CHAPTER 4

MORPHOMETRIC ANALYSIS

Tectonics induces permanent deformations on the earth surface and controls the drainage pattern and associated geomorphic/ sedimentary processes. The uplifted area goes under process of erosion, while the subsiding area is subjected to focusing of drainage and deposition. Primarily, tectonics manifests itself by either steepening or reducing the local valley gradient, which changes the existing slope of the channels. This introduces disturbance in the natural equilibrium of a river. In the process of restoring the equilibrium, the river tries to adjust to the new conditions by changing its slope, roughness, bed material size, cross-sectional shape and meandering pattern (Twidale, 1966; Schumm, 1986; Chang, 1988). Thus, the secondary changes as a consequence of tectonics are reflected in aggradation / degradation and variations in channel morphology. This variation in morphology of a river basin is studied in detail applying morphometric techniques. The various measurements related with the shapes and distribution of the drainage in a particular river basin is known as morphometric analysis. The morphometric studies of river basins were first initiated by Horton (1945) followed by Strahler (1964). The main purpose of morphometric analyses is to discover holistic stream properties from the measurement of various stream attributes. Thus, the science of morphometry is concerned with the quantitative measurement and generalization of the land surface geometry.

Different morphometric parameters such as sinuosity, long profile, valley floor to valley width ratio and the mountain front sinuosity characterize the degree and nature of tectonic activity while the drainage orientation studies help in reconstructing the sequence of recent tectonic activities in the area (Centamore et al., 1996). The orientation related to lower order streams are indicative of the most recent active tectonic phase because these streams are the youngest component of the drainage network (Centamore et al., 1996).

Basins of the five major rivers which are flowing towards north and crossing the KMF, thus in the most vicinity to the KMF, are taken for detailed morphometric analysis to decipher the nature of neotectonism in the area. These basins are as follows:

1. Kaswali River Basin
2. Pur River Basin
3. Kaila River Basin
4. Nirona River Basin
5. Chhari River Basin

Materials and Methods

As reference and base map preparation, six Survey of India topographic sheets on 1:50,000 scale were used. The digital data format from Indian Remote Sensing Satellite (IRS1D), LISS III (resolution 23.5 m) with four spectral bands i.e. B1 (blue) B2 (green), B3 (red) and B4 (near infrared) and ETM data of Landsat (resolution 30m merged with 15 m panchromatic band) were used to meet the requirement of remote sensing study of the area. Digitization work has been carried out for entire analysis of basin morphometry.

The drainage network of the Kaswali and Kaila River basins were derived from tracing them from 50,000 scale topographic sheets manually, digitizing them in the Arc GIS software and there after deriving the linear and aerial aspects using respective tools and calculating the other factors using the appropriate formulae.

The SRTM data of 90 m resolution and ASTER GDEM data of 30 m resolution have been used to generate the drainage of the Pur, Nirona and Chhari River basins. The radar data was processed using the ILWIS 3.3 software. The DEM hydro processing tools of the ILWIS were used to generate the slope, flow accumulation, drainage network ordering and catchment extraction. The drainage networks were extracted on 9 pixel thresholds (for SRTM data) on which the drainage matches most with the topographic sheet of 1:50,000 scale.

The drainage order was given to each stream following Strahler (1964) stream ordering rule. The attributes were assigned to create the digital data base for drainage layer of the river basins. Various morphometric parameters such as linear aspects of the drainage network: stream order (Nu), bifurcation ratio (Rb), stream length (Lu) and aerial aspects of the drainage basin: drainage density (D), stream frequency (Fs), texture ratio (T), elongation ratio (Re), circularity ratio (Rc), form factor ratio (Rf) of the basins were computed.

Parameters of Morphometric Analysis:

The parameters of morphometric analysis of a river basin can be grouped into linear and aerial elements on the basis of the aspect utilized for its calculation. The important linear aspects of drainage network are stream order (Nu), bifurcation ratio (Rb), stream length (Lu) and basin length while area of the basin, basin perimeter, drainage density, stream frequency, texture ratio, elongation ratio, circularity ratio and form-factor ratio are calculated under aerial aspects of analysis.

Stream Order (u)

Stream ordering is the first step in the morphometric analysis of a drainage basin. It is the linear property of fluvial system. The stream network is subdivided in various fluvial segments of increasing hierarchical order (Horton, 1945; Strahler, 1964). Horton emphasized topographic characteristics of the drainage area and gave hierarchical order to every channel in the drainage basin using a 'top-down' approach in which the smaller streams have lower order number and the central channel has the highest order number. In the present study, the channel segments of the drainage basin have been ranked according to Strahler's stream ordering system. According to Strahler (1964), the smallest fingertip tributaries are designated as order 1. Where two first order channels join, a channel segment of order 2 is formed, where two of order 2 streams join, a segment of order 3 is formed, and so forth. The trunk stream through which all discharge of water and sediment passes is therefore the stream segment of highest order.

Stream Number (N_u)

The total number of stream segments computed order wise is known as the stream number. Horton's (1945) laws of stream numbers states that the number of stream segments of each order forms an inverse geometric sequence, when plotted against order, most drainage networks show a linear relationship, with small deviation from a straight line. According to the Horton's law the plotting of logarithm of number of streams against stream order gives a straight line.

Bifurcation Ratio (Rb)

In a drainage basin the term bifurcation ratio (Rb) is used to express the ratio of the number of streams of any given order to the number of streams in next higher order (Schumm, 1956). The hydrographical network is subdivided in fluvial segments of increasing hierarchical order. Calculation of parameters of hierarchy allows defining the influence of tectonics on the hydrographic network evolution (Guarnieri and Pirrotta, 2008). The bifurcation ratio is the measure of the degree of branching within the hydrographic network (Horton, 1945; Strahler, 1952). It depends on the presence of hierarchical anomalies in the network and can give useful information on typology of the erosive processes and on the degree of evolution of the basin (Guarnieri and Pirrotta, 2008). Bifurcation ratios characteristically range between 3.0 and 5.0 for basins in which the geologic structures do not distort the drainage pattern (Strahler, 1964).

Stream Length (L_u)

Stream length is one of the most significant hydrological features of the basin as it reveals surface runoff characteristics of area. Longer lengths of streams are generally indicative of flatter gradients. Generally, the total length of stream segments is highest in first order streams and decreases as the stream order increases.

Area of a basin (A) and perimeter (P)

Area of the basin and its perimeter are the important parameters in quantitative morphology. The area of the basin is defined as the total area projected upon a horizontal plane feeding the streams of all orders of the basin. Perimeter is the length of the boundary of the basin which can be drawn from topographical maps or can be derived by digital data using GIS softwares.

Drainage Density (R_D)

Drainage density is the ratio of total channel segment lengths cumulated for all orders within a basin to the basin area, which is expressed in terms of km / sq km.

$$R_D = \sum L / A$$

Horton (1932) introduced the drainage density (**R_D**) as an important indicator of the linear scale of landform elements in stream eroded topography. The drainage density indicates the closeness of spacing of channels, thus providing a quantitative measure of the average length of stream channel for the whole basin. It has been observed from drainage density measurements made over a wide range of geologic and climatic types that a low drainage density is more likely to occur in regions of highly permeable subsoil material under dense vegetation cover, and where relief is low. High drainage density is the resultant of weak or impermeable subsurface material, sparse vegetation and mountainous relief. Low drainage density leads to coarse drainage texture while high drainage density leads to fine drainage texture (Strahler, 1964).

Stream Frequency (Fs)

Stream frequency or channel frequency (Fs) is the total number of stream segments of all orders per unit area (Horton, 1932).

$$Fs = \Sigma \ Nu / A$$

Texture Ratio (T)

Texture ratio (T) is an important factor in the drainage morphometric analysis and depends on the underlying lithology, infiltration capacity and relief aspect of the terrain. It is the ratio of number of all the 1st order streams (N1) to the perimeter of the basin.

Elongation Ratio (Re)

Schumm (1956) defined elongation ratio (Re) as the ratio of diameter of a circle of the same area as the basin to the maximum basin length. It is a very significant index in the analysis of basin shape which helps to give an idea about the hydrological character of a drainage basin. Values near to 1.0 are typical of regions of very low relief (Strahler, 1964).

$$Re = Dc / Lb$$

where, Dc is diameter of a circle of the same area of the basin and Lb is the maximum basin length.

Circularity Ratio (Rc)

The ratio between total basin area and the area of a circle having the same perimeter as the basin is known as Circularity ratio of the basin (Miller, 1953). He described that the basins of the circularity ratios 0.4 to 0.5 indicate strongly elongated and highly permeable homogenous geologic materials. The elongated basins may be due to neotectonic activities in the area.

The elongation and circularity ratios are recently used effectively as a very important tool for indirectly providing information about the degree of maturity of the basin by quantitatively describing the planimetric shape of the basin. The basins draining tectonically active areas are more elongated and tend to become more circular with the cessation of uplift (Bull and McFadden, 1977).

Relief Ratio (Rr)

Relief ratio is defined as the ratio between the basin relief and the longest dimension of the basin parallel to the principal drainage line i.e. basin length. Schumm (1956) gives a simple expression for describing relief ratio (Rr) as:

$$Rr = h / L$$

Where L is the maximum length of the basin parallel to the principal drainage line, and h is the difference in elevation between the mouth of the basin and the highest point on the drainage divide.

Form Factor Ratio (Rf)

Quantitative expression of drainage basin outline form was made by Horton (1932) through a form factor ratio (Rf), which is the dimensionless ratio of basin area to the square of basin length. Basin shape may be indexed by simple dimensionless ratio of the basic measurements of area, perimeter and length (Singh, 1998).

PATTERN OF DRAINAGE NETWORK

Drainage network development of an area is a result of combination of factors such as climate, lithology and the attitude of the strata, active tectonics, regional uplift and subsidence. Drainage patterns of stream network from the basin have been observed as dendritic type in some stretches/reaches which indicates the homogeneity in texture and lack of structural control. This pattern is characterized by a tree like pattern with branches that intersect primarily at acute angles. In some parts of the basins parallel and radial pattern are observed. A parallel drainage pattern is shown by tributaries of lower orders that flow nearly parallel to one another and all the tributaries join the main channel at approximately the same angle. Parallel drainage suggest that the area has a gentle, uniform slope and with less resistant bed rock. A radial drainage pattern forms when water flows outward from a dome like feature, flowing away from a central high point (Jensen, 2006). The properties of the stream networks are very important to study the landform making processes (Strahler and Strahler, 2002). The drainage network development provides clues which can be used to understand the history of development of the landscape of the area.

Various aerial and linear parameters calculated for the river basins are given in the tables from 4.1A to 4.5B.

The Kaswali River is identified as 5^{th} order stream whereas Kaila and Chhari are 6^{th} order and Pur and Nirona are 7^{th} order streams. Total channel length and stream frequencies are quite high in all the river basins (Table 4.1A to 4.5B, Fig. 4.1- 4.5). Length and number of lower order streams suggest moderate to high head-water relief in the head water area, however, lesser number and length of the higher order streams suggest small extent of the river basins.

