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Morphotectonic analysis of Kosi River basin in Kumaun Lesser Himalaya: an evidence of neotectonics

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Abstract The Himalayan arc is one of the prominent sites on Earth, for ongoing research on active tectonics because of the frequent occurrence of earthquakes of low-moderate intensity that occur in various sectors of the region. The present study is an attempt to decipher the active uplift and relative tectonic activity in Kosi River basin, a part of the southern Kumaun Himalayas. Several morphotectonic parameters such as asymmetry factor (AF), hypsometric integral (HI), mountain front sinuosity (S_{mf}), channel sinuosity (S), and basin elongation ratio (R_e) have been calculated with an objective to compare different sub-basins in the Kosi watershed that may prove useful in deciphering of relative tectonic activity. The watershed delineation of the Kosi River basin as well as its sub-basins, and detailed drainage network has been accomplished by using the CARTOSAT-1 DEM with the help of ArcGIS 10.3 software, using TauDEM tool and Global Mapper 18. Analysis of these morphotectonic parameters reveals that although the whole of the Kosi River basin lies in the seismically active zone, but the northern part along North Almora Thrust (NAT), central part around South Almora Thrust (SAT), Ramgarh Thrust (RT), and southern part along Himalayan Frontal Thrust (HFT) are tectonically more active

and undergoing neotectonic rejuvenation. The information derived would prove beneficial in identification of hazard prone areas and in planning of socio-economic development in mountainous terrain.

Introduction

The Himalaya displays greatest relief on the Earth with most of the peaks rising 8000 m above the mean sea level. The formation of Himalaya resulted from the collision of Indian continental plate with the Eurasian plate around 65 Ma, and the suturing and welding of both the continents was completed by 55–50 Ma. The northward-moving Indian plate at the rate of 180–195 mm/year during Paleocene slowed down to 45 mm/year at 55 Ma, due to its collision with Eurasian continent. This collision zone was highly active during Paleocene to Middle Eocene (Valdiya 2010).

The rugged terrain characterized by thrusts, fault scarps, steep slopes, gorges, unpaired terraces, V-shaped valleys, and similar geomorphological features along with frequent occurrences of low to medium intensity earthquakes indicate towards tectonic activity being active even in Holocene.

The present study presents the results of the morphological evidences in relation to the relative tectonic activity in the Kosi River watershed extending between 29° 18′ N–79° 02′ E and 29° 51′ N–79° 51′ E in the Kumaun Lesser Himalaya. The Kosi catchment covers an area of 2135 km^2 wherein the river flows N-S in the northern and southern parts of the watershed while in the middle part, it follows the E-W trend incising the bedrocks and forming broad valleys, strath as well as unpaired terraces. The Kosi River has produced an actively

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The present paper is an attempt to understand the ongoing neotectonic activity in the Kosi River watershed in Kumaun Lesser Himalaya, based on evident geomorphological signatures and using remote sensing and GIS technology in deciphering the relative tectonic transformation. Himalaya-Hindukush-Zagros are the parts of same orogen and lie in seismo-tectonically active zone. Thus, we believe that this study would have implications in understanding any of the watersheds in these regions pertaining to ongoing active tectonics.

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eroded landscape with bedrock incision evident at several locations. The present morphotectonic analysis using geomorphic parameters covers whole of the Kosi River basin and includes 28 sub-basins on the basis of flow directions and slope (Fig. 1).

Geology of the area

The tectono-stratigraphy of the Kumaun Lesser Himalaya has been characteristically a piggy-back type duplex structure (Gansser 1964; Saklani and Bahuguna 1983; Jhonson, 1986; Valdiya 1998, 2001a, b; Kothyari and Pant 2008). Several blocks of metamorphic rocks ranging from medium to high grade are being thrust over younger sedimentary formations in the study area. The thrusts present in the Kosi River basin from north to south are North Almora Thrust in north eastern part of basin, followed by South Almora Thrust (SAT), Ramgarh Thrust (RT), and Main Boundary Thrust (MBT) in the south separating Siwalik Group from Lesser Himalaya. Forming the part of the Lesser Himalaya, the rocks of the area are highly deformed. The sedimentary succession of the Rautgara and Gangolihat formations in the north are overlain

by thrust sheet of Almora Group along the North Almora Thrust (Heim and Gansser 1939; Gansser 1964; Powar 1980; Valdiya 1980). The sedimentaries exposed in the north comprise cross-bedded quartzites, slates, and lithic arenites of the Rautgara Formation, overlain by calcareous sequence of Gangolihat Dolomites, predominantly along the Almora Thrust. The Gangolihat Dolomites comprise micrites, dolomitic limestone, and stromatolitic dolomites. The sedimentary succession is overlain by mesograde metamorphic rocks of the Almora Group along the Almora Thrust. The northern flank of the synformally folded Almora crystalline sheet is known as North Almora Thrust (NAT), and the southern limb is called South Almora Thrust (SAT).

Along the southern limb, the rocks of the Ramgarh Group, forming another thrust sheet overlying the Krol Belt, are exposed. The low-grade metamorphic rocks of Ramgarh Group mainly comprise phyllonite, quartzites, mylonite, and quartz porphyries. The Ramgarh Group is thrust over the rocks of the Krol Belt, along Ramgarh Thrust. The Krol Belt in the southern part in turn is thrust over the foreland Siwalik Belt along the Main Boundary Thrust (MBT).

