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Morphometric analysis of the Ladhiya and Lohawati river basins, Kumaun Lesser Himalaya, India

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with 5 figures and 6 tables

Summary. The morphometric analysis is widely used to assess the drainage characteristics, watershed development and management plans of the river basins. These studies have also proved to be very useful tools to study the active tectonics. Stream frequency, drainage density, drainage texture and other parameters in the Ladhiya and Lohawati River Basins show a strong structural/tectonic control over the drainage of the Tanakpur-Champawat area. Field studies reveal that several parts of the study area are structurally controlled and neotectonically active. Such neotectonic activities are especially associated with the configuration and evolution of the present day topography. Ample evidence of active tectonics such as landslides, river terraces, vertical down-cutting of the rivers, deep gorges of rivers, triangular facets (flatirons) and tilting of beds, have been noticed in various parts of the study area. In some basins the morphometric parameters suggest a possibility of flash floods and high discharges.

Key words: Morphometric analysis, Neotectonics, Tanakpur-Champawat area, Kumaun Lesser Himalaya

Introduction

The drainage network in the young mountain chains is believed to represent a good indicator of active tectonics. The drainage basin morphometric analysis reflects steady state condition of rocks during active deformation (Seeber & Gornitz 1983, Ouchi 1985, Marple & Talwani 1993, Koons 1995, Hallet & Molnar 2001, Thomson et al. 2001, Arisco et al. 2006). A simple approach to describe such adjustments of drainage network against lithological variations during the ongoing tectonic processes is to calculate the parameters which describe the physical changes in the drainage system. The overall morphometric analysis of the drainage network has been carried out following the methods suggested by Horton (1945) and Strahler (1964). The drainage morphometry of a watershed in a terrain is not only controlled by climatic conditions prevailing in the area but also by the lithology and the result of release of stresses along the tectonic planes. Geological structures have great control over the drainage as they influence the nature of flow, erosion and sediment transport (Nag et al. 2003). The permeability, the structural characteristics and the degree of fracturing also affect the extent to which the material can be detached by fluvial process (Derbyshire et al. 1981). Therefore, the role of the geological structures in

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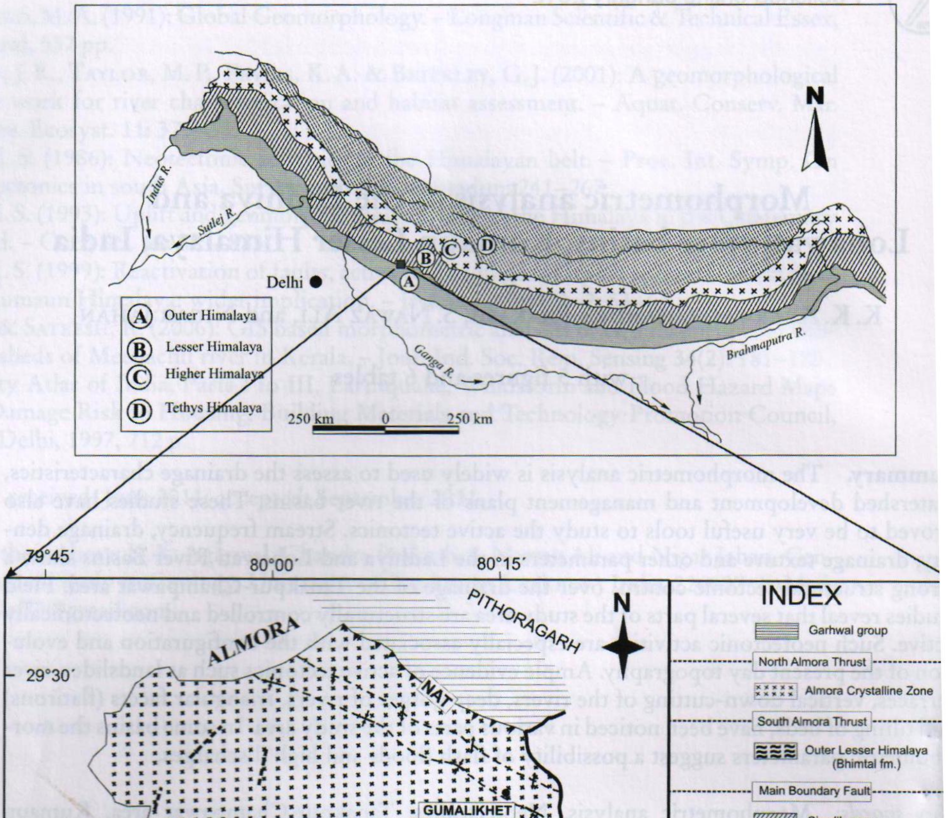

Fig. 1. Generalised geological map of the Himalaya (above); Generalised Geological map of the area, showing various geological formations of the area of present study (modified after VALDIYA 1980, AHMAD et al. 1980) (below).

the development of drainage networks can be better understood by a quantitative morphometric analysis (Nag et al. 2003). Morphometric analysis has been defined as quantitative measurements of landscape shape (Keller & Pinter 1996). Geology, relief and climate are the primary determinants of running water action at the basin scale (Lotspeich & Flatts 1982, Frissel et al. 1986). The morphometric analysis of drainage basin carried out by Horton (1945), Strahler (1952) and others is based on the fact that for the given conditions of lithology, climate, rainfall and other relevant parameters of the basin, the river network, the slope and the surface relief tend to reach a steady state in which the morphology is adjusted to transfer the sediments and excess flow produced. This study also allows the description of the physical changes in a drainage system over time in response to natural disturbances or human impact.

Study area

The Kumaun Himalaya, lying between the River Kali in the east and Sutlej in the west, include a 320 km stretch of mountainous terrain. The study area Tanakpur-Champawat falls in the eastern part of the Kumaun Himalaya (fig. 1). The Ladhiya and Lohawati rivers form the major drainage system of the area. The route from south to north traverses across Bhabhar Formation, Siwalik Group of rocks, Bhimtal Quartzites and Almora Crystallines. The geological formations are separated by major tectonic planes viz. the Himalayan Frontal Faults (HFF), Main Boundary Fault (MBF) and South Almora Thrust (SAT) (fig. 1). Out of the entire Himalayan terrain, the outer Himalaya is believed to show excellent signatures of active tectonics. The Main Boundary Thrust (MBT) that separates the Outer and Lesser Himalaya have a recorded history of tectonic activity in the recent past (Bali et al. 2009). A number of geomorphic features e. g. abrupt changes in the course of the river, terraces, waterfalls, faultscarps, etc. in the area manifest the active tectonic in the area. Numerous later-developed faults are also responsible for off-setting the country rocks, composed of the Rautgara, Deoban, Mandhali & Berinag formations (Valdiya 1993, 1999). Quaternary to recent deposits in the section are characterized by fluvial terraces, large debris deposits, slope wash material and river borne material. Conspicuous geomorphic features such as structural denudational hills, alluvial fans, intermontane valleys etc., have also been observed along this section.

Mass wasting is prevalent all along the route and out of 31 major and minor landslide incidences observed, 16 are debris flows and remaining 15 are rockslides. The quartzites and metavolconics of Bhimtal Quartzites, bounded by the MBF in the south and SAT in the north, are more prone to landslides largely due to proximity to these elements. The landslide hazards within this formation are of rockslide type developed in the sheared and jointed quartzites. The gneisses and schists of the Almora Crystallines are least prone to slides in this section. The processes of erosion and denudation and high intensity of rainfall have been remarkably instrumental in inducing debris slides and flows in alternate sequence of siltstone, clay, shale and sandstone of the Siwalik Group of rocks and slope forming materials of Bhabhar formation exposed in the southern extremity of this area. The landslides hazards along the route indicate conspicuous geomorphic and structural controls of mass wasting processes in the area (Agarwal et al. 2009).

Morphometric analysis

In the present study, morphometric analyses of the Ladhiya and Lohawati river basins have been carried out with the help of Survey of India topographical maps on 1:50,000 scale (fig. 2). The drainage network of the Ladhiya and Lohawati river basins and its sub-basins have been digitized and quantitative analyses of the morphometric parameters of the basin like stream number, stream length, and stream order etc. have been calculated using ARC VIEW 3.2 and ERDAS 8.5 softwares. The morphometric parameters have been divided into three categories viz. linear, areal and shape parameters. The overall drainage network has been analysed according to Horton's (1945) laws stream orders were established according to Strahler (1964).

Linear parameters

Stream order (Nu)

Stream ordering means the determination of the hierarchical position of a stream within a drainage basin. According to Strahler (1952), ordering of stream begins from the fingertip tributaries, which do not have their own feeders (fig. 2). The number of streams (N) of each order (U) for Ladhiya and Lohawati basin is shown in tables 1 and 2. The details of the stream characteristics confirm Horton's (1945) first law of stream numbering, which states that the number of streams of different orders in a given drainage basin tends closely to approximate an inverse geometric ratio.

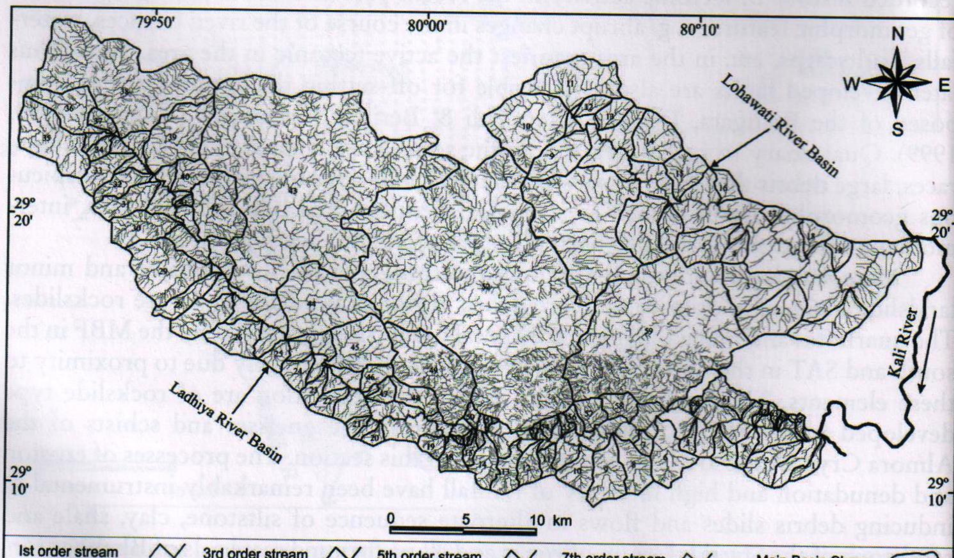

Fig. 2. Sub-basins in Ladhiya & Lohawati river basins, Uttarakhand.

Stream length (Lu)

It is the total length of streams of a particular order. The stream length characteristics of the sub-basins conforms HORTON's (1945) second law, "The Law of Stream Lengths", which states that the average length of the streams of each order in a drainage basin tends closely to approximate a direct geometric ratio. Stream length in all sub-basins of various orders has been measured on Survey of India topographical maps. The total stream length of the Ladhiya and Lohawati river basins is 3,504.39 km and 634.87 km respectively, while the stream lengths of the sub-basins are presented in tables 1 and 2.

Stream length ratio (Rl)

Stream Length ratio (Rl) may be defined as the ratio of the mean length of the one order to the next lower order of stream segment (HORTON 1945) and have been computed as

$Rl = Lu / Lu-1$,

Rl = Stream length ratio,
Lu = stream length of order u,
Lu−1 = stream segment length of the next lower order

The mean stream length ratio of the Ladhiya and Lohawati River Basin is 0.76 and 0.78 respectively. The Rl between streams of different order in the study area reveals that the Rl for sub-basins ranges between 0.35–2.39 (Ladhiya River basin) and 0.23–1.87 (Lohawati River basin) (tables 1 and 2). It seems that the Rl between successive stream orders varies due to differences in slope and topographic conditions, and has an important relationship with the surface flow discharge and erosional stage of the basin (SREEDEVI et al. 2005).

Bifurcation ratio (Rb)

The ratio of number of streams of a given order (Nu) to the number of segment of the higher order (Nu+1) is termed as Bifurcation ratio (Rb) (HORTON 1945, STRAHLER 1964) and computed as

$Rb = Nu / Nu+1$

STRAHLER (1957) demonstrated that Rb shows only a small variation for different regions in different environments except where powerful geological control dominates. The present study shows that the Ladhiya and Lohawati river basins have the mean Rb value of 3.74 and 4.08 respectively, while for the sub-basins it varies from 8.42 to 2.16 (Ladhiya River basin) and 6.44 to 2.0 (Lohawati river basin) (Tables 1 and 2).

RHO coefficient (RHO)

RHO coefficient is the ratio between the stream length ratio (Rl) and the bifurcation ratio (Rb) (HORTON 1945),

$RHO = Rl / Rb$

Table 1. Linear aspects of the Ladhiya Tributary Basin.

Sub basin no.	Stream order						Total no. of Stream (Nu)	Bifurcation Ratio				
	N_1	N_2	N_3	N_4	N_5	N_6		N_1/N_2	N_2/N_3	N_3/N_4	N_4/N_5	N_5/N_6
1	5	2	1				8	2.5	2			
2	20	4	1				25	5	4			
3	15	2	1				18	7.5	2			
4	14	4	2				20	3.5	2			
5	7	2	1				10	3.5	2			
6	40	9	4				53	4.44	2.25			
7	9	2	1				12	4.5	2			
8	34	7	3	1			45	4.85	2.3	3		
9	33	9	3	1			46	3.66	3	3		
10	33	8	1				42	4.12	8			
11	22	5	2	1			30	4.4	2.5	2		
12	30	8	1				39	3.75	8			
13	46	12	2	1			61	3.83	6	2		
14	41	9	2	1			53	4.55	4.5	2		
15	14	5	1				20	2.8	5			
16	4	3	1				8	1.33	3			
17	6	2	1				9	3.0	2			
18	44	9	3	1			57	4.8	3	3		
19	26	5	2	1			34	5.2	2.5	2		
20	7	2	1				10	3.5	2			
21	7	2	1				10	3.5	2			
22	11	3	1				15	3.6	3			
23	12	2	1				15	6.0	2			
24	13	3	1				17	4.33	3			
25	8	2	1				11	4.0	2			
26	31	7	1				39	4.42	7			
27	30	7	1				38	4.28	7			
28	20	4	1				25	5.0	4			
29	85	24	3	1			113	3.54	8	3		
30	50	13	1				64	3.84	13			
31	36	7	1				44	5.14	7			
32	22	5	1				28	4.4	5			
33	23	6	2	1			32	3.83	3	2		
34	9	2	1				12	4.5	2			
35	62	12	3	1			78	5.16	4	3		
36	35	7	2	1			45	5.0	3.5	2		
37	13	3	1				17	4.33	3			
38	224	44	12	2	1		283	5.09	3.66	6	2	
39	59	14	3	1			77	4.21	4.66	3		
40	19	3	1				23	6.33	3			
41	5	2	1				8	2.5	2			
42	75	14	3	1			93	5.35	4.66	3		
43	567	128	28	7	3	1	734	4.42	4.57	4	2.33	3
44	65	12	3	1			81	5.41	4	3		

Table 1. continued.

Stream Length (km)						Length Ratio					Rb	Rl	RHO
L_1	L_2	L_3	L_4	L_5	L_6	L_2/L_1	L_3/L_2	L_4/L_3	L_5/L_4	L_6/L_5			
4.28	0.59	2.63				0.13	4.41				2.25	2.27	1.01
9.55	3.16	3.16				0.33	1.0				4.5	0.66	0.14
4.26	1.28	1.53				0.30	1.19				4.75	0.74	0.15
5.19	0.91	4.21				0.17	4.60				2.75	2.39	0.86
2.09	0.84	1.67				0.40	1.98				2.75	1.19	0.43
14.52	4.09	3.02				0.28	0.73				3.34	0.51	0.15
3.09	0.54	1.21				0.17	2.24				3.25	1.20	0.37
13.70	2.98	1.52	3.08			0.21	0.51	2.02			3.38	0.91	0.27
13.81	4.30	2.54	3.22			0.31	0.59	1.26			3.22	0.72	0.22
9.55	5.53	2.81				0.57	0.50				6.06	0.54	0.08
6.85	0.92	2.15	0.52			0.13	2.33	0.24			2.96	0.90	0.30
8.53	3.57	3.00				0.41	0.84				5.87	0.62	0.10
13.73	3.37	0.80	2.96			0.24	0.23	3.70			3.94	1.39	0.35
12.96	4.72	1.74	1.88			0.36	0.36	1.08			3.68	0.60	0.16
2.71	0.93	2.09				0.34	2.24				3.9	1.29	0.33
0.86	0.18	0.57				0.21	3.16				2.16	1.68	0.77
1.03	0.36	0.55				0.34	1.52				2.5	0.93	0.37
11.93	3.59	1.31	1.21			0.30	0.36	0.92			3.6	0.52	0.14
6.49	1.88	2.06	0.14			0.29	1.09	0.06			3.23	0.48	0.14
2.96	0.92	0.62				0.31	0.66				2.75	0.49	0.17
3.27	0.76	0.69				0.23	0.90				2.75	0.57	0.20
4.38	1.40	1.92				0.31	1.37				3.3	0.84	0.25
5.52	1.54	1.05				0.27	0.68				4.0	0.48	0.12
6.44	2.42	1.76				0.37	0.72				3.66	0.55	0.15
5.20	1.01	0.97				0.19	0.95				3.0	0.57	0.19
13.81	5.46	2.22				0.39	0.40				5.71	0.40	0.07
16.72	2.28	4.17				0.13	1.82				5.64	0.98	0.17
8.64	2.94	2.98				0.34	1.01				4.5	0.67	0.15
37.85	8.31	6.96	3.73			0.21	0.83	0.53			4.84	0.53	0.10
22.13	6.48	4.64				0.29	0.71				8.42	0.50	0.05
14.46	3.72	3.93				0.25	1.05				6.07	0.65	0.10
9.41	2.43	3.71				0.25	1.53				4.70	0.89	0.19
10.58	2.61	1.19	2.10			0.24	0.45	1.76			2.94	0.82	0.27
3.06	2.57	0.56				0.83	0.21				3.25	0.52	0.16
29.03	10.94	2.80	3.40			0.37	0.25	1.21			4.05	0.61	0.15
14.70	4.71	4.47	0.54			0.32	0.94	0.12			3.50	0.46	0.13
5.16	1.10	1.53				0.21	1.38				3.66	0.80	0.28
113.54	22.85	15.46	16.12	1.35		0.20	0.67	1.04	0.08		4.18	0.50	0.11
31.66	7.31	7.81	3.04			0.23	1.06	0.38			3.95	0.56	0.14
8.93	2.35	1.86				0.26	0.79				4.66	0.52	0.11
1.97	0.97	0.36				0.49	0.37				2.25	0.43	0.19
31.88	8.28	7.05	1.13			0.25	0.85	0.16			4.33	0.42	0.09
267.31	83.96	47.47	10.8	20.94	13.83	0.31	0.56	0.22	1.93	0.66	3.66	0.74	0.20
39.20	10.48	6.14	3.03			0.26	0.58	0.49			4.13	0.44	0.10

Table 1. Linear aspects of the Ladhiya Tributary Basin.

Sub basin no.	Stream order						Total no. of Stream (Nu)	Bifurcation Ratio				
	N_1	N_2	N_3	N_4	N_5	N_6		N_1/N_2	N_2/N_3	N_3/N_4	N_4/N_5	N_5/N_6
45	40	10	2	1			44	4.0	5	2		
46	13	2	1				16	6.5	2			
47	14	3	1				18	4.66	3			
48	32	9	3	1			45	3.55	3	3		
49	219	50	12	3	1		285	4.38	4.16	4	3	
50	12	3	1				16	4.0	3			
51	7	3	1				11	2.33	3			
52	955	203	50	13	3	1	1,225	4.70	4.06	3.84	4.33	3
53	7	2	1				10	3.5	2			
54	14	5	2	1			22	2.8	2.5	2		
55	8	3	1				12	2.66	3			
56	16	3	1				20	5.33	3			
57	29	5	1				35	5.80	5			
58	36	7	2	1			46	5.14	3.5	2		
59	597	133	28	7	4	1	770	4.48	4.75	4	1.75	4
60	9	2	1				12	4.50	2.0			
61	43	11	3	1			58	3.90	3.66	3		
62	8	3	1				12	2.66	3.0			
63	6	2	1				9	3.0	2.0			
64	9	3	1				13	3.0	3.0			
65	15	4	1				20	3.75	4.0			

It is considered to be an important parameter as it determines the relationship between the drainage density and the physiographic development of the basin, and allows the evaluation of the storage capacity of the drainage network (HORTON 1945). The mean RHO coefficient of the Ladhiya and Lohawati river basins is 0.23 and 0.22 respectively, while, the RHO of the sub-basins ranges between 0.05 to 1.10 (Ladhiya River basin) and 0.03 to 0.58 (Lohawati River basin) respectively (Tables 1 and 2).

Areal parameters

Area, perimeter and basin length (L)

The Area is the entire area considered between the drainage divide and the outfall with all sub-basin and inter-basinal areas (MESA 2006). Perimeter is the total length of the drainage basin boundary. The Ladhiya and Lohawati river basins cover an area (A) of about 746.83 km^2 and 220.51 km^2 respectively and have a perimeter (P) of 159.74 km and 82.83 km respectively. In the case of the sub-basins of Ladhiya River basin the area ranges from 159.27 km^2 (sub-basin no. 52) and 0.27 km^2 (sub-basin no. 16) and for Lohawati River basin the area ranges between 41.09 km^2 (sub basin no. 8) and 0.95 km^2 (sub basin no. 17). Similarly, the perimeter for these sub-basins

Table 1. continued.

Stream Length (km)						Length Ratio					Rb	Rl	RHO
L_1	L_2	L_3	L_4	L_5	L_6	L_2/L_1	L_3/L_2	L_4/L_3	L_5/L_4	L_6/L_5			
21.54	5.51	4.71	1.52			0.25	0.85	0.32			3.66	0.47	0.13
5.05	2.38	0.97				0.47	0.40				4.25	0.43	0.10
4.99	1.19	1.26				0.23	1.05				3.83	0.64	0.16
9.78	3.77	2.31	0.84			0.38	0.61	0.36			3.18	0.45	0.14
66.13	17.20	8.14	4.10	5.31		0.26	0.47	0.50	1.29		3.88	0.63	0.16
3.72	1.08	0.97				0.29	0.89				3.50	0.59	0.16
2.12	0.39	0.73				0.18	1.84				2.66	1.01	0.38
385.24	106.26	54.88	35.83	11.43	17.1	0.27	0.51	0.65	0.31	1.49	3.98	0.65	0.16
1.71	0.34	0.57				0.19	1.68				2.75	0.94	0.34
3.98	1.32	0.84	0.63			0.33	0.63	0.75			2.43	0.57	0.23
2.37	1.66	0.71				0.70	0.42				2.83	0.56	0.19
3.35	1.45	1.23				0.43	0.84				4.16	0.64	0.15
10.86	4.40	1.33				0.40	0.30				5.40	0.35	0.06
11.72	3.87	1.32	0.87			0.33	0.34	0.65			3.54	0.44	0.12
183.20	61.15	28.34	16.52	9.45	4.01	0.33	0.46	0.58	0.57	0.42	3.79	0.47	0.12
2.31	0.33	0.83				0.14	2.52				3.25	1.33	0.40
14.74	4.80	1.67	2.04			0.32	0.34	1.22			3.52	0.63	0.17
1.54	1.10	1.10				0.71	0.99				2.83	0.85	0.30
2.11	1.21	0.64				0.57	0.53				2.50	0.55	0.22
1.58	0.66	0.93				0.41	1.40				3.0	0.91	0.30
3.27	1.37	1.62				0.41	1.18				3.87	0.80	0.20

(Ladhiya River basin) ranges between 62.77 km (sub-basin no. 43) and 2.50 km (sub-basin no. 17) and for the sub basins of Lohawati the perimeter varies between 31.35 km (sub-basin no. 8) and 4.07 km (sub-basin no. 17). The area and perimeter of all the sub-basins is shown in Tables 3 and 4.

The basin length corresponds to the maximum length of the basin and sub-basin measured parallel to the main drainage line (Mesa 2006) and basin length is obtained by measuring the longest basin diameter between the mouth of the basin and most distant point on the perimeter (Gregory & Walling 1973). The main basin length for Ladhiya and Lohawati River basins is 60.97 km and 28.95 km respectively and the basin lengths of all sub-basins are shown in Tables 3 and 4.

Stream frequency (Fs)

Horton (1932) introduced the term Stream frequency (Fs) or Channel frequency. Stream frequency is the total number of stream segments of all orders per unit area, and is calculated as,

$Fs = \Sigma Nu/A$,

ΣNu = total number of stream segments of all orders,
A = area of the basin

Table 2. Linear aspects of the Lohawati Tributary Basin.

Sub basin no.	Stream order N_1	N_2	N_3	N_4	N_5	Total no. of Stream (Nu)	Bifurcation Ratio N_1/N_2	N_2/N_3	N_3/N_4	N_4/N_5	Stream Length (km) L_1	L_2	L_3	L_4	L_5	Length Ratio L_2/L_1	L_3/L_2	L_4/L_3	L_5/L_4	Rb	Rl	RHO
1	19	4	1			24	4.75	4			12.69	3.90	2.57			0.30	0.65			4.37	0.48	0.11
2	23	6	2	1		32	3.83	3	2		13.67	5.47	3.96	1.08		0.40	0.72	0.27		2.94	0.46	0.15
3	25	7	1			33	3.57	7			15.75	4.27	3.50			0.27	0.81			5.28	0.54	0.10
4	9	1	1			11	9	1			5.16	0.77	1.21			0.15	1.55			5	0.85	0.17
5	28	6	2	1		37	4.66	3	2		13.17	5.34	2.34	1.94		0.40	0.43	0.82		3.22	0.55	0.17
6	14	1	1			16	14	1			9.34	3.05	0.41			0.32	0.13			7.5	0.23	0.03
7	34	8	1			43	4.25	8			20.53	7.19	3.32			0.35	0.46			6.12	0.40	0.06
8	161	31	8	2	1	203	5.19	3.87	4	2	82.77	23.95	8.94	8.08	4.35	0.28	0.37	0.90	0.53	4.35	0.52	0.12
9	26	6	3	1		36	4.33	2	3		13.23	4.33	1.08	2.93		0.32	0.25	2.70		3.11	3.28	1.05
10	76	12	3	1		92	6.33	4	3		31.89	8.13	8.30	1.95		0.25	1.02	0.23		4.44	0.50	0.11
11	42	11	4	2	1	60	3.81	2.75	2	2	20.84	8.47	4.93	1.55	0.90	0.40	0.58	0.31	0.58	2.64	0.47	0.17
12	9	3	1			13	3	3			3.99	0.98	1.64			0.24	1.66			3	0.95	0.31
13	11	5	1			17	2.2	5			5.84	1.96	1.58			0.33	0.80			3.6	0.57	0.15
14	28	4	2	1		35	7	2	2		13.58	5.87	0.86	1.46		0.43	0.14	1.68		3.66	0.75	0.20
15	26	5	1			32	5.2	5			9.99	5.12	2.35			0.51	0.45			5.1	0.48	0.09
16	8	2	1			11	4	2			3.55	1.86	0.63			0.52	0.34			3	0.43	0.14
17	5	2	1			8	2.5	2			2.32	0.33	0.39			0.14	1.17			2.25	0.65	0.29
18	11	2	1			14	5.5	2			5.64	1.62	1.30			0.28	0.80			3.75	0.54	0.14
19	8	2	1			11	4	2			4.73	0.61	1.35			0.12	2.21			2	1.17	0.58

The Stream frequency is related with permeability, infiltration capacity and relief of a basin (Vijith & Satheesh 2006). The Fs values for the Ladhiya and Lohawati river basins are 11.51 km^{-2} and 4.86 km^{-2} respectively, while for the sub-basins they vary between 4.03 to 29.41 (Ladhiya River basin) and 2.41 to 8.36 (Lohawati River basin) (Tables 3 and 4). In the study area, the sub-basins with relatively high Fs values are indicative of relatively high relief and lower infiltration capacity of the bedrock.

Drainage density (Dd)

Drainage density (Dd) is an expression of spacing of channels within a basin (Horton 1932). Dd provides a numerical measure of landscape dissection and runoff potential (Vijith & Satheesh 2006). It is measured as the total length of streams of all orders per unit area divided by the area of the drainage basins

$Dd = \Sigma Lt/A$,

ΣLt = total length of all the ordered streams,
A = area of the basin

It is considered as a parameter determining the travel time by water. It varies between 0.55 and 2.09 km^{-1} in humid regions with an average density of 1.03 km^{-1} (Longbein 1947). It is controlled by climate, lithology, relief, infiltration capacity, vegetation cover, surface roughness and runoff intensity index. The amount and type of precipitation influences directly the quantity and character of surface runoff. Low Dd generally results in the areas of highly resistant or permeable subsoil material, dense vegetation and low relief (Nag 1998). High Dd results from weak or impermeable subsurface material, sparse vegetation and mountainous relief. Low Dd leads to coarse drainage texture while high Dd leads to fine drainage texture. The amount of vegetation and the rainfall absorption capacity of soils, which influences the rate of surface runoff, affect the drainage texture of an area (Chopra et al. 2005). The mean Dd of Ladhiya and Lohawati River Basin is 4.52 km^{-1} and 2.99 km^{-1} respectively, while the Dd of all the sub-basins is presented in Tables 3 and 4.

Drainage texture (T)

It is the total number of stream segments of all orders per perimeter of that area (Horton 1945). Horton recognized infiltration capacity as the single important factor which influences drainage texture and conceived drainage texture (T) to include both drainage density and stream frequency. According to Smith (1950), on the other hand, drainage texture depends upon a number of physical factors such as climate, rainfall, vegetation, rock and soil type, infiltration capacity, relief and stage of development of a basin.

$T = Dd \times Fs$,

Dd = drainage density,
Fs = stream frequency

Based on the values of T, it is classified as (Smith 1950):
Very Coarse (<2); Coarse (2–4); Moderate (4–6); Fine (6–8); Very Fine (>8).

Table 3. Areal aspects of the Ladhiya Tributary Basin.

Sub basin no.	Area A (km^2)	Total stream length (Lt. in km)	Stream frequency Fs = ΣNu / A (km^{-2})	Drainage density Dd = ΣLt / A (km^{-1})	Texture T = Dd × Fs (km^{-3})	Basin Length (km)	Perimeter (km)
1	1.88	7.52	4.32	3.98	17.24	3.79	8.46
2	5.31	15.89	4.70	2.99	14.09	4.10	10.57
3	2.04	7.07	8.79	3.45	30.39	3.02	6.93
4	2.66	10.32	7.51	3.88	29.18	2.92	7.69
5	1.21	4.60	8.25	3.80	31.41	2.59	6.13
6	7.47	21.63	7.09	2.89	20.53	4.96	13.28
7	1.37	4.84	8.75	3.53	30.98	1.96	4.93
8	5.42	21.29	8.29	3.92	32.59	4.30	11.17
9	6.91	23.89	6.65	3.45	22.99	5.21	12.73
10	4.41	17.91	9.51	4.05	38.56	3.39	9.27
11	1.82	10.45	16.48	5.74	94.71	2.71	6.43
12	3.12	15.11	12.48	4.83	60.36	3.30	8.46
13	3.71	20.87	16.41	5.61	92.25	3.91	10.62
14	4.15	21.32	12.77	5.13	65.60	3.95	10.36
15	1.09	5.73	18.19	5.22	95.02	2.53	6.06
16	0.27	1.62	29.41	5.97	175.78	1.12	2.72
17	0.29	1.94	31.03	6.70	208.02	1.04	2.50
18	2.83	18.06	20.10	6.37	128.06	2.40	7.48
19	1.94	10.58	17.44	5.43	94.75	1.58	5.62
20	1.18	4.52	8.43	3.81	32.13	1.73	4.97
21	1.23	4.73	8.10	3.83	31.05	1.88	5.04
22	2.39	7.70	6.26	3.22	20.18	2.63	7.30
23	2.13	8.12	7.03	3.81	26.82	2.93	7.16
24	3.02	10.63	5.62	3.52	19.81	2.82	6.63
25	2.17	7.19	5.05	3.30	16.69	2.11	6.45
26	5.99	21.50	6.51	3.59	23.37	3.15	10.61
27	6.82	23.18	5.57	3.39	18.93	4.47	11.46
28	4.33	14.58	5.76	3.36	19.37	5.11	11.57
29	13.80	56.87	8.18	4.12	33.72	5.09	15.98
30	7.07	33.26	9.05	4.70	42.57	4.51	12.06

31	5.37	22.12	8.18	4.11	33.65	4.39	11.09
32	3.70	15.56	7.56	4.20	31.81	4.20	9.80
33	4.25	16.49	7.51	3.87	29.12	3.91	9.80
34	1.57	6.19	7.60	3.92	29.86	2.43	5.64
35	13.19	46.17	5.91	3.50	20.68	4.78	16.60
36	7.24	24.44	6.21	3.37	20.96	5.34	13.00
37	1.76	7.79	9.65	4.43	42.78	2.25	5.66
38	41.31	169.34	6.85	4.09	28.07	9.23	33.63
39	12.85	49.84	5.99	3.87	23.22	6.98	16.12
40	3.71	13.15	6.18	3.54	21.90	2.96	8.15
41	0.60	3.30	13.22	5.45	72.15	1.20	3.52
42	11.57	48.36	8.03	4.17	33.54	4.82	14.48
43	125.89	444.34	5.83	3.52	20.57	13.56	62.77
44	19.17	58.86	4.22	3.07	12.96	5.63	19.37
45	10.89	33.3	4.03	3.05	12.33	4.42	13.88
46	2.42	8.41	6.61	3.47	22.99	2.81	6.80
47	1.77	7.45	10.16	4.21	42.79	1.97	5.96
48	3.87	16.72	11.60	4.31	50.03	3.59	9.72
49	19.38	100.90	14.70	5.20	76.52	8.25	20.74
50	1.07	5.77	14.92	5.38	80.38	1.93	4.66
51	0.45	3.25	24.28	7.18	174.56	1.03	3.38
52	159.27	610.76	7.69	3.83	29.48	19.49	62.41
53	0.37	2.63	27.02	7.12	192.62	1.24	2.86
54	1.05	6.78	20.85	6.43	134.18	1.89	4.71
55	0.83	4.74	14.45	5.71	82.67	1.75	4.44
56	1.23	6.05	16.24	4.91	79.84	2.03	5.41
57	3.06	16.60	11.42	5.42	61.94	2.42	7.39
58	3.28	17.80	13.99	5.41	75.72	2.23	7.80
59	75.45	302.70	10.20	4.01	40.93	9.52	38.41
60	0.61	3.48	19.51	5.66	110.43	1.39	3.47
61	4.24	23.25	13.67	5.48	74.94	3.14	10.73
62	0.72	3.75	16.62	5.19	86.34	1.83	4.90
63	0.68	3.97	13.17	5.82	76.74	1.82	4.49
64	0.44	3.17	29.14	7.12	207.55	1.28	3.46
65	0.93	6.27	21.43	6.72	144.24	1.97	5.16

Table 4. Areal aspects of the Lohawati Tributary Basin.

Sub basin no.	Area A (km^2)	Total stream length (Lt. in km)	Stream frequency $Fs = \Sigma Nu / A$ (km^{-2})	Drainage density $Dd = \Sigma Lt / A$ (km^{-1})	Texture $T = Dd \times Fs$ (km^{-3})	Basin Length (km)	Perimeter (km)
1	8.13	19.17	2.95	2.35	6.96	5.47	13.50
2	9.30	24.20	3.43	2.60	8.93	4.91	13.25
3	8.74	23.53	3.77	2.69	10.14	5.19	13.56
4	2.25	7.14	4.87	3.16	15.43	2.78	6.55
5	6.76	22.80	5.46	3.36	18.41	4.11	11.71
6	3.63	12.80	2.41	3.52	8.49	3.50	8.41
7	10.17	31.05	4.22	3.05	12.89	5.23	14.40
8	41.09	128.11	4.93	3.11	15.39	7.02	31.35
9	7.50	21.59	4.79	2.87	13.80	4.98	11.60
10	16.48	50.28	5.58	3.05	17.02	5.34	16.43
11	12.83	36.70	4.67	2.86	13.37	3.28	16.73
12	1.98	6.62	6.55	3.33	21.88	2.62	6.08
13	3.02	9.39	5.62	3.11	17.51	2.71	7.21
14	7.75	21.79	4.51	2.81	12.69	3.27	11.0
15	5.11	17.46	6.25	3.41	21.34	3.36	9.82
16	2.47	6.05	4.44	2.45	10.90	2.46	7.82
17	0.95	3.05	8.36	3.19	26.76	1.24	4.07
18	2.73	8.57	5.12	3.13	16.09	2.72	7.63
19	2.42	6.70	4.53	2.76	12.51	2.36	6.65

The drainage texture of the Ladhiya and Lohawati river basins is 59.16 and 14.76 respectively. For the individual sub-basins T ranges from 12.33 to 207.55 (Ladhiya River Basin) and 6.96 and 26.76 (Lohawati River Basin) (Tables 3 and 4).

Shape parameters

Elongation ratio (Re)

Elongation ratio (Re) is the ratio between the diameter (D) of a circle of the same area as the drainage basin and basin length (L) (Schumm 1956), and is calculated as

$$Re = D / L = 1.128 \sqrt{A} / L,$$

A = area of the basin

The values of elongation ratio vary from zero (highly elongated shape) to one (circular shape). The Re of the Ladhiya and Lohawati river basins is 0.16 and 0.17 respectively, indicates it to be elongated with high relief and steep slopes. The value of Re for the sub-basins is shown in Tables 5 and 6.

Table 5. Shape aspects of the Ladhiya Tributary Basin.

Sub basin no.	Elongation Ratio $Re = 1.128 \sqrt{A} / L$	Circularity index $Rc = 4 \pi A / P^2$	Form Factor A / L^2
1	0.20	0.33	0.13
2	0.16	0.59	0.31
3	0.23	0.53	0.22
4	0.18	0.56	0.31
5	0.27	0.40	0.17
6	0.14	0.53	0.30
7	0.27	0.70	0.35
8	0.12	0.54	0.29
9	0.12	0.53	0.25
10	0.13	0.64	0.38
11	0.22	0.55	0.24
12	0.13	0.54	0.28
13	0.10	0.41	0.24
14	0.11	0.48	0.26
15	0.20	0.37	0.17
16	0.36	0.46	0.21
17	0.31	0.58	0.26
18	0.10	0.63	0.49
19	0.15	0.77	0.77
20	0.27	0.60	0.39
21	0.26	0.61	0.34
22	0.23	0.56	0.34
23	0.20	0.52	0.24
24	0.18	0.86	0.37

Table 5. continued.

Sub basin no.	Elongation Ratio $Re = 1.128 \sqrt{A} / L$	Circularity index $Rc = 4 \pi A / P^2$	Form Factor A / L^2
25	0.23	0.65	0.48
26	0.13	0.66	0.60
27	0.13	0.65	0.34
28	0.16	0.40	0.16
29	0.07	0.67	0.53
30	0.09	0.61	0.34
31	0.12	0.54	0.27
32	0.14	0.48	0.20
33	0.14	0.55	0.27
34	0.23	0.62	0.26
35	0.09	0.60	0.57
36	0.12	0.53	0.25
37	0.19	0.68	0.34
38	0.04	0.45	0.48
39	0.08	0.62	0.26
40	0.16	0.70	0.42
41	0.26	0.61	0.41
42	0.07	0.69	0.49
43	0.03	0.40	0.68
44	0.08	0.64	0.60
45	0.11	0.70	0.55
46	0.21	0.65	0.30
47	0.20	0.62	0.45
48	0.13	0.51	0.29
49	0.05	0.56	0.28
50	0.20	0.61	0.28
51	0.23	0.49	0.42
52	0.02	0.51	0.41
53	0.26	0.59	0.23
54	0.17	0.59	0.29
55	0.22	0.52	0.27
56	0.21	0.52	0.29
57	0.12	0.70	0.52
58	0.11	0.67	0.66
59	0.11	0.64	0.83
60	0.25	0.63	0.31
61	0.09	0.46	0.42
62	0.25	0.37	0.21
63	0.23	0.42	0.20
64	0.23	0.46	0.27
65	0.17	0.43	0.23

Table 6. Shape aspects of the Lohawati Tributary Basin.

Sub basin no.	Elongation Ratio $Re = 1.128 \sqrt{A} / L$	Circularity index $Rc = 4 \pi A / P^2$	Form Factor A / L^2
1	0.17	0.55	0.27
2	0.14	0.66	0.38
3	0.14	0.59	0.32
4	0.24	0.66	0.29
5	0.13	0.62	0.39
6	0.17	0.64	0.29
7	0.11	0.61	0.37
8	0.06	0.52	0.83
9	0.14	0.70	0.30
10	0.09	0.76	0.57
11	0.11	0.57	1.19
12	0.24	0.67	0.28
13	0.21	0.72	0.41
14	0.14	0.80	0.72
15	0.15	0.66	0.45
16	0.29	0.50	0.40
17	0.36	0.72	0.61
18	0.22	0.58	0.36
19	0.26	0.68	0.43

Circulatory index (Rc)

The circulatory Ratio (Rc) has been used as a quantitative measure and is expressed as the ratio of the basin area (A) to the area of a circle having the same perimeter as the basin (MILLER 1953, STRAHLER 1964) and is calculated as

$Rc = 4 \pi A / P^2$,

A = area of the basin and
P = perimeter of the basin

The values of circularity index range from zero (for a line) to unity i. e. one (for a circle). The higher is the value of Rc, the more circular is the shape of the basin. The circulatory ratio is influenced by length, the frequency of streams (Fs), geological structure, land cover, climate, relief and slope of the basin. It is a significant ratio, which indicates the stage of denudation of the basin. (SREEDEVI et al. 2005). The Rc of the Ladhiya and Lohawati river basins is 0.56 and 0.64 respectively, while that of other sub-basins is shown in Tables 5 and 6.

Form factor (Ff)

The Ff of a drainage basin is expressed as a ratio between the area of the basin (A) and the square of the basin length (L^2) (HORTON 1945) and is computed as

$Ff = A/L^2$.

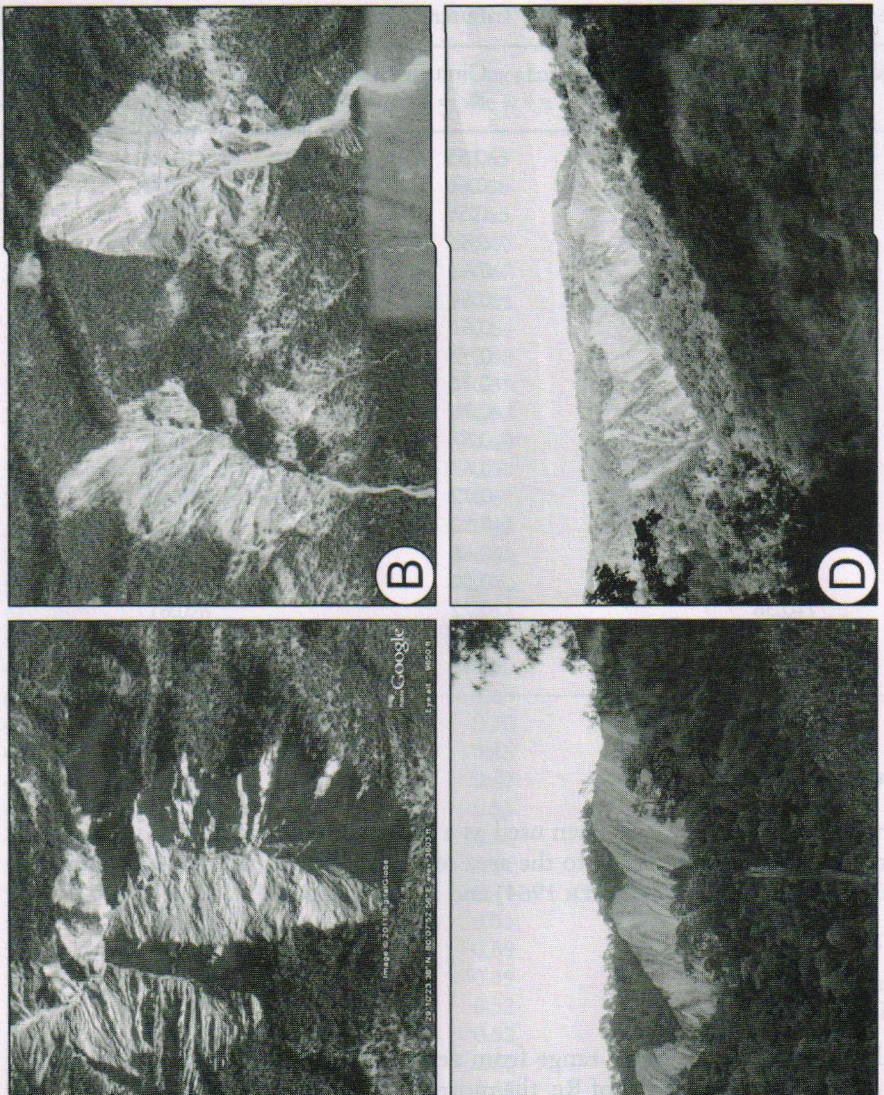

Fig. 3. Landslide zone in the study area. (A–B) Google image of landslide, (C–D) Field photographs of landslide near Jol village, Sukhidhang. Loc. N 290° 10′ 05.4″ E 0800° 07′ 37.0″

The value of form factor is always less than 0.7854 (for a perfectly circular basin). The smaller is the value of form factor, more elongated is the basin. The basin with high Ff have high peak flows of shorter duration, whereas elongated sub catchments with low form factor have lower peak flow of longer duration (Chopra et al. 2005). The Ff of the Ladhiya and Lohawati River Basin is 0.35 and 0.46 respectively, while the Ff of sub-basins is presented in Tables 5 and 6.

Geomorphological evidence of active tectonics

Active tectonics broadly includes the ongoing deformation of the Earth's surface and is defined as "those processes that produce deformation of the Earth's crust on a time scale of significance to human society" (Keller & Pinter 1996). Several pieces of evidence of neotectonics such as landslides, river terraces, river incision, formation of deep gorges, triangular facets and tilting of beds, have been noticed in various parts of the study area. The topographic features, geological structures and recurrent seismicity of the Himalaya are a consequence of the continued northward push and collision of the Indian Plate with Eurasia (Quereshy et al. 1989). As a result, the Himalayan mountain belt is still under the process of crustal adjustment. Such adjustments are manifested in neotectonic activity experienced in different segments of the Himalaya and producing distinct landforms (Valdiya 1986, Bali et al. 2003, Agarwal et al. 2009, Agarwal & Sharma 2011).

Seismic activity

The entire Himalayan terrain is found to be highly vulnerable to earthquakes (Bilham et al. 2001, Feldl & Bilham 2006). The area belongs to Zones IV and V (Vulnerability atlas of India 1997). The neotectonic activity in the area is well documented by the occurrence of a number of seismic events in the recent years, including the Uttarkashi earthquake of 1991 and the Chamoli earthquake of 1999 (Rajendran et al. 2000). Recently an earthquake of 5.7 magnitude has been recorded in Uttarakhand. Evidences of active tectonism are also well documented in the Kumaun area. The geological formations in the area are separated by major tectonic planes like the Himalayan Frontal Faults (HFF), Main Boundary Fault (MBF) and South Almora Thrust (SAT). Moreover, the area is crossed by a number of smaller partly active faults and thrusts.

Landslides

Like other parts of Himalaya the landslides are very common in the study area, particularly along the Tanakpur-Champawat road (fig. 3). According to Agarwal & Sharma (2011) a total of 31 major and minor landslides have been observed out of which 16 are of debris flow type and 15 are rockslides. Most of landslides present in the area have been found to be structurally controlled. Two major landslides (fig. 3A) of the Ladhiya river valley, in the vicinity of the SAT, and (fig. 3B) in the Sukhidhang area are associated with the MBF.

River terraces

When a river valley has been subjected to alternating aggradation and dissection, a series of terraces develop on the both sides of the river. Paired terraces occur in uplifting areas or when downcutting is more intense than lateral erosion (Keller & Pinter 1996), whereas unpaired terraces are usually formed when lateral erosion dominates. Both paired (symmetrical as well as asymmetrical) and unpaired terraces are present in the study area suggesting that the rate of incision was rapid in comparison to lateral channel migration and the rate of uplift was more intense. The presence of asymmetrical terraces present further suggest that the rates of movement on the two sides of river valley were not uniform. At some places (fig. 4) up to four terraces have been observed (T_0, T_1, T_2 & T_3).

Triangular facets (Flatirons)

Triangular facets may be defined as a physiographic feature having a broad base and an apex at top on the end of a spur, or, triangular shaped steep sloped hill or cliff formed usually by the erosion of a fault truncated hill (Summerfield 1991). The presence of well developed triangular facets is a signature of a fresh fault scarp, of neotectonics. Triangular facets have been noticed at a numerous places. Three triangular facets (fig. 5) are very prominent near Chalthi village.

Discussion and Conclusions

The development of drainage network in the young mountain chains is believed to be a good indicator of active tectonics and drainage basin is study state condition of rocks during active deformation (Seeber & Gornitz 1983, Ouchi 1985, Marple &

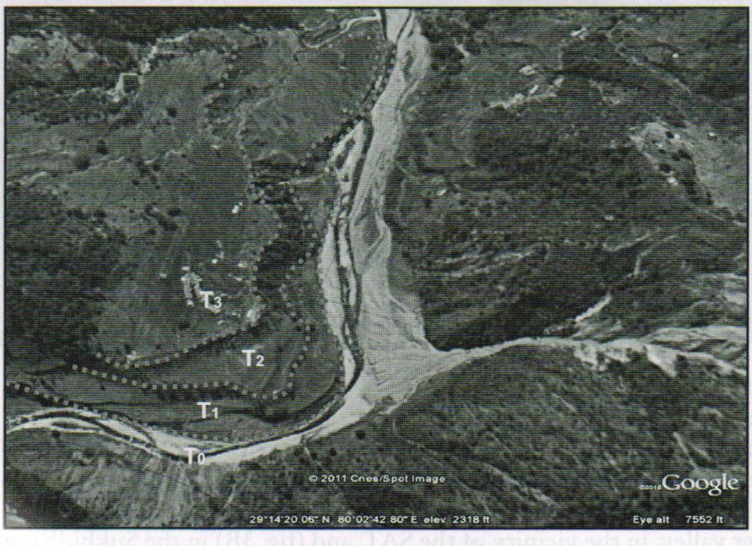

Fig. 4. Asymmetric River Terraces in the Ladhiya River Valley.

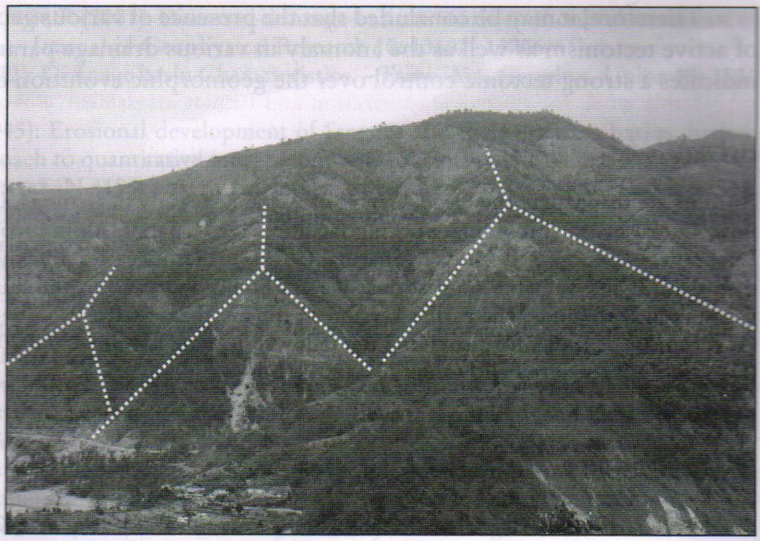

Fig. 5. Triangular facets at the left bank of Ladhiya River Valley.

Talwani 1993, Koons 1995, Hallet & Molnar 2001, Arisco et al. 2006). The effects of ongoing tectonic processes in a drainage basin and the adjustment of drainage network to lithological variations can be shown by some morphometric parameters.

The overall drainage pattern of the Ladhiya and Lohawati basins is dendritic to subdendritic. It has been observed that the total number of streams gradually increases as the stream order decreases and vice-versa. The high degree of variation in the order and size of the tributary basins is attributed to the physiography of the area. The higher number of streams indicates a juvenile topography. The bifurcation ratio (related to the drainage density, junction angle, lithological characteristics, basin shape and basin area) of Ladhiya and Lohawati river basins ranges between 8.42 to 2.16 and 6.44 to 2.0 respectively. A bifurcation ratio greater than five is an indication of structural control (Strahler 1957). The sub-basins with bifurcation ratios above 5 present a strong control by faults, lineaments and others structural features over drainage. Stream frequency is an indication of inclination: higher values suggests steep slopes and vice-versa. In the study area the stream frequency and drainage texture are relatively high suggesting the minute dissection of the terrain. The higher value of drainage density point to impermeable subsurface rocks and high relief.

The shape parameters indicating the general shape of the basin helpful in delineating the areas prone to flash floods and high river discharges during the monsoon. The various shape parameters of the Ladhiya and Lohawati river basins suggests an elongated shape. The higher values of the form factor indicate that the sub-basins experience high peak flows (flash floods) from time to time (Chopra 2005). Delineating the sub-basins on the basis of higher values of shape parameters thus may form an important tool to locate the areas prone to short high peak flows during flash flood.

Therefore, it may be concluded that the presence of various geomorphic features of active tectonism as well as the anomaly in various drainage parameters of the area indicates a strong tectonic control over the geomorphic evolution of the area.

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