1. KASWALI RIVER BASIN:

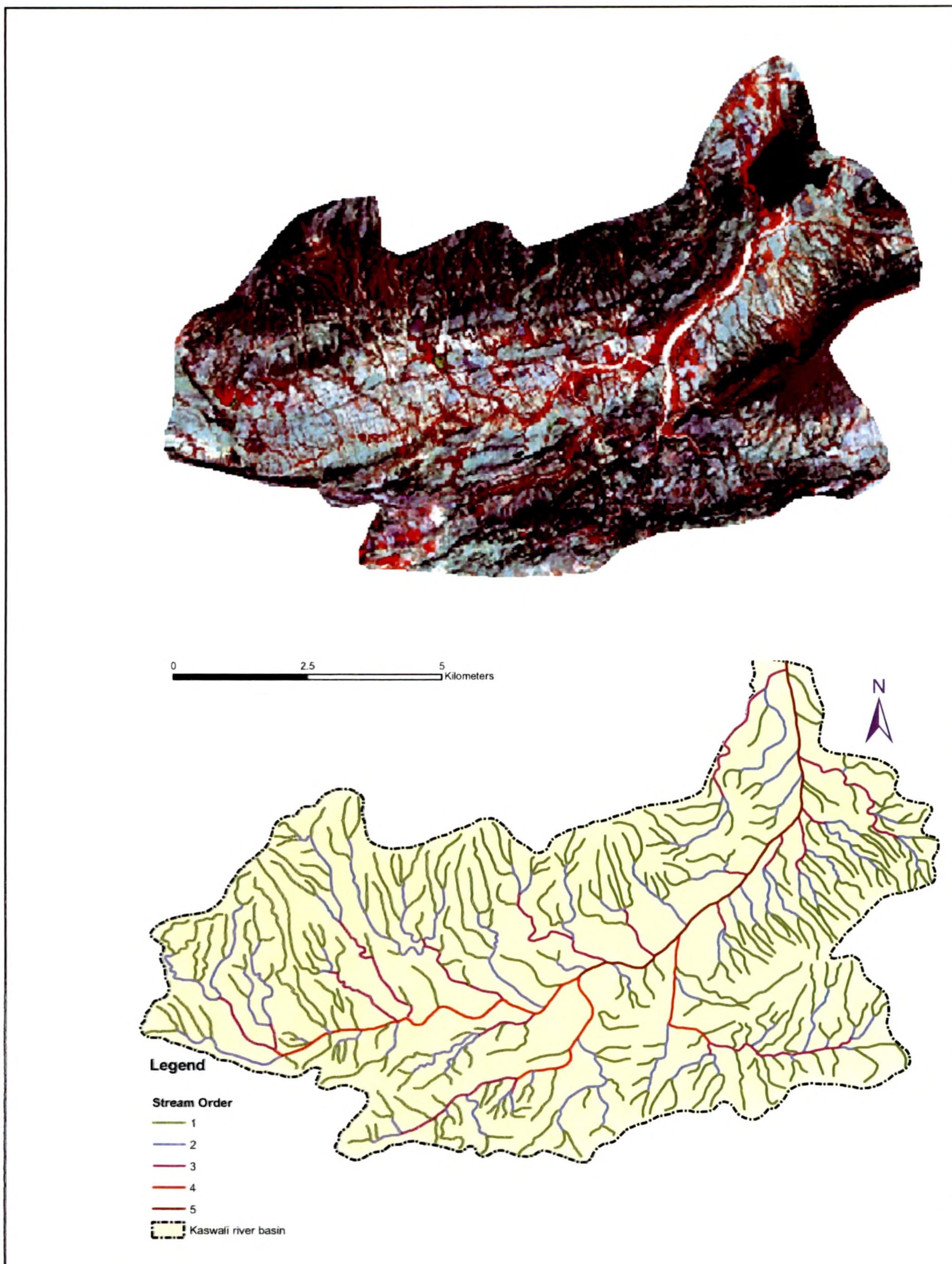

Fig.4.1: LISS-III FCC imagery of Kaswali River basin and detailed drainage map of the basin showing different order of streams.

Table 4.1A: Linear aspects of the drainage network of the Kaswali River basin

River Basin	Stream Order u	Stream Numbers N_u	Total length of the streams in km L_u	Average stream length (km)	Log N_u	Log L_u
	1^{st}	276 (N1)	177.86	0.644	2.441	2.250
Kaswali River Basin	2^{nd}	70	61.05	0.872	1.845	1.786
	3^{rd}	20	25.60	1.280	1.301	1.408
	4^{th}	4	11.40	2.85	0.602	1.057
	5^{th}	1	8.03	8.03	0.000	0.905
		$\Sigma N_u =$ 371	$\Sigma L_u =$ 283.94			

Bifurcation Ratio (R_b)				Mean Bifurcation Ratio
1^{st} order/ 2^{nd} order	2^{nd} order/ 3^{rd} order	3^{rd} order/ 4^{th} order	4^{th} order/ 5^{th} order	
3.942	3.50	5.0	4.0	3.369

Table 4.1B: Aerial aspects of the morphometric analysis of the Kaswali River Basin

Area of the River basin	**A**	70.98 sq km
Perimeter	**P**	45.89 km
Drainage Density (km/sq km)	$D = \Sigma L_u / A$	4.00
Stream Frequency	$F_s = \Sigma N_u / A$	5.23 streams / sq km
Texture Ratio	$T = N_1/P$	6.01
Basin Length	L_b	14.1 km
Basin Relief	H_b	225 m
Relief Ratio	$R_R = H_b / L_b$	15.96 m/ km
Elongation Ratio	$R_E = (2 \sqrt{A/\pi}) / L_b$	0.674
Ruggedness Number	$R_N = (D \times H_b) / 1000$	0.564
Circularity ratio	$R_C = 4 \pi A / P^2$	0.424
Form factor ratio	$R_F = A / L_b^2$	0.357

2. PUR RIVER BASIN:

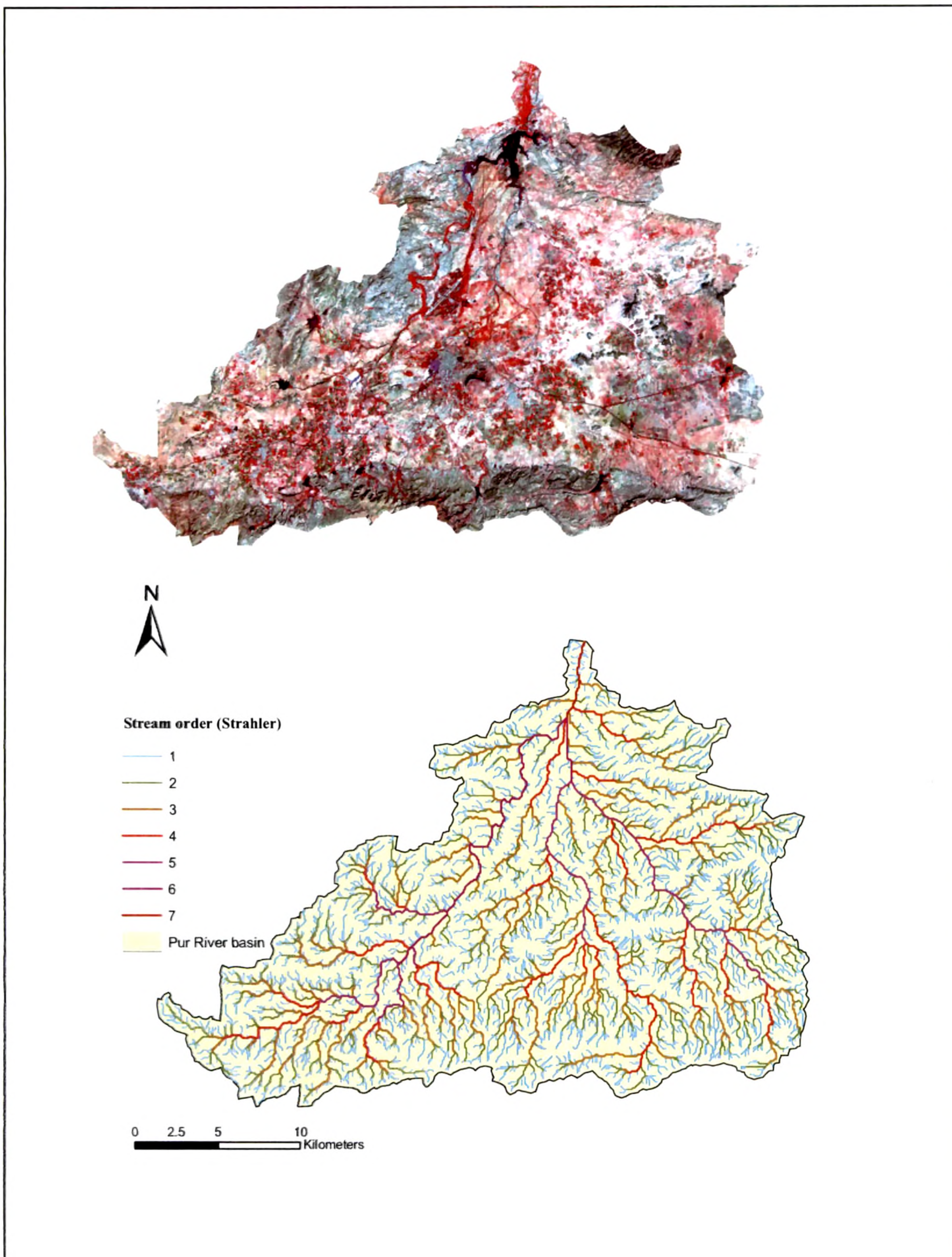

Fig.4.2: ETM Landsat FCC imagery (234) of the Pur River basin and detailed drainage map of the basin showing different order of streams.

Table 4.2A: Linear aspects of the drainage network of the Pur River basin

River Basin	Stream Order u	Stream Numbers N_u	Total length of the streams in km L_u	Average stream length (km)	Log N_u	Log L_u
	1st	2413 (N1)	1051.98	0.436	3.383	3.022
	2nd	456	402.96	0.8885	2.659	2.605
	3rd	108	247.81	2.295	2.033	2.394
PUR RIVER BASIN	4th	24	102.71	4.280	1.380	2.012
	5th	6	53.1	8.850	0.778	1.725
	6nd	2	27.52	13.760	0.301	1.440
	7th	1	5.19	5.190	0.000	0.715
		ΣN_u = 3010	ΣL_u = 1891.27	0.628		

Bifurcation Ratio (R_b)						Mean R_b
1st order/ 2nd order	2nd order/ 3rd order	3rd order/ 4th order	4th order/ 5th order	5th order/ 6th order	6th order/ 7th order	
5.292	4.222	4.500	4.000	3.000	2.000	**3.835**

Table 4.2B: Aerial aspects of the morphometric analysis of the Pur River basin

Area of the River basin	**A**	601.70 sq km
Perimeter	**P**	149.97 km
Drainage Density (km/sq km)	$D = \Sigma L_u / A$	3.143
Stream Frequency	$F_s = \Sigma N_u / A$	5.00 streams / sq km
Texture Ratio	$T = N_1/P$	16.1
Basin Length	L_b	42.8 km
Basin Relief	H_b	212 m
Relief Ratio	$R_R = H_b / L_b$	6.18 m/ km
Elongation Ratio	$R_E = (2 \sqrt{A/\pi}) / L_b$	0.647
Ruggedness Number	$R_N = (D \times H_b) / 1000$	0.666
Circularity ratio	$R_C = 4 \pi A / P^2$	0.336
Form factor ratio	$R_F = A / L_b^2$	0.511

3. KAILA RIVER BASIN:

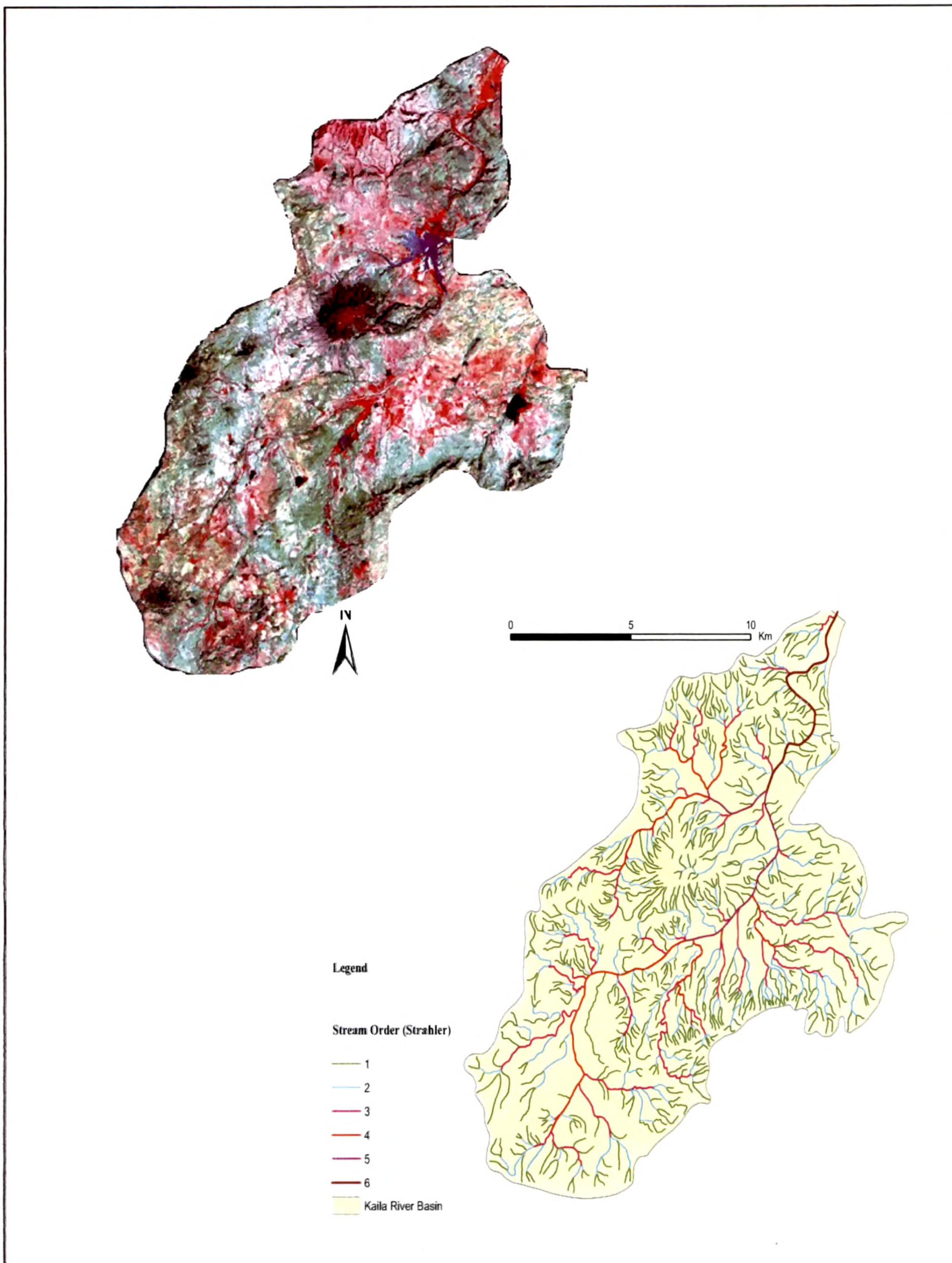

Fig.4.3: LISS-III FCC imagery of Kaila River basin and detailed drainage map of the basin showing different order of streams.

Table 4.3A: Linear aspects of the drainage network of the Kaila River Basin

River Basin	Stream Order u	Stream Numbers N_u	Total length of the streams in km L_u	Average stream length (km)	Log N_u	Log L_u
	1^{st}	662 (N1)	380.4	0.575	2.821	2.580
	2^{nd}	168	134.84	0.798	2.225	2.130
KAILA RIVER BASIN	3^{rd}	44	67.00	1.523	1.643	1.826
	4^{th}	9	27.24	3.027	0.954	1.435
	5^{th}	2	10.44	5.220	0.301	1.019
	6^{th}	1	8.98	8.98	0.000	0.953
		$\Sigma N_u =$ 886	$\Sigma L_u =$ 628.9			

Bifurcation Ratio (R_b)					Mean R_b
1^{st} order/ 2^{nd} order	2^{nd} order/ 3^{rd} order	3^{rd} order/ 4^{th} order	4^{th} order/ 5^{th} order	5^{th} order/ 6^{th} order	
3.940	3.818	4.889	4.500	2.000	3.829

Table 4.3B: Aerial aspects of the morphometric analysis of the Kaila River Basin

Area of the River basin	**A**	180.93 sq km
Perimeter	**P**	72.14 km
Drainage Density (km/sq km)	$D = \Sigma L_u / A$	3.476
Stream Frequency	$F_s = \Sigma N_u / A$	4.897 streams / sq km
Texture Ratio	$T = N_1/P$	9.177
Basin Length	L_b	23.5 km
Basin Relief	H_b	299 m
Relief Ratio	$R_R = H_b / L_b$	12.723 m/ km
Elongation Ratio	$R_E = (2 \sqrt{A/\pi}) / L_b$	0.646
Ruggedness Number	$R_N = (D \times H_b) / 1000$	1.039
Circularity ratio	$R_C = 4 \pi A / P^2$	0.437
Form factor ratio	$R_F = A / L_b^2$	0.328

4. NIRONA RIVER BASIN:

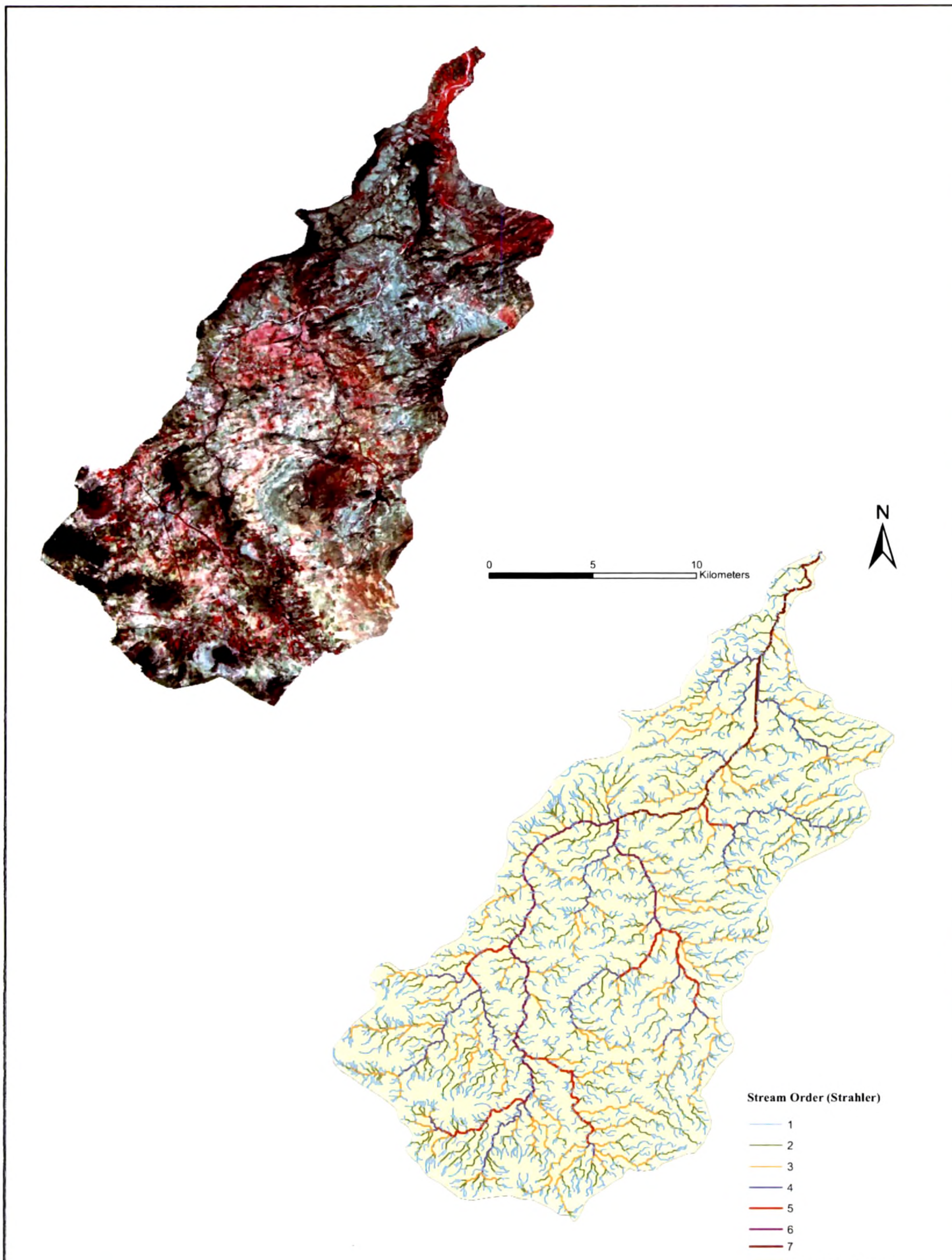

Fig.4.4: LISS-III FCC imagery of Nirona River basin and detailed drainage map of the basin showing different order of streams.

Table 4.4A: Linear aspects of the drainage network of the Nirona River basin

River Basin	Stream Order u	Stream Numbers N_u	Total length of the streams in km L_u	Average stream length (km)	Log N_u	Log L_u
NIRONA RIVER BASIN	1^{st}	2378 (N1)	680.057	0.286	3.376	2.833
	2^{nd}	482	323.325	0.671	2.683	2.510
	3^{rd}	101	176.788	1.750	2.004	2.247
	4^{th}	22	61.729	2.806	1.342	1.790
	5^{th}	6	28.213	4.702	0.778	1.450
	6^{nd}	2	27.130	13.565	0.301	1.433
	7^{th}	1	19.8	19.80	0.000	1.297
		$\Sigma N_u =$ 2992	$\Sigma L_u =$ 1317.042			
Bifurcation Ratio (R_b)						**Mean R_b**
1^{st} order/ 2^{nd} order	**2^{nd} order/ 3^{rd} order**	**3^{rd} order/ 4^{th} order**	**4^{th} order/ 5^{th} order**	**5^{th} order/ 6^{th} order**	**6^{th} order/ 7^{th} order**	
4.933	4.772	4.591	3.667	3.000	2.000	**3.827**

Table 4.4B: Aerial aspects of the morphometric analysis of the Nirona River Basin

Area of the River basin	**A**	389.00 sq km
Perimeter	**P**	103.00 km
Drainage Density (km/sq km)	**$D = \Sigma L_u / A$**	3.386
Stream Frequency	**$F_s = \Sigma N_u / A$**	7.69 streams / sq km
Texture Ratio	**$T = N_1/P$**	23.087
Basin Length	**L_b**	35.9 km
Basin Relief	**H_b**	298 m
Relief Ratio	**$R_R = H_b / L_b$**	8.031 m/ km
Elongation Ratio	**$R_E = (2 \sqrt{A/\pi}) / L_b$**	0.620
Ruggedness Number	**$R_N = (D \times H_b) / 1000$**	1.009
Circularity ratio	**$R_C = 4 \pi A / P^2$**	0.461
Form factor ratio	**$R_F = A / L_b^2$**	0.302

5. CHHARI RIVER BASIN:

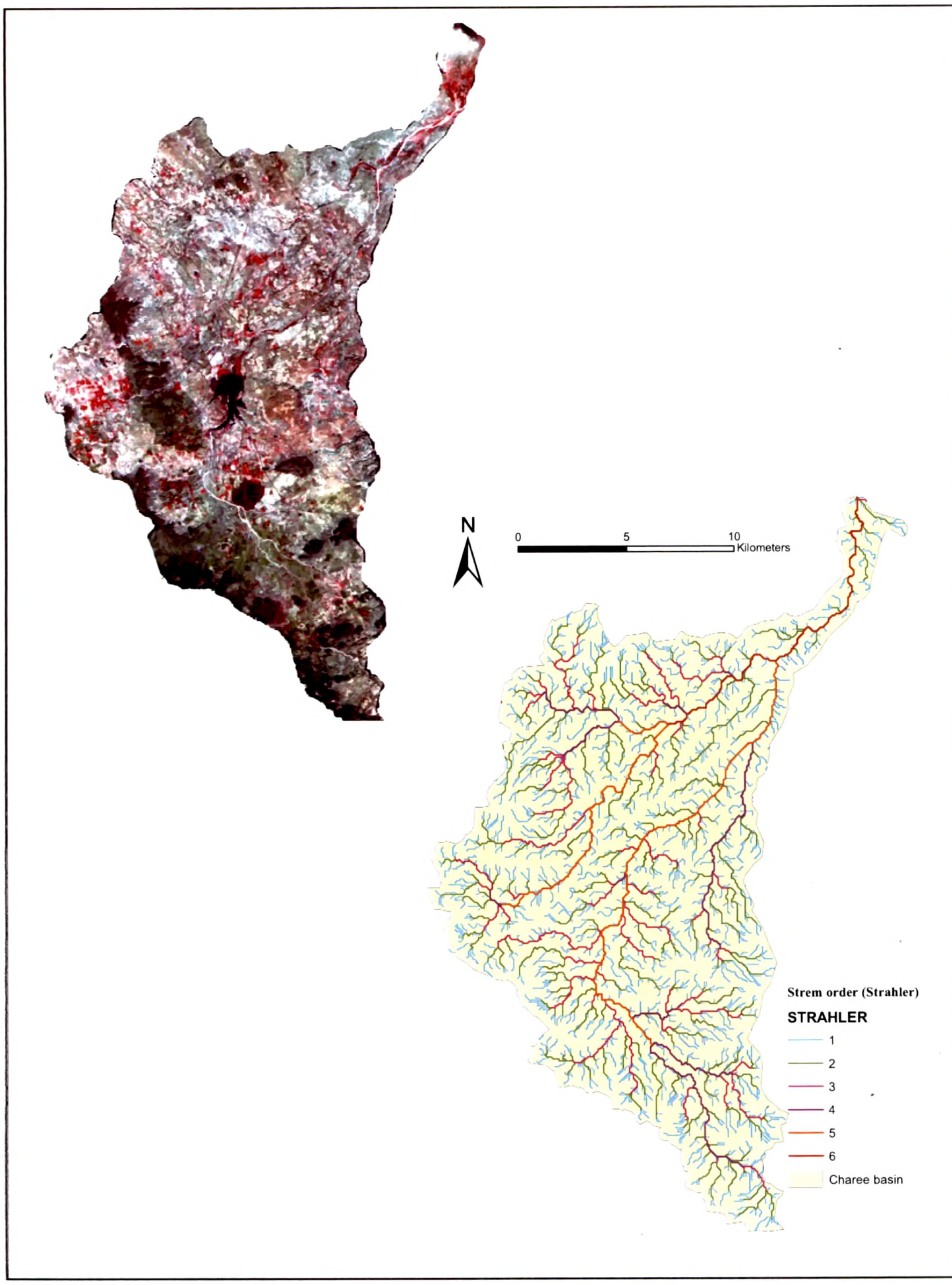

Fig.4.5: ETM Landsat FCC imagery (234) of Chhari River basin and detailed drainage map of the basin showing different order of streams.

Table 4.5A: Linear aspects of the drainage network of the Chhari River Basin

River Basin	Stream Order u	Stream Numbers N_u	Total length of the streams in km L_u	Average stream length (km)	Log N_u	Log L_u
	1[st]	1261 (N1)	551.369	0.437	3.101	2.741
	2[nd]	226	235.630	1.043	2.354	2.372
Chhari River Basin	3[rd]	54	102.385	1.896	1.732	2.010
	4[th]	11	42.057	3.823	1.041	1.624
	5[th]	3	42.630	14.210	0.477	1.630
	6[th]	1	18.600	18.600	0.000	1.270
		$\Sigma N_u =$ 1556	$\Sigma L_u =$ 992.671			

Bifurcation Ratio (R_b)					Mean R_b
1[st] order/ 2[nd] order	2[nd] order/ 3[rd] order	3[rd] order/ 4[th] order	4[th] order/ 5[th] order	5[th] order/ 6[th] order	
5.579	4.185	4.909	3.667	3.000	4.268

Table 4.5B: Aerial aspects of the morphometric analysis of the Chhari River Basin

Area of the River basin	**A**	311.042 sq km
Perimeter	**P**	112.870 km
Drainage Density (km/sq km)	$D = \Sigma L_u / A$	3.191
Stream Frequency	$F_s = \Sigma N_u / A$	5.003 streams / sq km
Texture Ratio	$T = N_1/P$	11.172 streams/ km
Basin Length	L_b	32.5 km
Basin Relief	H_b	245 m
Relief Ratio	$R_R = H_b / L_b$	7.538 m/ km
Elongation Ratio	$R_E = (2 \sqrt{A/\pi}) / L_b$	0.612
Ruggedness Number	$R_N = (D \times H_b) / 1000$	0.782
Circularity ratio	$R_C = 4 \pi A / P^2$	0.307
Form factor ratio	$R_F = A / L_b^2$	0.294

The stream frequency values range from lowest of 4.897 for Kaila basin to highest of 7.69 for Nirona basin. The value of stream frequency (Fs) for the basin exhibit positive correlation with the drainage density value of the area indicating the increase in stream population with respect to increase in drainage density. Melton (1958) related the frequency and drainage density by the equation F = 0.694 D2. The dimension less number F/D2 tends to approach a constant value of 0.694 even under diverse physiographic situations and size of drainage basin. Here this constant is ranging from 0.654 to 0.795 indicating that the basins originated from under diverse physiographic conditions.

Horton's (1945) law of stream numbers states that the number of stream segments of each order form an inverse geometric sequence plotted against order. The plotting of logarithm of number of streams against stream order is given in Fig. 4.6. The plots are straight as per the Horton's law.

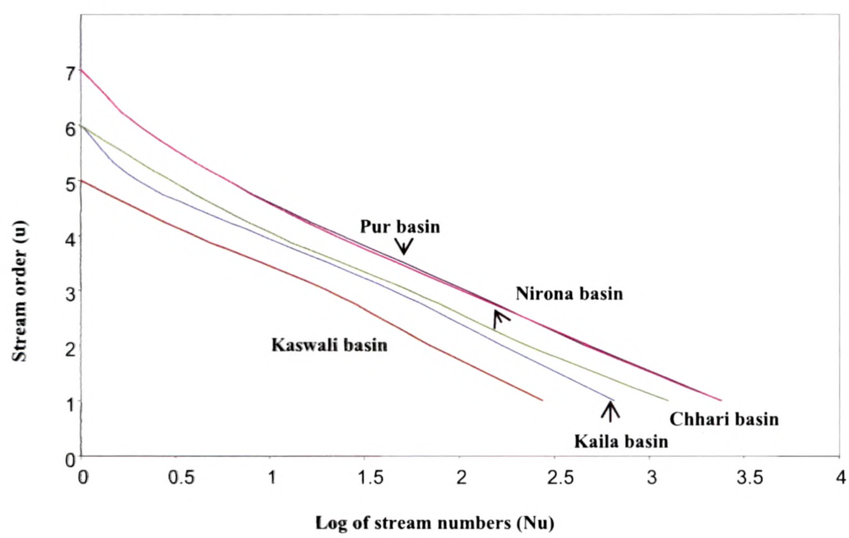

Fig. 4.6: Regression log of Stream numbers versus Stream order.

The circularity ratio values range from 0.307 for Chhari basin to 0.437 for Kaila basin. Highest elongation ratio is for the Kaila basin while for all the basin it is near 0.6 which indicate that all the basin are elongated in shape. The basins draining tectonically active areas are more elongated and tend to become more circular with the cessation of uplift (Bull and McFadden, 1977), so it is interpreted that the elongated shape of Kaila Chhari and Nirona basins points towards the area undergoing active tectonism.

The bifurcation ratio tends to be constant for a drainage basin having a uniform climate, lithology and stages of development. The bifurcation ratios of the various basins, especially Pur, Nirona and Chhari basins indicate that they arise from hilly terrains and have high gradient. This ratio is generally higher for lower orders and higher bifurcation ratios may be attributed to the high degree of tectonic activity in the area during Quaternary.

Drainage density varies from 3 to 4 km / sq km. Increase in the drainage density decreases the size of the individual units. Factors affecting drainage density are erodibility of rock and climate. Drainage density is generally lower in arid climates but comparatively high in humid terrain (Gardiner et al., 1987). In case of the river basins of the area it is ranging from 3-4 km/ sq km which come under high density class (Horton, 1945). Since area falls in the arid climate, the high density is attributed to neotectonic activity.

Texture ratios of basins vary from 6.01 in Kaswali basin to as high as 23.087 for Nirona basin which is extremely high. This high texture ratio is indicative of recent upliftment.

The ruggedness for the Kaila and Nirona basins is more than 1 while it is about 0.5 to 0.7 for Kaswali, Pur and Chhari basins. These values suggest high drainage density and comparatively low relief, indicating neotectonic activity in the area.

Trend analysis of the 1stand 2nd order streams of the Kaswali and Kaila basins indicate that majority of the streams are oriented in the NNW-SSE direction and a quite few in the NE-SW to ENE-WSW directions. This analysis reveals that the lower order streams are governed by the tilting of the basins.

BASIN ASYMMETRY

The shape of a river basin is attained by the slope of the area. The slope is the function of tilting hence the basin asymmetry can be used to decipher the tilting of the area, thus neotectonic activities (Hare and Gardner, 1985; Cox, 1994). The basin asymmetry is defined in the form of Asymmetry Factor. Asymmetry Factor (AF) has been developed to detect the tilting transverse to flow of the channels.

$$\mathbf{AF = 100 \times (Ar / At)}$$

Where, Ar is the area of the basin to the right (facing downstream) of the trunk stream and At is the total area of the drainage basin. AF values are sensitive to the tectonic tilting transverse to the trend of the trunk stream. Value of AF will be either less or more than 50 in case of tectonic tilting and tributaries present on the tilted side of the main stream will grow longer compared to the other side (Keller and Pinter, 1996). If bedrock dip has a negligible influence on stream migration, then the direction of regionally preferred migration implies a period of ground tilting in that direction.

The asymmetry factor has been calculated for the five river basins of the area around KMF. The AF values are given in the table-4.6.

Table 4.6: Asymmetry factor of the river basins

River basin	Total area (sq km)	Area in the right of the trunk stream (Ar)	AF	Deviation from 50
Kaswali River basin	70.98	37.7	53.11	3.11
Pur River basin	601.70	470.78	78.3	28.3
Kaila River basin	180.93	88.55	48.94	1.06
Nirona River basin	388.68	257.53	66.26	16.66
Chhari River basin	311.042	207.66	66.76	16.76

The general trend of the beds in all the river basins studied is east-west dipping moderately to steeply near the KMF while the amount of dip decreases away from the KMF (Ghevariya, 1984, 87; Singh et al., 2008). All the river basins studied are extending roughly across the KMF. The general strike of the beds is East-West in the area. Thus the streams are transverse to the general trend of the beds of litho-units and the little influence of the beds on the drainage is nullified on either side of the river basins.

The AF calculated for the Kaswali, Pur, Kaila, Nirona and Chhari basins are 53.11, 78.3, 48.94, 66.26 and 66.76 respectively. This is interesting to know that four river basins out of five show broader right sides whereas for the Kaila River basin right and left sides are roughly equal with RF 48.94. (Fig.4.8). It indicates that the river basins are tilted towards west in the area. Since all the river basins are showing westward tilting, it is concluded that the Mainland block has undergone westward tilting in the Quaternary Period.

West ward tilting of the Kachchh Mainland is also manifested in the form of general bending of the streams towards west after crossing the Kachchh Mainland Fault, where they are not obstructed by the hard rocks of valley sides and show deflection following the direction of gradient changes (Fig.4.7).

Fig. 4.7: Drainage map of the area along Kachchh Mainland Fault showing the deflection of the streams towards west.

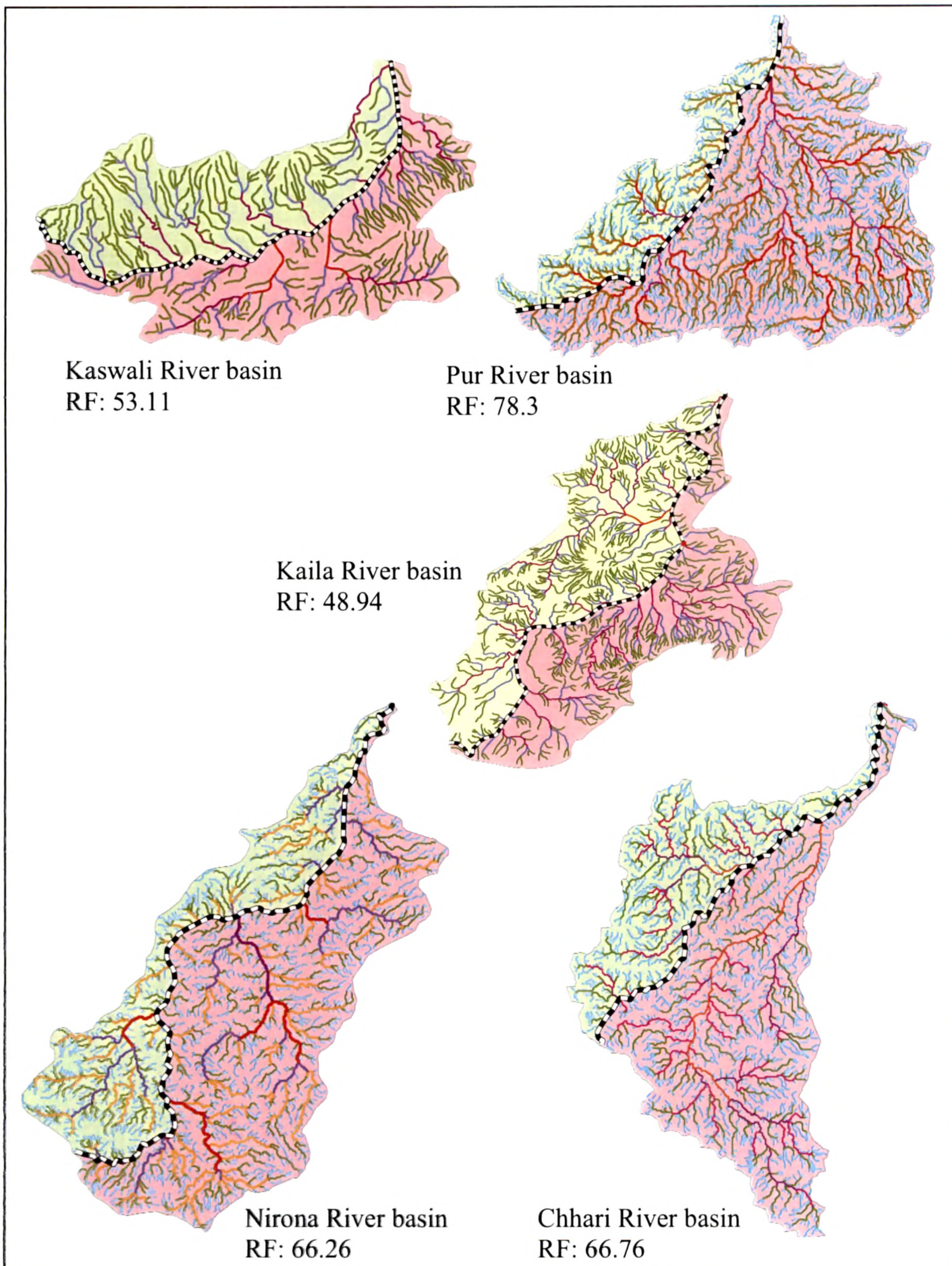

Fig. 4.8: River basins with their main trunks and left and right tributaries showing basin asymmetry.

VALLEY CROSS SECTION

Study of the cross section of the river valley may give clues of the tectonic insinuations the area has suffered. Valley incision is a measure that can be used to define relative uplift (Bull and McFadden, 1977; Ouchi, 1985). It basically describes the maturity of the valley. The Valley floor width to Valley height ratio (Vf) is an index developed by Bull and McFadden (1977) to study the relative rate of uplift an area is undergoing. Rockwell et al. (1984) also tested this index for mountain fronts and found the trends to be similar to those established by Bull and McFadden.

The formula for this parameter (Valley floor width-Valley height ratio) is as follows:

$$Vf = 2\ Vfw / [(Eld - Esc) + (Erd\text{-}Esc)]$$

where, Vf = Valley floor width-Valley height ratio, Vfw = width of the valley floor, Eld = elevation of the left divide, Erd = elevation of the right divide and Esc = altitude of the stream channel.

The valley floor width is measured between the abrupt slope increases adjacent to the river and valley height is estimated from the elevation between the stream channel and the water divides on either sides of the river. A high value of the Vf, as seen in the broader valleys, is indicative of a tectonic quiescence because of availability of enough time for lateral erosion. Conversely, a low Vf, as seen in the steep narrow valleys, is associated with the recent tectonic movements (Mayer, 1986).

The cross-valley profiles are generated taking the data from various sources like topographic maps, SRTM 90 radar data, Aster data (30 m), google map and geo-referenced imagery of the area. Vf has been calculated for the Kaswali, Pur, Kaila, Nirona and Chhari Rivers and their tributaries at several distances from the source. The streams near the source show very low Vf (from 0.24 to 1.4) whereas it increases as we move away from source due to increase in the valley floor width. At places it becomes very low, as valley incision is quite high for a particular part of the area, indicating periodic tectonic activity. The higher values near the mountain fronts indicate the broad valley floors and lateral cutting of the streams. It is important to mention that the lithology, climatic factors and hydraulic conditions of the rivers also play important role in shaping the valley cross section but for the most part of the stream channels of the area these factors appeared to be constant.

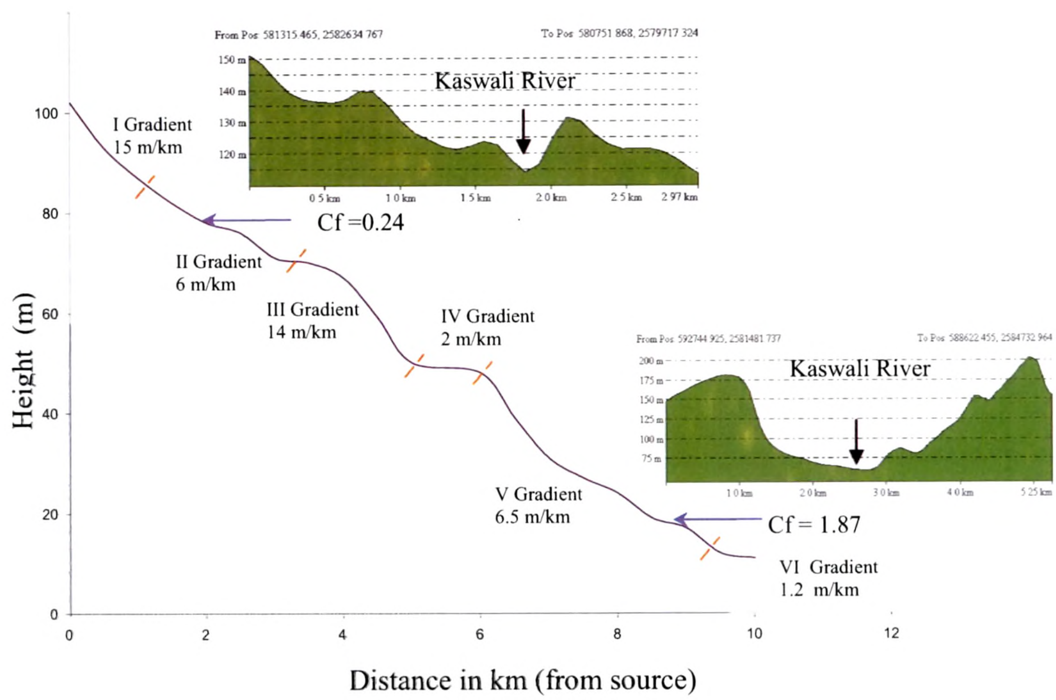

Fig. 4.9: Longitudinal profile of the Kaswali River with Vf values and valley cross section; near source cross section is V-shaped whereas away from source it is U-shaped.

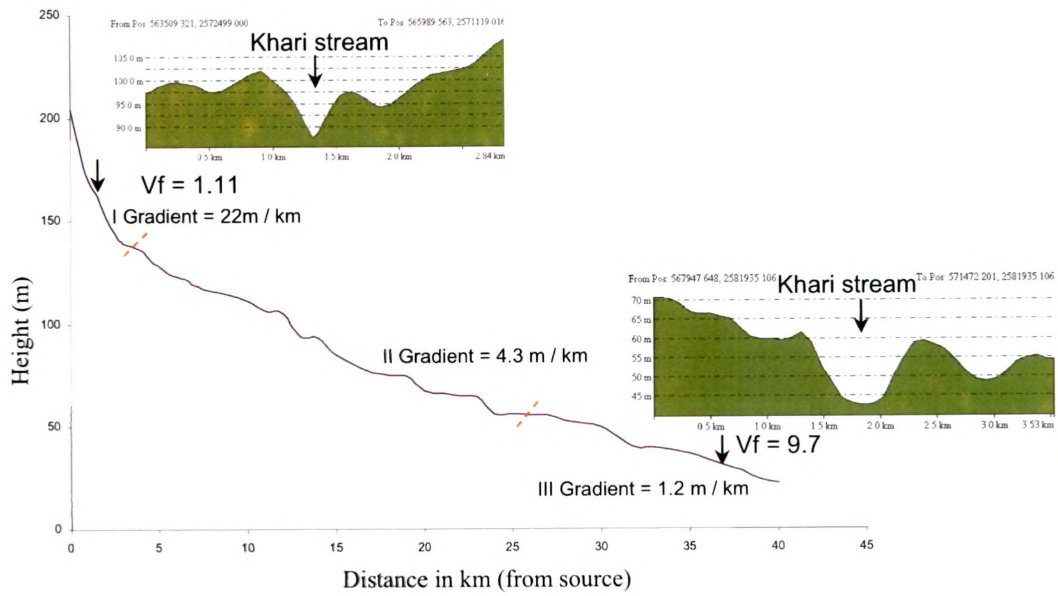

Fig. 4.10: Longitudinal profile of the Khari stream of the Pur River with Vf values and valley cross section.

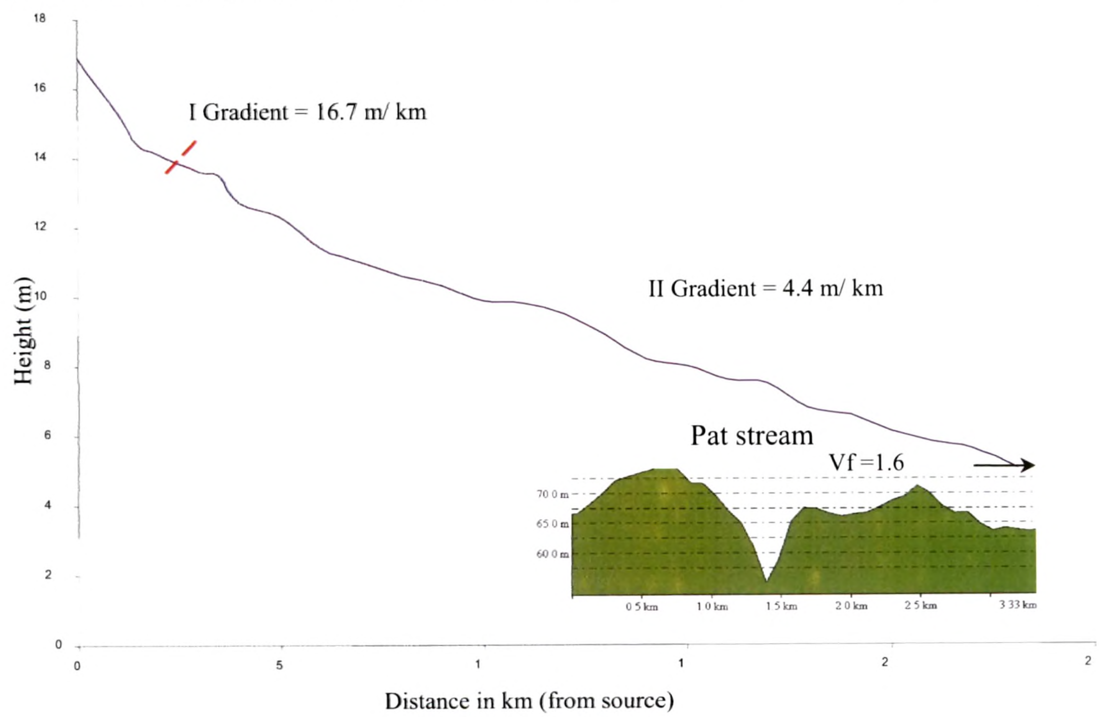

Fig. 4.11: Longitudinal profile of the Pat stream of the Pur River with Vf values and valley cross section.

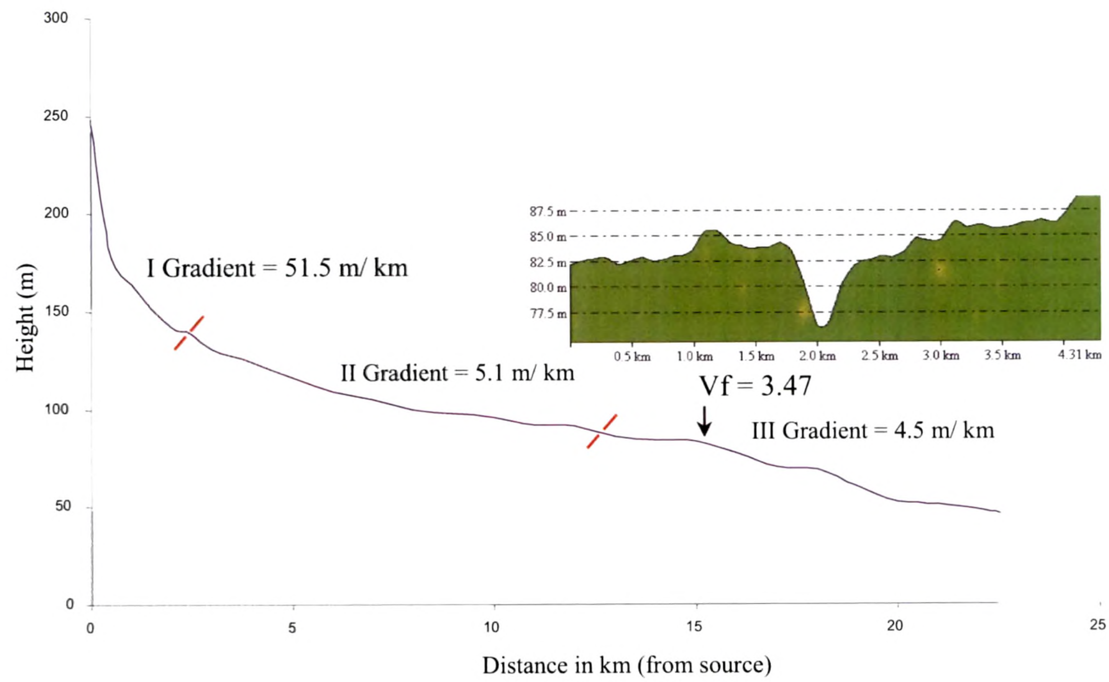

Fig. 4.12: Longitudinal profile of the Pur River with Vf value and valley cross section.

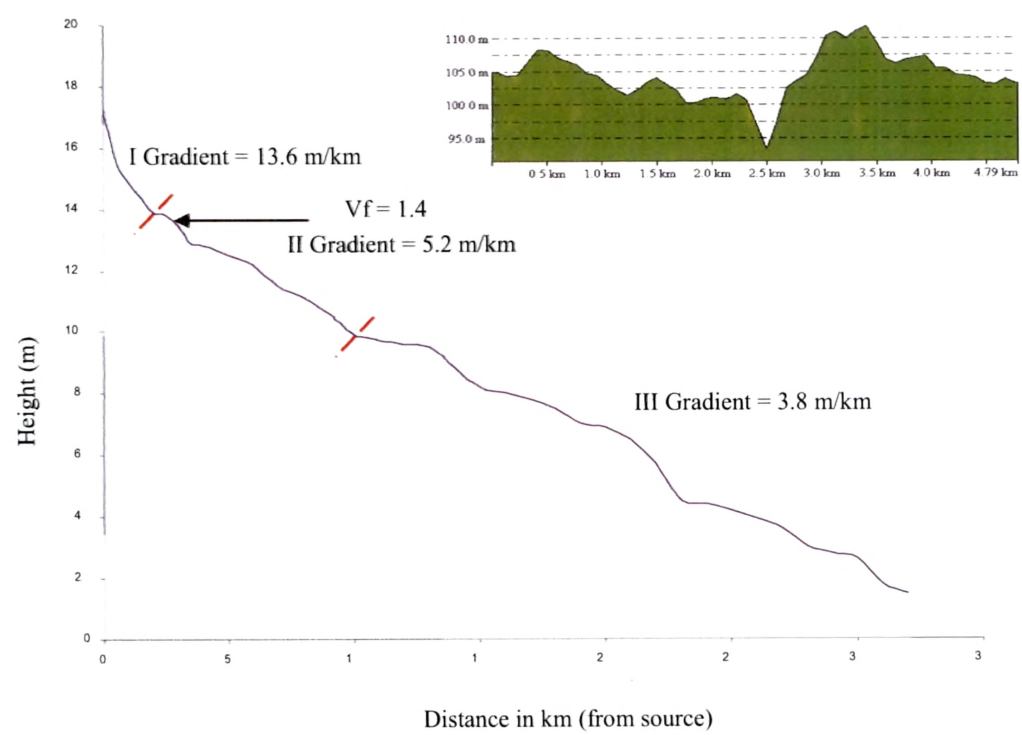

Fig. 4.13: Longitudinal profile of the Kaila River with Vf value and valley cross section.

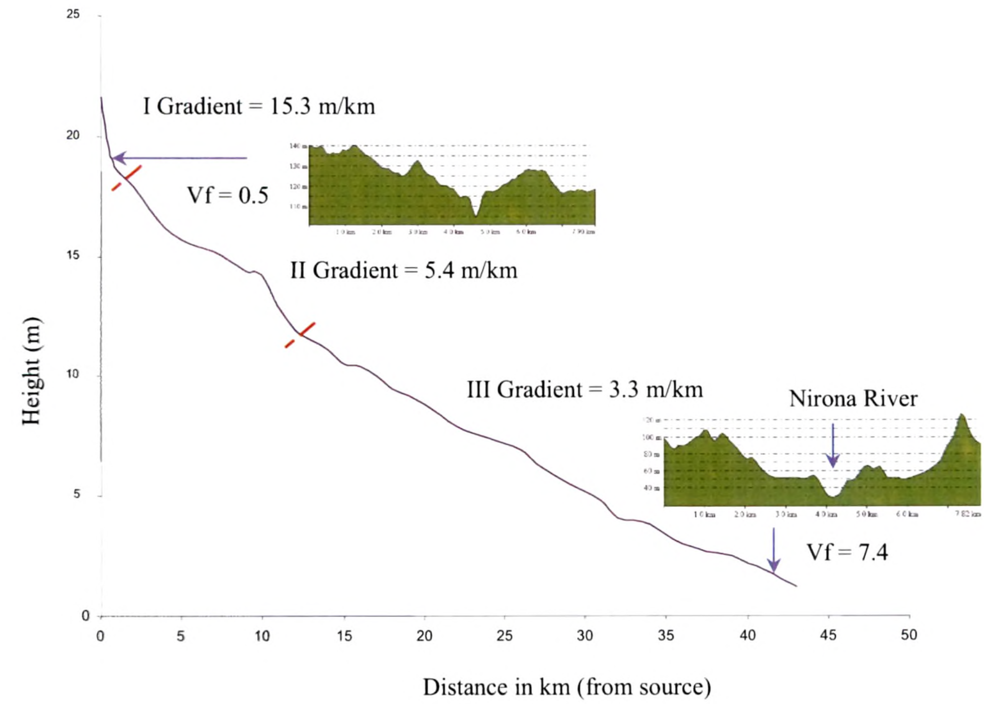

Fig. 4.14: Longitudinal profile of the Nirona River with Vf value and valley cross section.

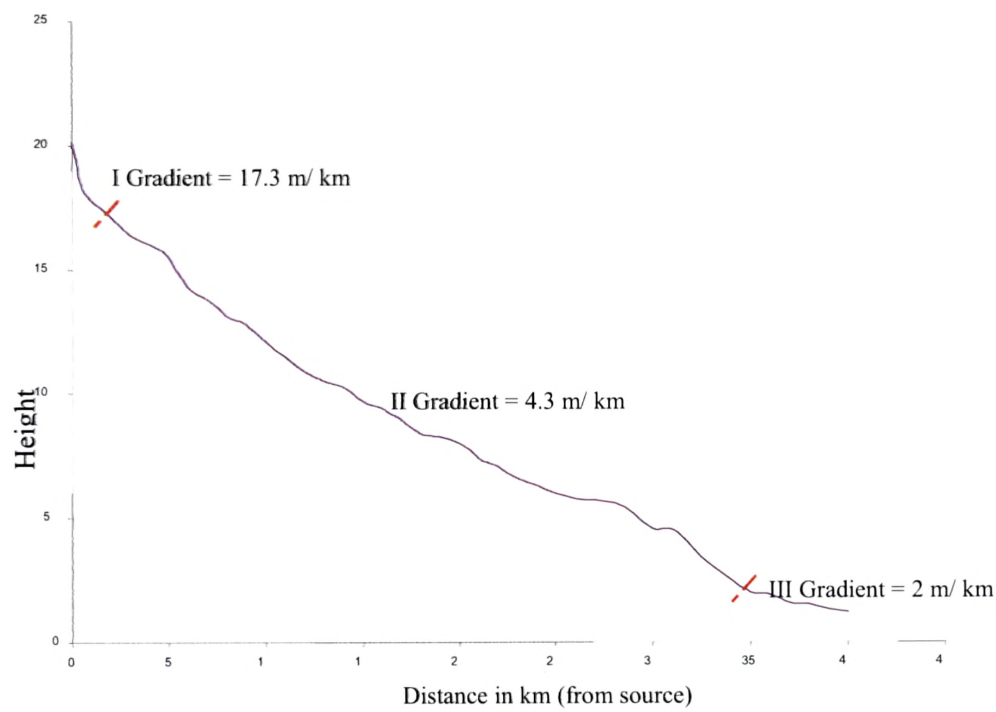

Fig. 4.15: Longitudinal profile of the Chhari River showing gradient in sectors.

LONG PROFILE ANALYSIS

The long profile is the plot of river channel length with respect to channel elevation above sea level. Long profiles of stream channels result from the interactions between fluvial incision, lithology, tectonics and base level change (Larue, 2008). The shape of the long profile is the result of the influence of each of these factors and of the evolution time. The longitudinal profile of a river reflects the tectonic activity the area has experienced (Rhea, 1993). To quantify the general shape of stream long profile, the pseudo-hypsometric integral (PHI) has been measured. It reflects the relative amount of deformation and degradation that has occurred on each river (Rhea, 1993). In some earlier studies hypsometric analysis (or area-altitude analysis), which is the study of the distribution of horizontal cross-sectional area of a landmass with respect to elevation (Strahler, 1952), was used to classify and differentiate between erosional landforms at different stages during their evolution (Strahler, 1952, Schumm, 1956). It provides a measure of the distribution of landmass volume remaining beneath or above a basal reference plane. But recently pseudo-hypsometric integral is used more effectively to numerically compare the long profiles of various rivers. Pseudo Hypsometric Index parameter is calculated as follows:

$$PHI = Ap / Ar$$

where, PHI is the Pseudo Hypsometric Integral, Ap is the area under long profile and Ar is the area of the rectangle formed by the height and length of the river basin.

PHI of the streams were calculated using the longitudinal profile of the rivers derived using topographic maps, high resolution google earth images and SRTM height data (Fig.4.16).

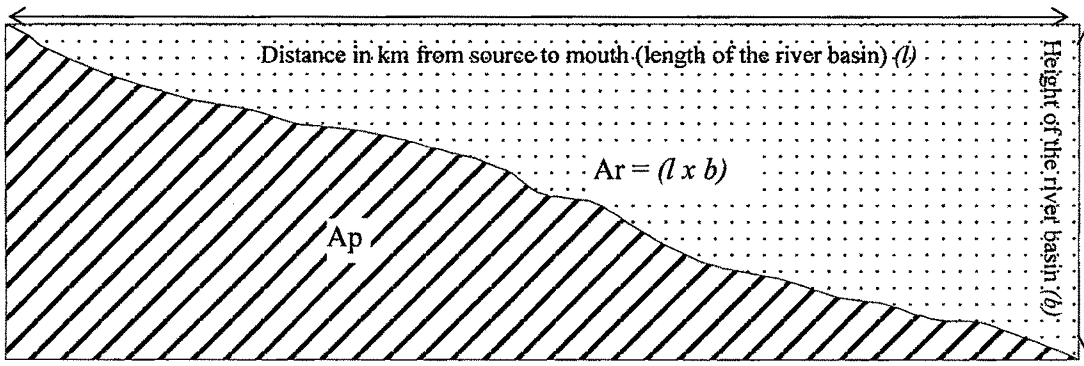

Fig. 4.16: Longitudinal profile of the Kaswali River showing Ap and Ar for PHI calculation.

Table 4.7: Pseudo Hypsometric Integral values of the rivers

River (stream)	PHI (in%)
Kaswali River	48.49 %
Khari stream of Pur River	31.29 %
Pat stream of Pur River	39.94 %
Pur River	25.85 %
Kaila River	42.14 %
Nirona River	38.13 %
Chhari River	39.25 %

The long profiles of the rivers show prominent breaks in their longitudinal profiles (Fig.4.9 to 4.15). These breaks are indicative of rejuvenations forming knick point which is strong evidence of neotectonic activity in the area. The convex-up curves with high integrals are typical for youth and disequilibrium stage of the landscape which is characteristic of the Kaswali stream and thus indicate the influence of the neotectonism in the area. The PHI of the river are in agreement with the long profile as they are in general high, specially for the Kaswali, Kaila and Chhari Rivers which indicate that the area has under gone rejuvenation in the recent past.

MOUNTAIN FRONT SINUOSITY

Geomorphic indices for mountain-front sinuosity was developed by Bull and McFadden (1977) which is useful in the general assessment of the degree of tectonic activity experienced by an area.

The Mountain Front Sinuosity (S) is defined as the ratio of the length of a mountain front, as measured from an aerial photograph or topographic map or other method, to the straight-line length along the mountain front. It therefore, reflects a balance between the tendency of erosional processes to produce an irregular or sinuous mountain front and the effect of vertical active tectonic movement on steeply dipping, range-bounding faults, which tend to produce a relatively straight front. Broadly speaking, a straight mountain front is indicative of an active fault or fold while the irregular fronts indicate tectonic pause when erosion has got enough time to act upon and make the front irregular (Bull and McFadden, 1977). The Mountain front sinuosity index is calculated as follows:

Mountain Front Sinuosity (S) = Lmf / Ls

Where, Lmf is the length along the edge of the mountain-piedmont junction and Ls is the straight length of mountain front.

Low values of the S correlate with relatively high rates of uplift along faults which bound mountain ranges. Mountain front sinuosity of the fronts calculated along the Kachchh Mainland Fault is calculated using more accurate data of Google Earth, zooming the image enough to get all the details available, keeping the 3D view on. The fronts were selected for analysis along the KMF which were continuous for more than 2 km in length (Fig.4.17). The detail of the analysis is given in Table 4.8.

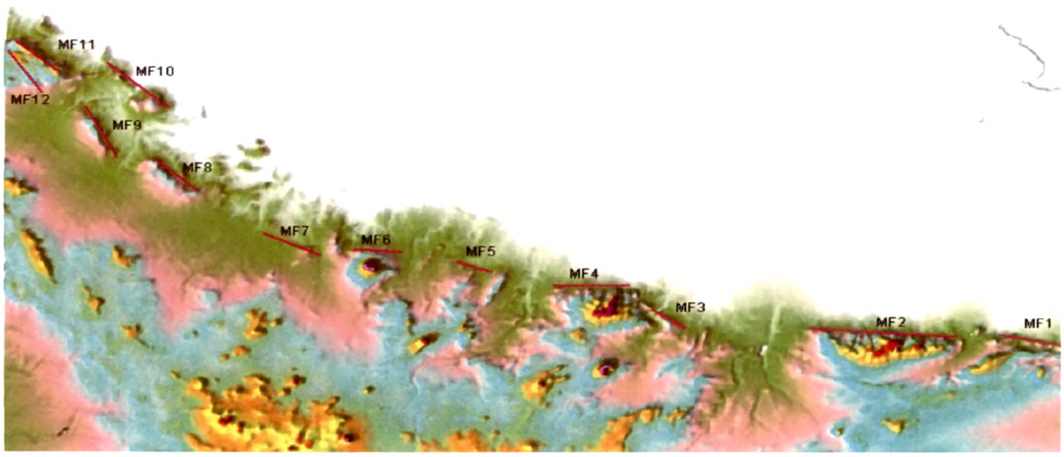

Fig. 4.17: Location of mountain fronts selected for sinuosity index calculation.

Table 4.8: Mountain front sinuosity of the selected fronts along the KMF

Mountain Front	**Lmf (km)**	**Ls (km)**	**Sinuosity Index (S)**	**Tectonic Activity Class**
1	13.92	13.69	**1.02**	**I**
2	14.81	14.60	**1.01**	**I**
3	3.51	3.23	**1.09**	**I**
4	8.83	8.64	**1.02**	**I**
5	2.45	2.32	**1.05**	**I**
6	4.08	3.70	**1.10**	**I**
7	2.10	2.02	**1.04**	**I**
8	7.04	6.37	**1.10**	**I**
9	12.92	12.25	**1.01**	**I**
10	17.84	17.22	**1.04**	**I**
11	6.30	6.23	**1.01**	**I**
12	10.66	9.98	**1.07**	**I**

The analysis of the Mountain front sinuosity index of the East-West trending mountain fronts associated with the KMF fall within the tectonic activity class I of Bull and McFadden (1977) indicating that the area is experiencing active tectonism.

RIVER SINUOSITY

Sinuosity of a river is its tendency to deviate from a straight line. The river sinuosity parameters have been used to understand the role of tectonism (Rhea, 1993). The sinuosity of a meandering stream is the result of topographic and hydraulic factors which can be expressed by a ratio called the index of sinuosity (Mueller, 1968). Friend and Sinha (1993) suggested a simpler method of measuring sinuosity by dividing the river into segments and determining the sinuosity parameter for each segment. Leopold and Langbein (1966) described Topographic Sinuosity Index (TSI) and the Hydraulic Sinuosity Index (HSI) as additional variables for defining the sinuosity of the channels. A higher value of the TSI over HSI is indication of rejuvenation, i.e. tectonic factors domination over hydraulic factors.

The indices of sinuosity are calculated as follows:

Channel Index (CI)	**= CL / AL** where, CL is Channel Length and AL is air Length (Straight Length)
Valley Index (VI)	**= VL / AL**, where VL is Valley length
Standard Sinuosity Index (SSI)	**= CI / VI**
Hydraulic Sinuosity Index (HSI)	**= (CI - VI / CI - 1) x 100**
Topographic Sinuosity Index (TSI)	**= (VI-1 / CI – 1) x 100**

The Sinuosity indices of the two rivers, the Kaswali and the Nirona, have been calculated in the present course of study. The Google earth images have been used to calculate the channel length, valley length and their aerial lengths zooming the images up to about 1:2000 to 1:5000 scale.

Sinuosity Indices of Kaswali River

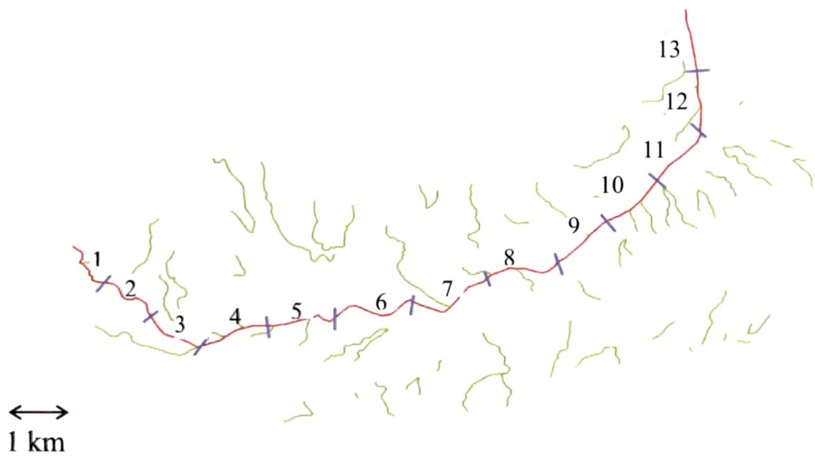

Fig.4.18: Segments of the Kaswali River used for calculation of river sinuosity.

Table 4.9: Table showing values of Channel Index (CI), Valley Index (VI), Standard Sinuosity Index (SSI), Hydraulic Sinuosity Index (HSI) and Topographic Sinuosity Index (TSI) computed for the various segments of Kaswali main channel

Segment Number	Channel Index (CI)	Valley Index (VI)	S.S.I.	H.S.I. (in %)	T.S.I. (in %)
1	1.02	1.02	1.00	0.00	100.00
2	1.06	1.06	1.00	0.00	100.00
3	1.09	1.09	1.00	0.00	100.00
4	1.03	1.03	1.00	0.00	100.00
5	1.22	1.18	1.03	16.67	83.33
6	1.27	1.22	1.04	19.05	80.95
7	1.19	1.13	1.05	31.25	68.75
8	1.06	1.06	1.00	0.00	100.00
9	1.14	1.09	1.04	33.33	66.67
10	1.39	1.33	1.04	14.29	85.71
11	1.01	0.98	1.03	50.00	50.00
12	1.02	1.01	1.01	50.00	50.00
13	1.09	1.07	1.02	25.00	75.00

Table 4.10: Table showing values of Channel Index (CI), Valley Index (VI), Standard Sinuosity Index (SSI), Hydraulic Sinuosity Index (HSI) and Topographic Sinuosity Index (TSI) computed for the various segments of Nirona main channel

Segment Number	**Channel Index (CI)**	**Valley Index (VI)**	**S.S.I.**	**H.S.I. (in %)**	**T.S.I. (in %)**
1	1.04	1.04	1.00	0.00	100.00
2	1.11	1.11	1.00	0.00	100.00
3	1.16	1.16	1.00	0.00	100.00
4	1.10	1.10	1.00	0.00	100.00
5	1.06	1.06	1.00	0.00	100.00
6	1.14	1.14	1.00	0.00	100.00
7	1.18	1.18	1.00	0.00	100.00
8	1.15	1.15	1.00	0.00	100.00
9	1.03	1.01	1.03	83.33	16.67
10	1.03	1.01	1.02	66.67	33.33
11	1.03	1.02	1.02	50.00	50.00
12	1.04	1.02	1.02	57.14	42.86
13	1.06	1.04	1.02	33.33	66.67
14	1.16	1.13	1.03	18.52	81.48
15	1.03	1.01	1.02	80.00	20.00
16	1.15	1.05	1.10	69.23	30.77
17	1.04	1.01	1.03	71.43	28.57
18	1.11	1.09	1.02	20.00	80.00
19	1.02	1.01	1.01	50.00	50.00
20	1.01	1.01	1.00	0.00	100.00
21	1.01	1.00	1.01	49.75	50.25
22	1.16	1.13	1.03	21.43	78.57

Sinuosity Indices of Nirona River

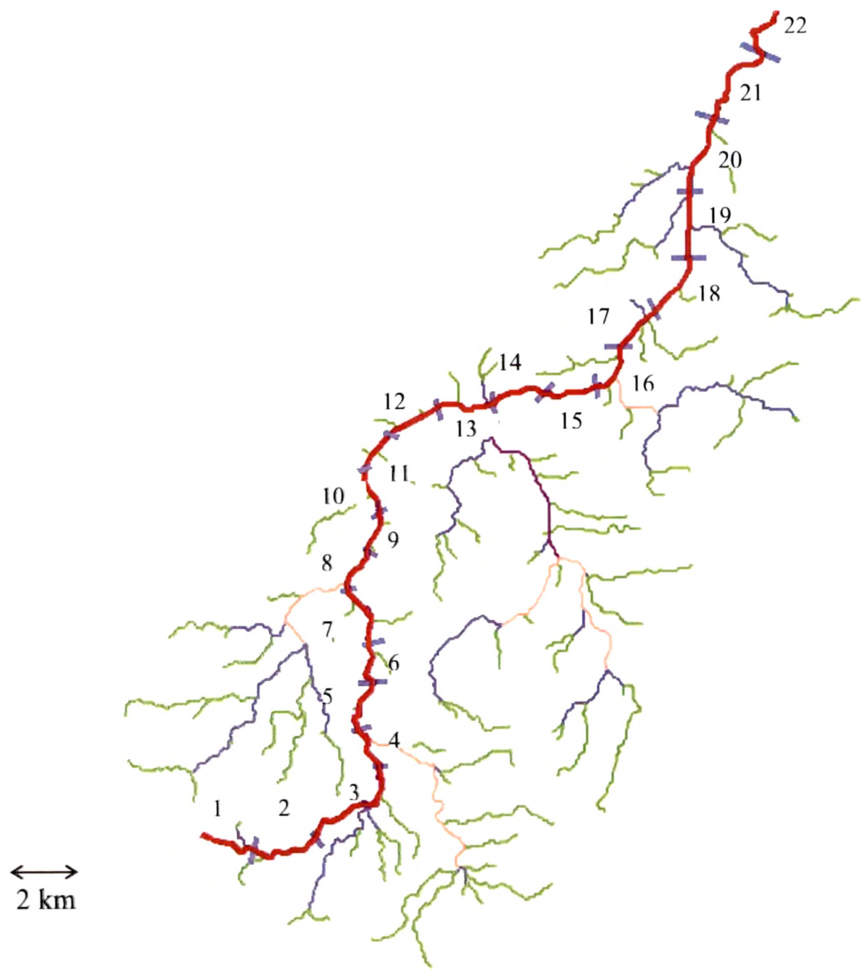

Fig. 4.19: Segments of the Nirona River used for calculation of river sinuosity.

The sinuosity indices for Kaswali River (Fig.4.18, Table 4.9)) and Nirona River (Fig.4.19, Table 4.10) show that the topographic sinuosity index is 100% in higher reaches while it starts decreasing in the middle reaches of rocky plains. Both the basins show high values of TSI as compared to HSI which indicate that the tectonic factors are dominating over hydraulic factors in shaping the course of the rivers.