The Krol Belt in the Betalghat Hills comprises Nagthat Formation of the Jaunsar Group at the base and is overlain
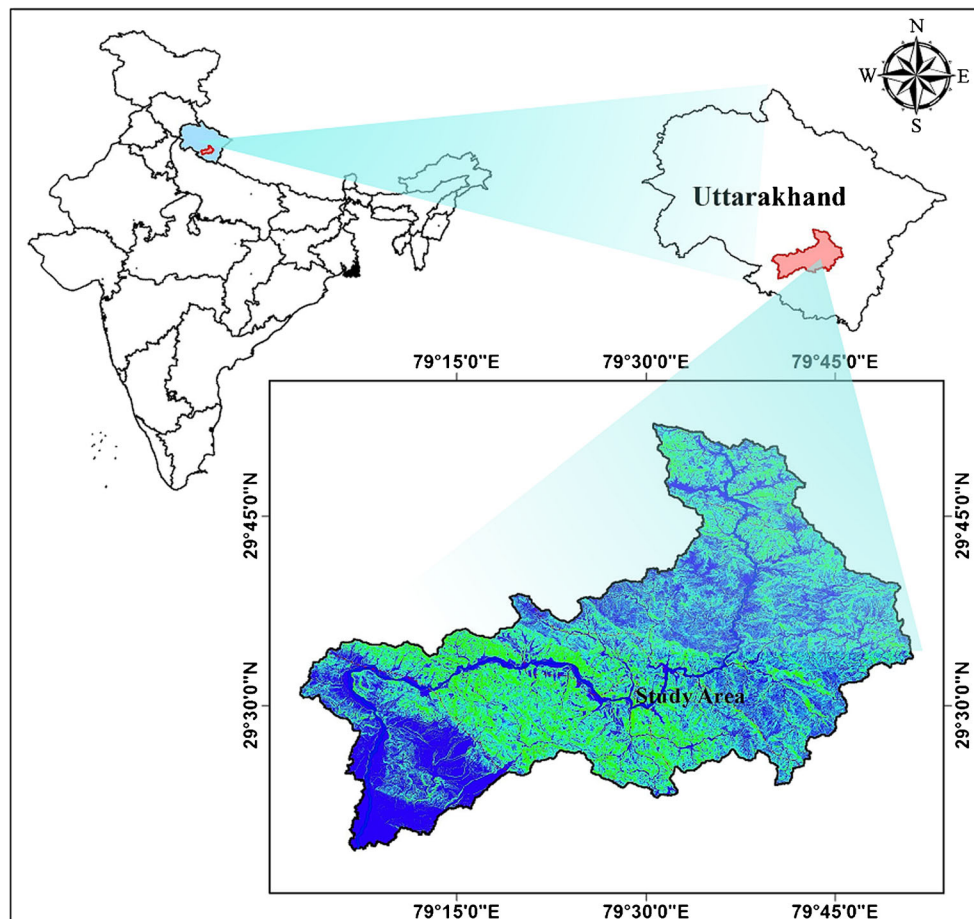

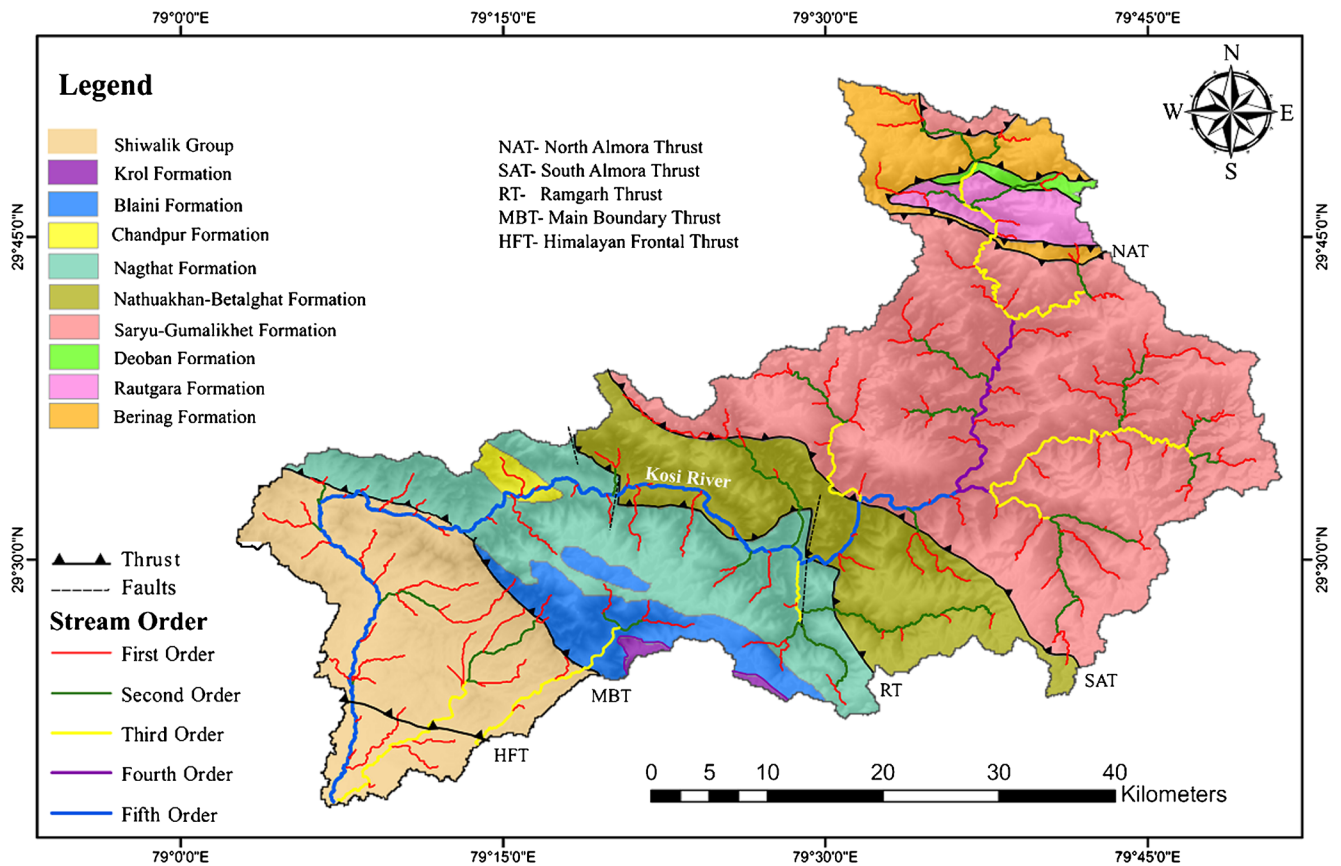**Fig. 1** Inset map of study area (Kosi watershed)

Fig. 2 Geological map of the study area showing major thrusts and faults with stream order of the river. (after K.S. Valdiya 1980)

by Mussoorie Group. The Mussoorie Group is constituted of Blaini—Infra Krol—Krol, and Tal formations in the area to the south and southeast of the area of investigation. The rocks show polyphased deformation and represent a complex tectonic setup. The distribution of different lithounits is shown in the geological map (Fig. 2.) The terrain is crisscrossed by a large number of transverse faults which are seismo-tectonically active (Pant and Paul 2007; Pathak et al. 2013).

Materials and methodology

Morphometry is defined as the quantitative analysis of landscape shape, size, elevation, and slope characteristics (Keller and Pinter 1996). Landscape evolves due to the combined effects of erosional-denudational processes as well as the relative tectonic upliftment or subsidence as a result of overburden removal. The geomorphology of an area is an imprint of the several geological processes active in carving the Earth's surface, and the quantitative measurement of such features helps to compare different landforms providing an aid in deciphering the deformation and relative tectonic activity involved (Schumm et al. 2002).

For the present study, topographic maps of Survey of India (SOI), Dehradun, at scale of 1:50,000 were procured and used

for digitizing various localities in the study area. Digital elevation model (DEM) of the indigenous satellite CARTOSAT-I with 2.5 m resolution was acquired from Bhuvan (ISRO's GeoPortal) and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Version 2 with 15 m resolution, procured from USGS, portal was used in ArcGIS 10.3 and Global Mapper 18 to derive the detailed drainage network and catchment boundaries of the Kosi watershed (Malik et al. 2014). The Terrain Analysis Using Digital Elevation Model (TauDEM) tool of ArcGIS developed by Tarboton and Department of Hydrology, University of Utah (1997), was used in the extraction of drainage network, sub-basins, and hydrologic analysis (Fig. 3).

The watershed delineation from DEM involved initial step of confirmation of hydrologically connected grids, i.e., every grid cell flowed into the next neighboring downstream cell of lowest elevation using D8 algorithm. The "pits" or holes present in data, representing null values, were filled by assigning average value of the neighboring grid cells. Further, the process was followed by calculation of the direction of flow from each grid cell to its downhill neighbor. This was achieved by examining the eight neighbors of the cell and determining the neighboring cell with steepest downhill descent. The flow directions hence obtained were coded as a value in the new flow direction grid. The flow-direction grid was used to sum the number of
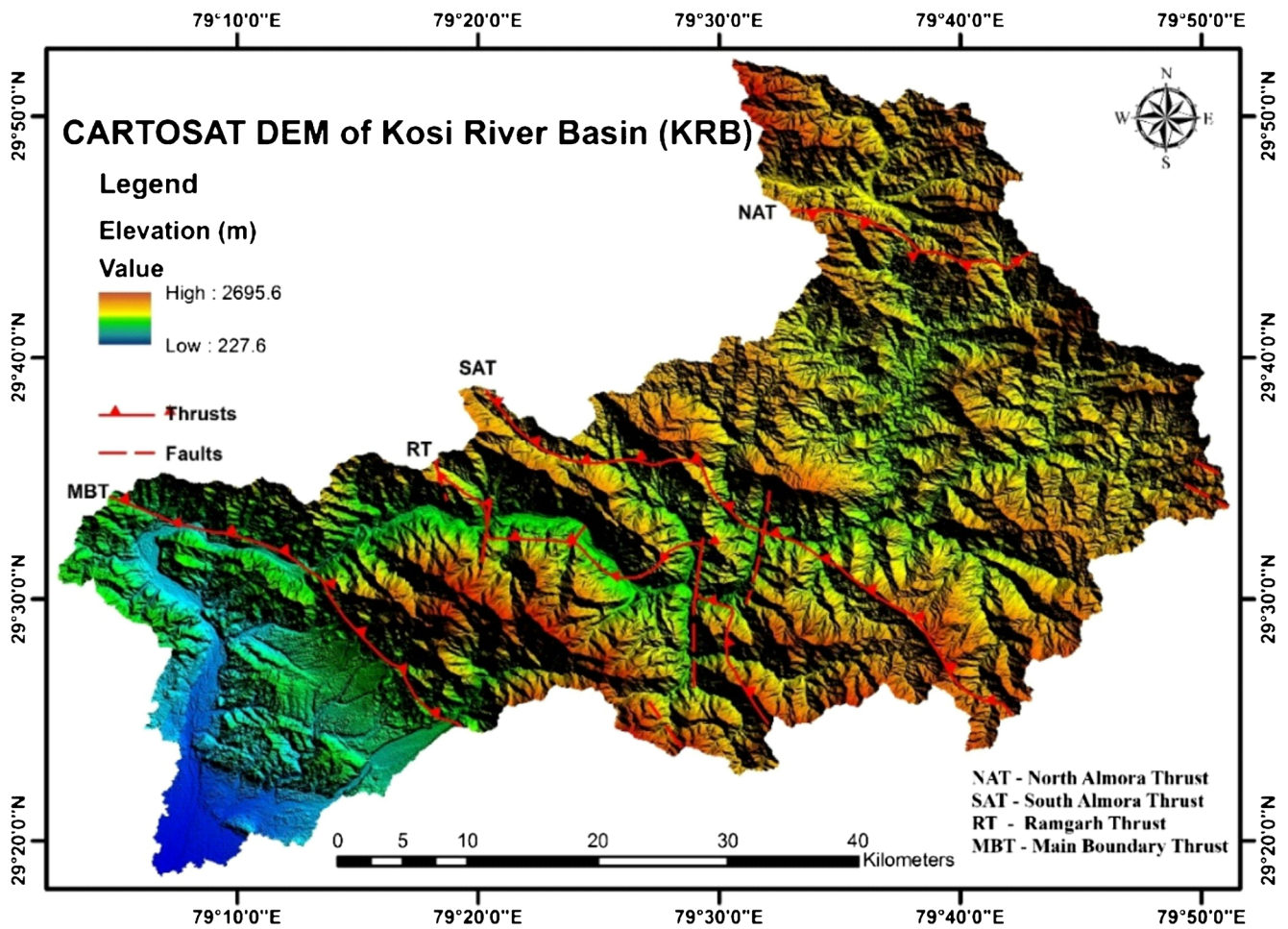
Fig. 3 CARTOSAT-I DEM showing elevation range and several thrusts and faults in the Kosi watershed

uphill cells that flow to any other cell. This summing was done for all cells within the grid to create a "flow-accumulation" grid in which each cell value represents the number of uphill cells flowing to it. Because a cell represents a geographic area (2.5 m × 2.5 m), the flow accumulation grid was multiplied by this area to calculate

Table 1 Formulae adopted for calculating morphotectonic parameters

| Morphotectonic parameters	Formulae	References	Values, inferences	Average range in study area
Mountain front sinuosity (S_{mf})	$S_{mf} = L_{mf}/L_s$	Bull and Mc Fadden (1977)	$S_{mf} < 1.4$, tectonically active, $S_{mf} = 1.4–3$, moderately active, $S_{mf} > 3$, inactive setting	1.21
Asymmetry factor (AF)	$AF = 100(Ar/At)$	Cox (1994)	$AF > 50$, suggest tilt	43.84
Channel sinuosity (S)	$S = SL/VL$	Mueller (1968)	Straight < 1.05 Sinuous > 1.05 Braided > 1.3 Meandering > 1.5 Anastomosing > 2.0	1.27
Hypsometric integral (HI)	$HI = \frac{mean\ elev - min.elev}{max.elev - min.\ elev.}$	Strahler (1952)	(0–0.3) indicates old stage of the basin (0.3–0.45) indicates mature stage of the basin (0.45–0.58) indicates youth stage of the basin	0.37
Basin elongation ratio (R_e)	$Re = (2\sqrt{A}:\sqrt{\pi})/L$	S.A. Schumn (1956)	Circular 0.9–0.10 Oval 0.8–0.9 Less elongated 0.7–0.8 Elongated 0.5–0.7 More elongated < 0.5	0.67
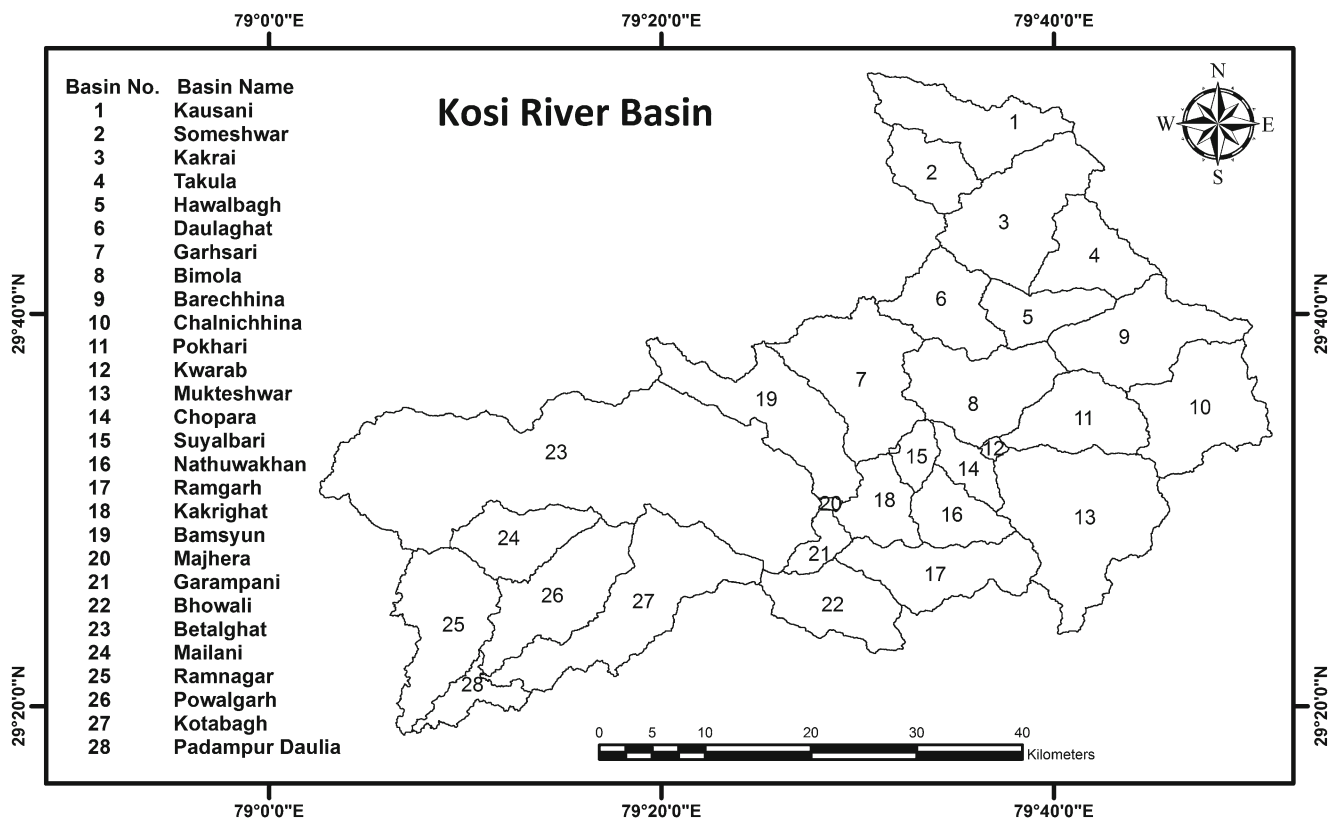
Fig. 4 Map of the Kosi watershed showing sub-basins with their entities

the total drainage area of the Kosi basin and its various sub-basins. The flow-direction and flow-accumulation grids were then used to delineate watershed and sub-watershed boundaries. These were then selected and converted to a polygon representing the watershed (Tarboton 1997, 1998; Farooq et al. 2015).

A total of 28 sub-basins were identified and demarcated in the Kosi watershed, and several sub-basins with less area than an average threshold were also undertaken due to abrupt changes in the river channel, coincidence with the knickpoints or were present along some previously studied faults as Ratighat-Khairna-Bamsyun fault, Jaurasi fault, Betalghat fault, etc. The following indices were calculated for all the 28 sub-basins of the Kosi watershed based on the formulae listed in Table 1, Fig. 4.

Mountain front sinuosity

Mountain front sinuosity (S_{mf}) is defined as the ratio of length of the mountain front at the foot of the mountain where prominent break in the slope occurs to the straight-line length of the mountain front (Bull and Mc Fadden, 1977; Keller and Pinter 1996). Tectonic forces being responsible for uplift in an area tend to produce straight mountain fronts along active faults. Continual erosion of the mountain fronts by rivers wherein

tends to carve a sinuous pattern. Thus, in regions of active tectonics and uplift or along any fault, mountain front sinuosity (S_{mf}) values are found to be low. Calculation of mountain front sinuosity (S_{mf}) was done by preparing a slope map from high-resolution CARTOSAT-I DEM and demarcating the mountain fronts along the major river channels.

Asymmetry factor

Asymmetry factor (AF) proposed by Keller and Pinter (1996) is the ratio of area to the right of the basin A_r (facing downstream) to the total area of the basin A_t normalized by multiplying the ratio with 100. The asymmetry factor is sensitive to tilting perpendicular to the trunk of the stream (Keller and Pinter 1996; Kothyari 2014; Ali et al. 2015). Variation in stream lengths of tributaries on either side of the main channel suggests tilting where AF is > 50 <. Asymmetry factor proves helpful in ascertaining relative tectonic upliftment for larger areas.

Channel sinuosity

Channel sinuosity (S) is defined as the ratio of curvilinear length of the channel to the Euclidean length (straight-line

Table 2   Morphometric indices calculated for the Kosi River basin depicting comparative analysis of sub-basins susceptive to tectonic activity.

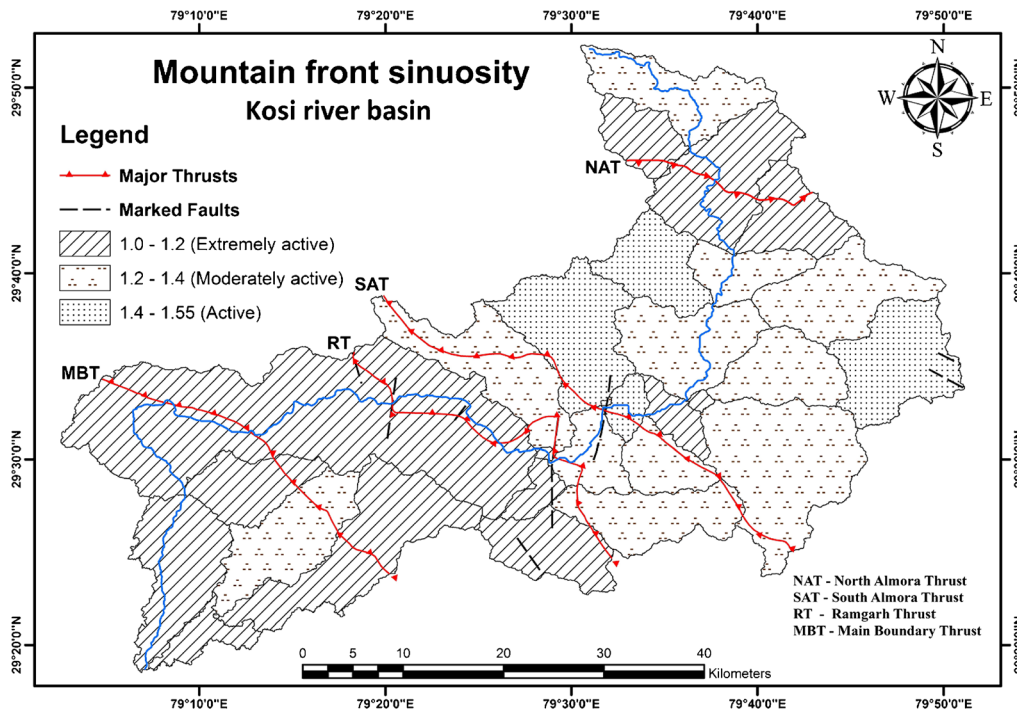| Basin ID	Basin name	Mountain front sinuosity	Asymmetry factor	Channel sinuosity	Hypsometric integral	Basin elongation ratio
1	Kausani	1.25	48.16	1.48	0.35	0.56
2	Someshwar	1.09	41.86	1.12	0.29	0.74
3	Kakrai	1.07	35.7	1.43	0.44	0.75
4	Takula	1.03	75.41	1.47	0.37	0.8
5	Hawalbagh	1.2	34.66	1.18	0.33	0.64
6	Daulaghat	1.41	56.37	1.49	0.38	0.77
7	Barechhina	1.23	50.98	1.23	0.32	0.63
8	Bimola	1.34	63.97	1.23	0.34	0.77
9	Garhsari	1.55	53.53	1.34	0.56	0.72
10	Chalnichhina	1.43	53.73	1.35	0.42	0.75
11	Pokhari	1.37	32.23	1.31	0.46	0.74
12	Bamsyun	1.26	45.5	1.36	0.51	0.5
13	Betalghat	1.19	51.42	1.85	0.34	0.57
14	Kwarab	1.12	30.67	1.09	0.43	0.83
15	Chopara	1.15	30.08	1.07	0.35	0.54
16	Mukteshwar	1.22	58.48	1.45	0.52	0.77
17	Suyalbari	1.49	55.34	1.15	0.3	0.67
18	Kakrighat	1.22	29.72	1.29	0.4	0.72
19	Nathuwakhan	1.24	31.58	1.25	0.45	0.76
20	Majhera	1.04	48.84	1.2	0.31	0.76
21	Garampani	1.06	22.73	1.06	0.36	0.71
22	Mailani	1.1	33.21	1.19	0.23	0.65
23	Ramnagar	1	32.39	1.08	0.29	0.6
24	Ramgarh	1.25	45.86	1.35	0.55	0.57
25	Bhowali	1.17	64.2	1.18	0.48	0.65
26	Kotabagh	1.16	35.22	1.17	0.36	0.5
27	Powalgarh	1.26	40.28	1.17	0.21	0.57
28	Padampur	1.01	25.52	1.14	0.24	0.54
Key	Active	1.0–1.2	22–39	1.0–1.2	0.45–0.56	≤0.5
	Moderately active	1.2–1.4	39–56	1.2–1.45	0.3–0.45	0.51–0.70
	Quiescent	1.4–1.55	56–76	1.45–1.85	<0.3	>0.70

Fig. 5   Map showing mountain front sinuosity in sub-basins of Kosi watershed
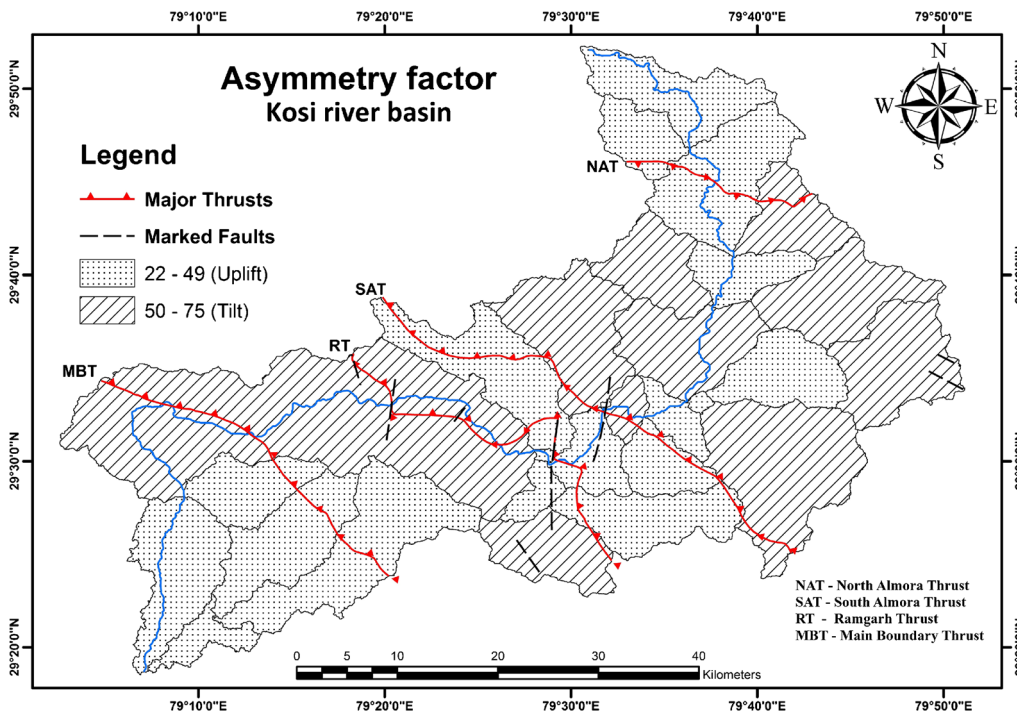
Fig. 6 Map showing uplift of sub-basins more prominently along thrusts and faults in Kosi watershed

length) of the river valley. Channel sinuosity is a key parameter in understanding the role of active tectonics. Practically, no river follows a straight course unless guided by some kind of deformation or relative tectonic activity. Along active faults where erosion rates are high due to the pulverized rock

material, river tends to erode its valley linearly forming strath terraces. Channel sinuosity values tend to be low in areas experiencing relatively high tectonic influence. Based on channel sinuosity index, Mueller 1968) and Morisawa (1985) proposed a classification of channel pattern as straight (< 1.05),
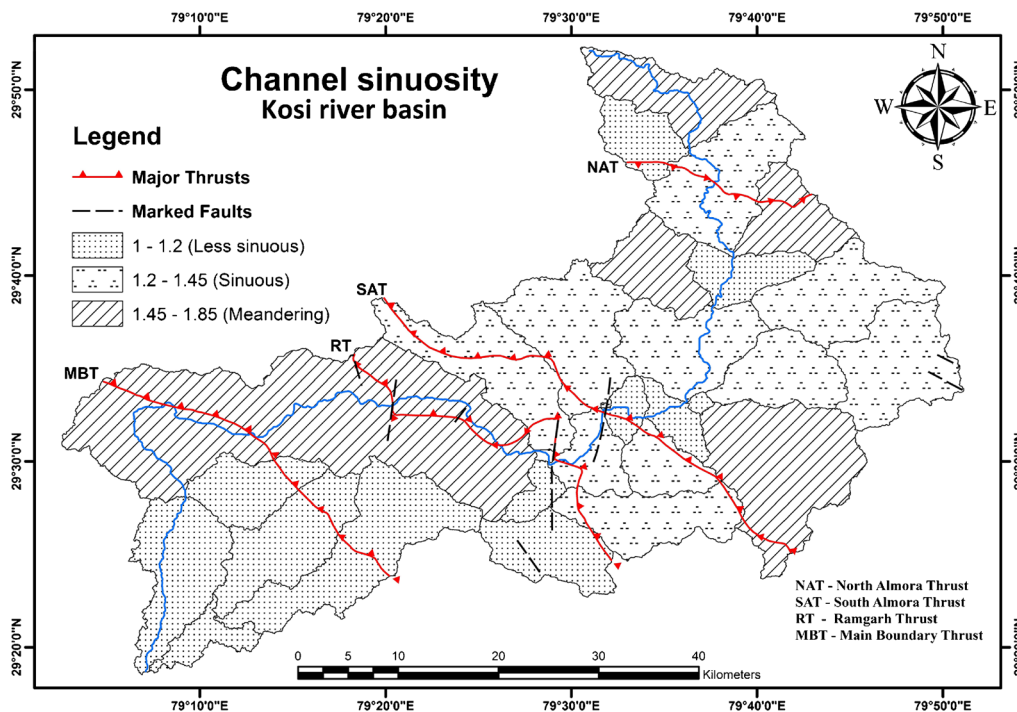

Fig. 7 Map showing channel sinuosity index calculated for sub-basins in Kosi watershed. Several tributaries and the main channel follow straight course along faults and thrusts
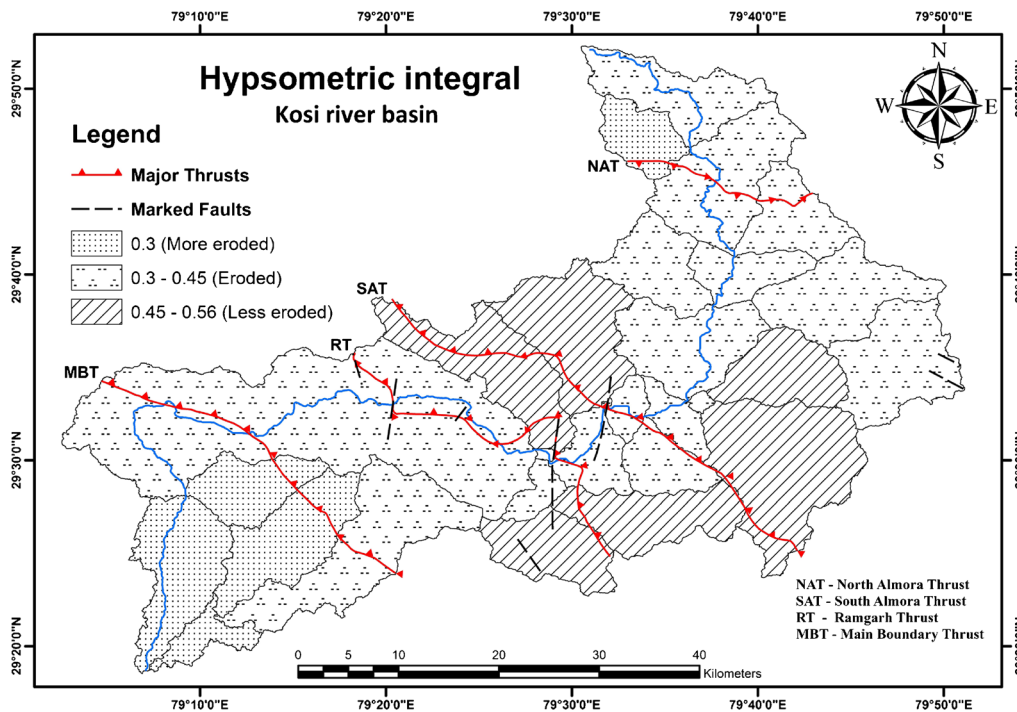
Fig. 8 Map showing comparative HI values range in various sub-basins of Kosi watershed

sinuous (> 1.05), braided (> 1.3), meandering (> 1.5), and anastomosing (> 2.0).

Hypsometric integral

Strahler (1952) proposed a dimensionless parameter hypsometric integral as a tool for measuring landscape evolution. Hypsometric analysis (or area-altitude analysis) is the study of the distribution of horizontal cross-sectional area of a landmass with respect to elevation. Hypsometric analysis has been used to interpret the relative amount of deformation or degradation due to hydrological and erosional processes that have taken place in a watershed during an appreciable part of geological time period. Hypsometric integral proves beneficial in calculating and comparing various sub-basins in a watershed having different area-elevation values irrespective of scale.

Hypsometric integral and its relationship to degree of dissection allow it to be used as an indicator of a landscape's stage in cycle of erosion. High HI values indicate that most of the topography is high relative to the mean representing a youthful topographic stage. Low HI values represent more evenly dissected drainage basins, indicating a mature stage of development (Keller and Pinter 1996; Pike and Wilson 1971; Ali et al. 2015).

Basin elongation ratio

Basin elongation ratio is a significant parameter for analysis of basin shape and is defined as the ratio of a circle with the same area as that of the basin to the maximum basin length. Basin elongation ratio suggests more elongated to moderately elongated sub-basins that are less flood prone than the oval sub-basins which are highly prone to flash floods and landslides during cloud burst events (Kothyari 2014; Farooq et al. 2015).

Results and discussions

The statistical summary of the obtained values is presented in Table 2. On the basis of the morphotectonic parameters calculated and interpreted, it may concluded that the Kosi River basin lies in the active tectonic regime, but several sub-basins within watershed along faults and thrusts are relatively more active than others.

Mountain front sinuosity-calculated basin wise indicates that the basins along thrusts and faults are tectonically active. Straight mountain fronts with most values ranging between 1.0 and 1.5 adhere to this conclusion. In the Kosi watershed, several sub-basins such as Someshwar (1.09), Karkai (1.07), Takula (1.07), Majhera (1.04), Garampani (1.06), and Betalghat (1.19) that lie along thrusts and faults are found to be active in the present study. Comparative analysis of the mountain front sinuosity values calculated in the Kosi River basin is shown in (Fig. 5). The transect along the Someshwar-Gananath near the NAT is tectonically very active. Likewise, the areas Bamsyun-Bhujan-Khairna located near to RT are also very active. The southernmost tectonic line MBT passing from Mohan-Kotabagh also depicts low mountain front sinuosity values inferring to relatively more tectonically active.
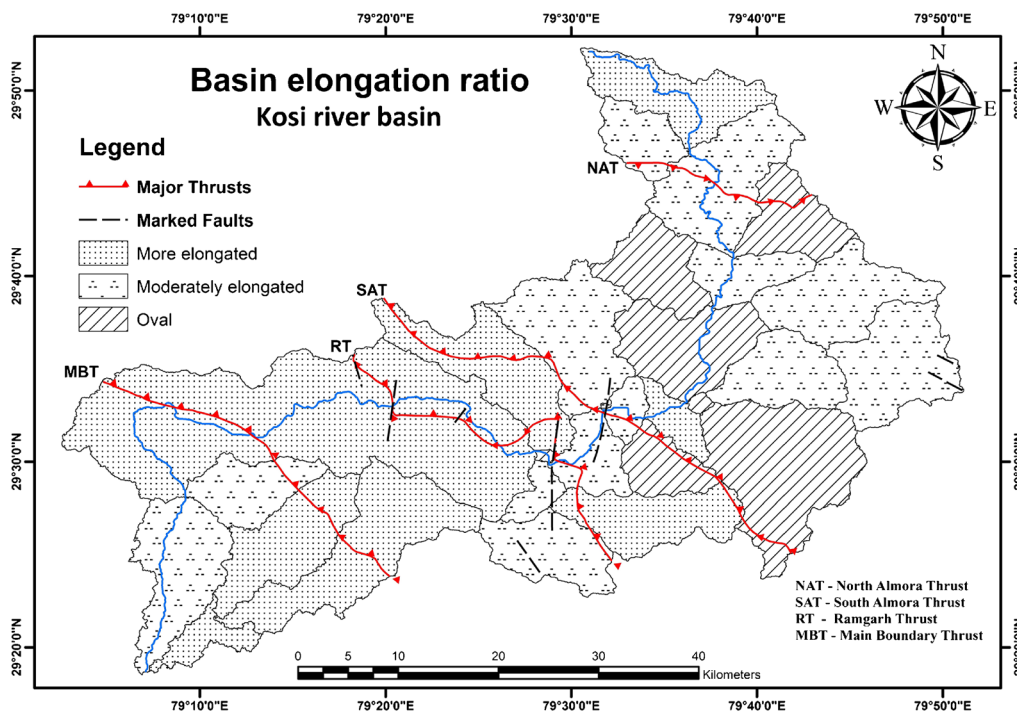
Fig. 9 Map showing elongated, moderately elongated, and almost oval sub-basins in Kosi watershed

Asymmetry factor proves helpful in ascertaining relative tectonic upliftment for larger areas. The upliftment is indicated in several sub-basins while others show tilting in response to the tectonic stress along South Almora Thrust (SAT), Ramgarh Thrust (RT), and Main Boundary Thrust (MBT). Asymmetry factor analysis suggests uplift in eastern and southern parts of the basin and southwest tilting along the North Almora Thrust (NAT), South Almora Thrust (SAT), Ramgarh Thrust (RT), Ratighat–Garampani Fault (RGF), and Jaurasi Fault (JF) (Fig.6).

Channel sinuosity is an indicator of the youthfulness of a river. The channel pattern and course of the Kosi River manifests a strong tectonic control. Based on the sinuosity, the values of sub-basin 23 of Kosi River show mature stage of river channel i.e., meandering pattern probably due to wide deformation zone of MBT and RT. The channel pattern and course of the Kosi River manifests strong tectonic control (Fig. 7).

Hypsometric integral values obtained sub-basin wise lie mostly in range 0.30 to 0.45 indicating the higher erosional rates, and hence, removal of sedimentary cover may cause isostatic uplifting in the Kosi River basin. Along the NAT, there is moderate to high erosion while the SAT in general shows less erosion. The Ramgarh thrust shows largely more erosion. It is along MBT; the Kosi River shows deflections and the transect shows moderate to high erosion (Fig. 8).

Basin elongation ratio finally calculated suggests more elongated to moderately elongated sub-basins that are less flood prone than the oval sub-basins which are highly prone to flash floods and landslides during cloud burst events. In the

Kosi River catchment sub-basin 19 (Bamsyun), 21 (Garampani) were found to be elongated due to local faults, and 23 (Betalghat) is exceptionally longer and covers an area approximately 421 km^2 as it lies in between Ramgarh and Main Boundary thrusts (MBT). The ratio range between 0.6 and 1.0 depicts a wide variety of climatic and geologic types (Schumn 1956). Elongation ratio index has been used for classification of varying slopes of watershed into circular (0.9–0.10), oval (0.8–0.9), less elongated (0.7–0.8), elongated (0.5–0.7), and more elongated (< 0.5). Elongated sub-basins in the Kosi watershed are less prone to flash floods due to ease in downstream discharge while oval to moderately elongated basins are quite prone to flooding. From the map shown in Fig. 9, it can be deciphered that sub-basins to the NE of SAT are moderately elongated to oval while in between RT and MBT; due to thrusting and shearing of the rocks, the basins are elongated having broad valleys in Simalkhan, Rataura, and Betalghat area along the Kosi River.

Five levels of terraces T_1-T_5 are present in the right bank of the present river channel in association to steep slopes on other bank in Kakrighat area (Fig. 10a). The Nathuakhan formation of the Ramgarh Group is uplifted, and the change in river course is well observed near the Suyalbari area where a paleochannel present, confirms to the shifting of river due to relative tectonic activity (Fig. 10b). Four levels of terraces T_1-T_4 adjacent to steep gradient on other bank of river channel are present in the Naugaon area, where T_1 lies over the Ramgarh Group of rocks being strath terrace that manifests the active incision of the river stream in bed rocks (Fig. 10c). Cross-bedded multi-storeyed fining upward deposits present in the

Fig. 10 **a** Five levels of terraces in association to steep slopes in the Kakrighat area. **b** Uplifted paleochannel of the Kosi River near Kakrighat. **c** Four levels of terrace development near Naugaon village with active incision of river stream in bedrocks. **d** Tilting in Quatrernary deposits along Khairna-Almora roadcut. **e** Broad river valley near Betalghat with five levels of terraces and steep slope on the other side in the Ramgarh thrust zone. **f** Huge fan-shaped landslide deposit with break in gradual slope in Simalkhan village

Quaternary profiles suggests the fluvial depositional environment in the past and tilting of the deposits to the NW adheres to the relative upliftment in S-SE direction. The presence of broad valley in the Betalghat area, having five levels of unpaired terraces and the presence of several landslides in a series present on the opposite side facing terraces, may be due to the neotectonic activity along the Ramgarh thrust passing from the area (Fig. 10e). The huge fan with a prominent break in gradient, along with several smaller slope failures and triangular facets in the Simalkhan village, confirms to the active tectonic influence (Fig. 10f). The geomorphological indices calculated and the evidences obtained undeniably indicate the neotectonic ascendancy in the area.

References

Ali Faghih, Nourbakhsh A, Kusky TM (2015) GIS-based analysis of relative tectonic activity along the Kazerun Fault zone, Zagros Mountains, Iran: insights from data mining of Geomorphic Data. J Earth Sci 26(5):712–723

Bull WB, Mc Fadden LD (1977) Tectonic geomorphology north and south of the Garlock fault. California, J Geomorphology 1:15–32

Cox RT (1994) Analysis of drainage-basin symmetry as a rapid technique to identify areas of possible Quaternary tilt-block tectonics: an example from the Mississippi Embayment. