3	121	26.4759	2.0828	1.4229
	4	61	16.0984	1.7853	1.2068
	5	19	7.1893	1.2788	0.8567
	6	234	16.6099	2.3692	1.2204
Baldi Nadi	1	301	135.4406	2.4786	2.1317
	2	126	30.1424	2.1004	1.4792
	3	81	18.9846	1.9085	1.2784
	4	62	11.3629	1.7924	1.0555
	5	31	15.9678	1.4914	1.2032
Suswa Nadi	1	518	384.4645	2.7143	2.5849
	2	278	173.9737	2.4440	2.2405
	3	162	153.3263	2.2095	2.1856
	4	41	88.3536	1.6128	1.9462
	5	31	40.5547	1.4914	1.6080

Table 3 Calculative value of Bifurcation Ratio and Mean Bifurcation Ratio

Sub-watershed	Bifurcation ratio R_b					Mean bifurcation ratio
	1st order/ 2nd order	2nd order/ 3rd order	3rd order/ 4th order	4th order/ 5th order	5th order/ 6th order	
Jakhan Rao	2.244	1.704	2.404	0.867	6	2.644
Song River	2.096	2.419	2.263	0.475	2.791	2.009
Bandal Nadi	2.076	1.843	1.984	3.211	0.081	1.839
Baldi Nadi	2.389	1.556	1.306	2.000	0	1.813
Suswa Nadi	1.863	1.716	3.954	1.323	0	2.213

Table 4 Calculative value of Length Ratio and Mean Length Ratio

Sub-watershed	Length ratio R_b					Mean length ratio
	2nd order/ 1st order	3rd order/ 2nd order	4th order/ 3rd order	5th order/ 4th order	6th order/ 5th order	
Jakhan Rao	0.258	0.430	0.532	1.956	1.572	0.949
Song River	0.270	0.385	0.436	2.932	0.349	0.845
Bandal Nadi	0.259	0.486	0.608	0.447	2.310	0.822
Baldi Nadi	0.223	0.630	0.599	1.405	0	0.714
Suswa Nadi	0.453	0.881	0.576	0.459	0	0.592

and given in Table 5. The Jakhan Rao, Song River and Suswa Nadi sub-watersheds with *Form Factors* of 0.121, 0.117 and 0.134, indicate elongated basin, and have a flatter peak of low flow for longer duration. Bandal and Baldi Nadi sub-watersheds with *Form Factors* of 0.319 and 0.215 indicate basin as semi circular in nature, and have a high peak flow for shorter duration. Flood flows of elongated basin are easier to manage than that of the circular basin (Nautiyal, 1994).

The values of *Circulatory Ratio (Rc)* of Jakhan Rao, Song River, Bandal Nadi, Baldi Nadi and Suswa Nadi sub-watersheds vary from 0.300, 0.528, 0.603, 0.437 and 0.351 respectively and *Elongation Ratio* varies from 0.393, 0.385, 0.637, 0.523 and 0.413 respectively, which indicates that Jakhan Rao, Song River and Suswa River sub-watersheds are elongated in nature and Baldi and Bandal sub-watersheds are semicircular in nature and the area is characterized by high to moderate relief and the drainage system is structurally controlled.

Calculative value of *Drainage density (Dd)* is represented in Table 5, Jakhan Rao, Song River, Bandal Nadi, Baldi Nadi and Suswa Nadi sub-watersheds have a *Drainage Density* of 2.897, 3.663, 4.002, 4.002 and 2.899 respectively. Bandal Nadi, Baldi Nadi and Song sub-watersheds have a high *Drainage Density* which indicates that the region is weak and consists of impermeable subsurface material and sparse vegetation cover and mountainous relief. Jakhan Rao and Suswa Nadi have a low *Drainage Density* which indicates that the area is covered by resistant permeable rocks with a dance vegetation cover.

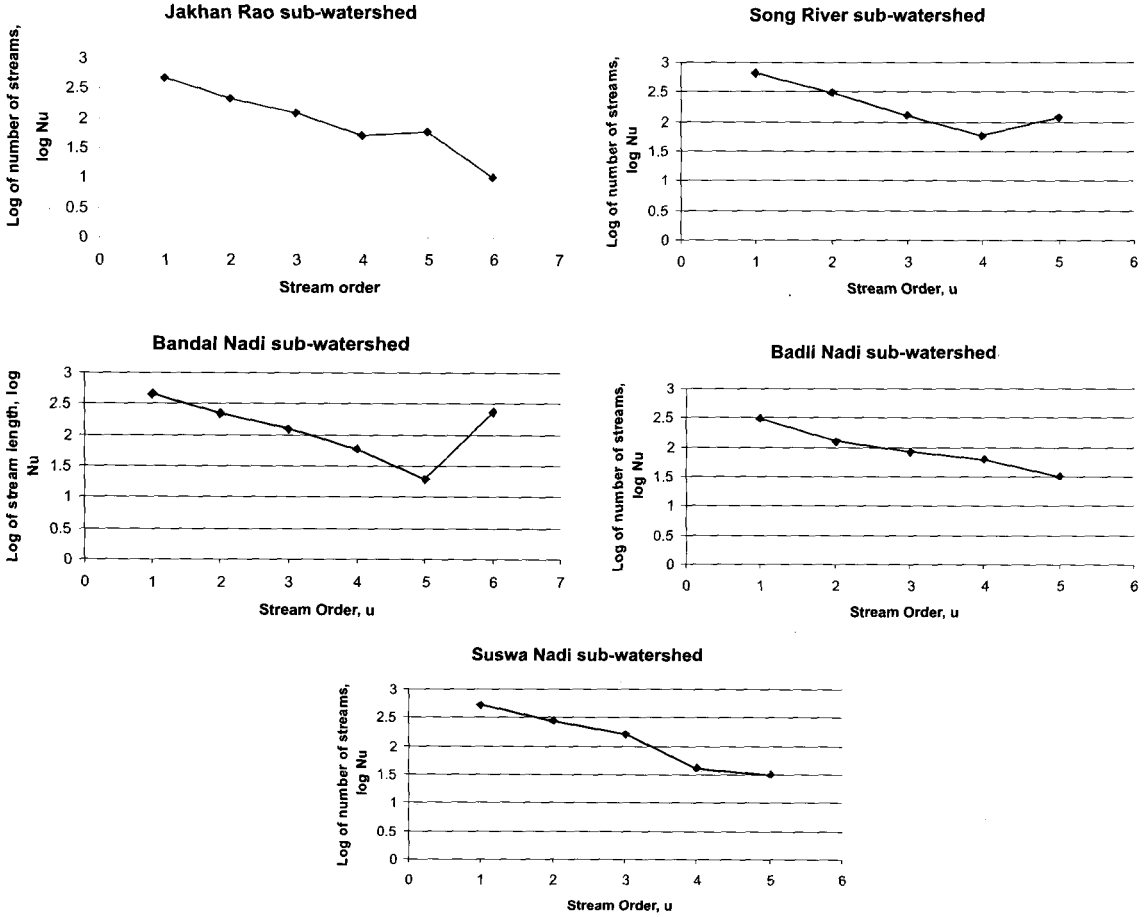

Fig. 2a Regression of logarithm of number of streams versus stream order.

Constant Channel Maintenance (C) is inverse of *Drainage Density* and the computed value is given in Table 5. The *Constant Channel Maintenance* of Jakhan Rao and Suswa Nadi sub-watersheds are same i.e., 0.345, on the other hand Song River, Bandal Nadi and Baldi Nadi sub-watersheds are 0.273, 0.249 and 0.247 respectively. It indicates that the above (Song River, Bandal Nadi and Baldi Nadi) sub-watersheds are under the influence of high structural disturbance, low permeability, steep to very steep slopes and high surface runoff.

Stream Frequency (Fs) is related to permeability, infiltration capacity and relief of the sub-watershed. In all the sub-watersheds, except Suswa Nadi sub-watershed, the *Stream Frequencies* are high i.e., 6.467, 9.824, 13.61 and 11.487 respectively. On the other hand the *Stream Frequency* of Suswa Nadi sub-watershed is 3.552. High Fs indicate the high relief and high infiltration capacity of the bed rocks pointing towards the increase in stream population respectively and is categorized as moderate to high in nature, which indicate erodibility of the rock

Table 5 Arial aspect of drainage network of Jakhan Rao, Song River, Bandal Nadi, Baldi Nadi and Suswa Nadi sub-watershed

Sub-watershed	Area	Perimeter	Basin order	Bh	Re	Dd	Fs	T	Rf	Rc	C
Jakhan Rao	145.05	77.99	6	1560	0.393	2.897	6.467	6.12	0.121	0.30	0.35
Song River	133.86	56.42	5	1800	0.385	3.663	9.824	11.59	0.117	0.53	0.27
Bandal Nadi	82.35	41.40	6	1835	0.637	4.022	13.61	11.18	0.32	0.60	0.25
Baldi Nadi	52.32	38.78	5	1912	0.523	4.044	11.487	7.76	0.22	0.44	0.25
Suswa Nadi	290.01	101.94	5	1440	0.413	2.899	3.552	5.08	0.13	0.35	0.35

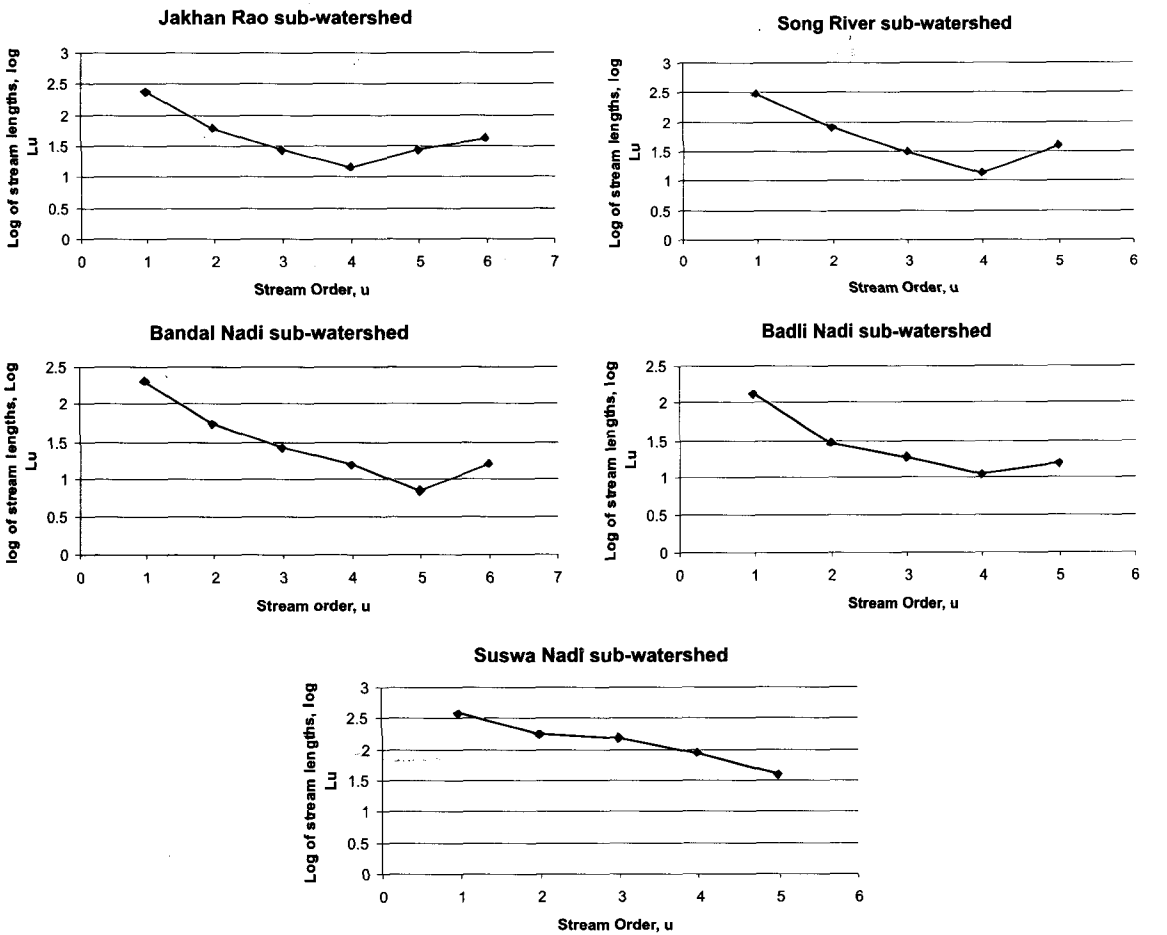

Fig. 2b Regression of logarithm of streams lengths versus stream order.

surface as moderate to high in nature and infiltration capacity and relief aspect of the terrain are also moderate to high.

Asymmetric factor was developed to detect tectonic tilting at drainage basin scale.

The asymmetric factor (AF) is defined as :

$$AF=100\ (Ar/At)$$

where, Ar = Area of the right (facing down stream) of the trunk stream, and
At = Total area of the drainage basin.

In Jhakhan Rao, Song River, Badli Nadi and Suswa Nadi sub-watersheds the asymmetric factors are 55%, 56%, 58% and 65% respectively indicating that tectonic rotation is upward to the right side of the drainage basin and in the case of Bandal Nadi the asymmetric factor is 48% indicating that the tectonic rotation is down to the right side of the drainage basin (Figs. 3a, b, c, d, e).

Landslide incidences have been recorded in 29, 47, 28, 28 and 52 respectively in the Jhakhan Rao, Song River, Bandal Nadi, Badli Nadi and Suswa Nadi sub-watershed represented in Fig. 3. Maximum landslide incidences are recorded in the 1st order stream. The right sides of the main stream of Bandal river sub-watershed, landslide incidences are 10 nos and in the left side it is 18 nos. So, the numbers of the landslide incidences are more in upward tilting side, than the downward rotational side. On the other hand Jhakhan Rao, Song River, Badli Nadi and Suswa Nadi sub-watershed, landslide incidences are 21, 36, 18 and 51 nos and in the left side it is 8, 11, 10 and 21 nos. So, the numbers of the landslide incidences are more in upward tilting side, than the downward rotational side (Figs. 3a, b, c, d, e).

Conclusions

The Jakhan Rao and Bandal Nadi are of 6th order and Song River, Baldi Nadi and Suswa Nadi sub-watershed are of 5th order respectively. The *Bifurcation Ratios* indicate that the drainage has been affected by the tectonic disturbance. Low value of *Drainage Density* (Jakhan Rao and Suswa Nadi) indicates that the areas are covered by the resistant permeable rocks with vegetative cover. High value of *Drainage Density* (Song River, Baldi Nadi and Bandal Nadi) indicates that the region is weak and

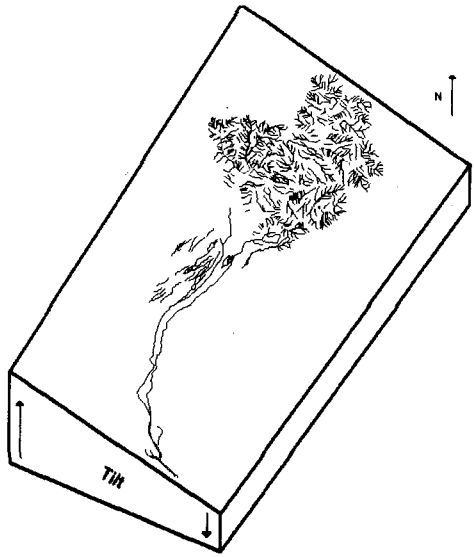

Fig. 3(a) Block diagram showing tilting of Jhakhan Rao sub-watershed with landslide incidences.

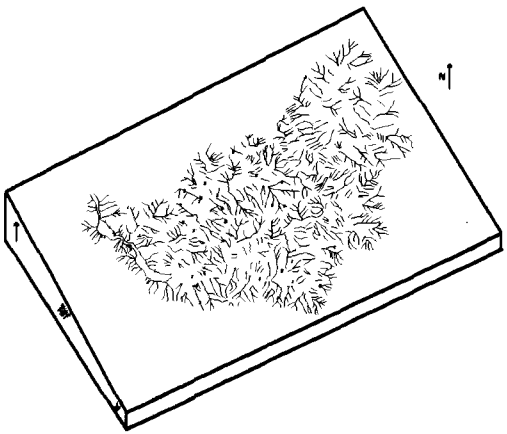

Fig. 3(b) Block diagram showing tilting of Song River sub-watershed with landslide incidences.

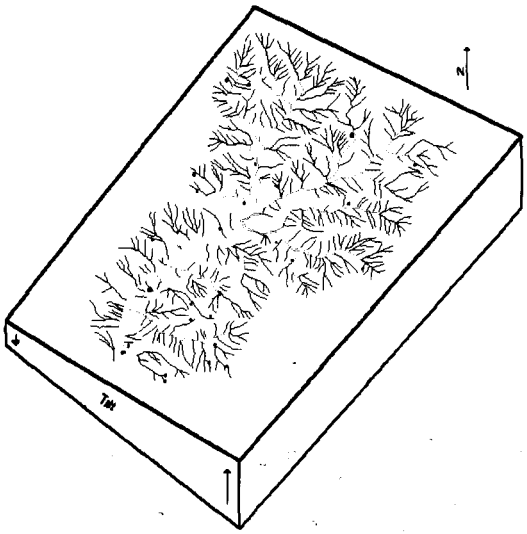

Fig. 3(c) Block diagram showing tilting of Bandal Nadi sub-watershed with landslide incidences.

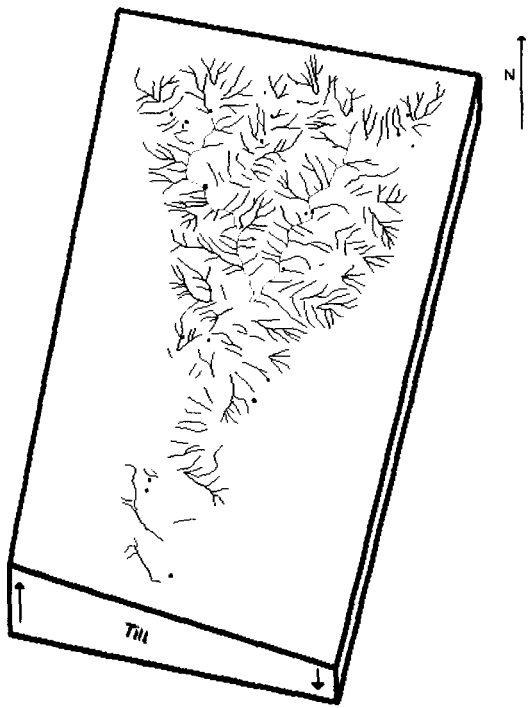

Fig. 3(d) Block diagram showing tilting of Badli Nadi sub-watershed with landslide incidences.

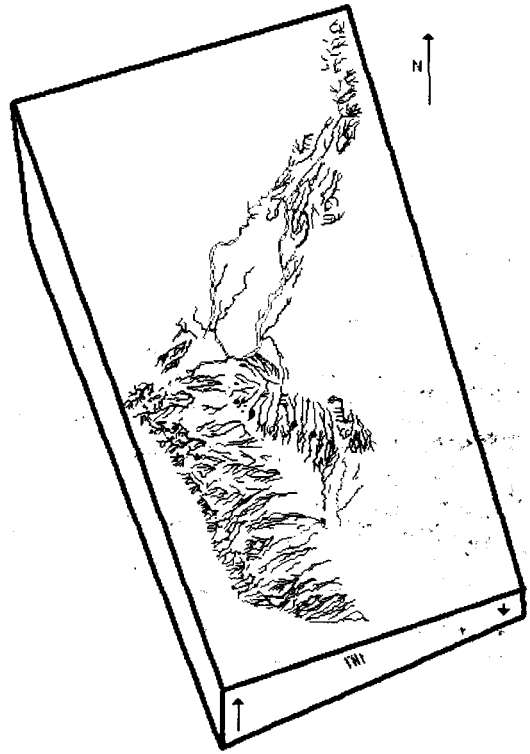

Fig. 3(e) Block diagram showing tilting of Suswa Nadi sub-watershed with landslide incidences.

covered by impermeable subsurface material, sparse vegetation and high mountainous relief. The linear pattern of the graphical representation indicates the homogeneous weathering erosional characteristic of the study area. *Elongation Ratio, Circulatory Ratio* and *Form Factor* values shows that the sub-watershed of Jakhan Rao and Suswa Nadi possess an elongated shape which indicates the low runoff and flatter peak of flow while Song River, Baldi Nadi and Bandal Nadi sub-watershed are semicircular in shape, have high peak flow for shorter duration. *Texture Ratio* indicates that infiltration capacity and relief aspect of the terrain are moderate to high in nature.

Thus the study shows that GIS techniques have efficient tools in delineation of the drainage pattern

to understand terrain parameters such as nature of bedrock, infiltration capacity, surface run off etc., which helps in better understanding the status of land form and their processes, drainage management and evolution of groundwater potential for watershed planning and management.

In Jhakhan Rao, Song River, Badli Nadi and Suswa Nadi sub-watersheds the asymmetric factors are 55%, 56%, 58% and 65% respectively indicating that tectonic rotation is upward to the right side of the drainage basin. In Bandal Nadi the asymmetric factor is 48% indicating that the tectonic rotation is down to the right side of the drainage basin. The numbers of the landslide incidences are more in the upward tilting side, than the downward rotational side.

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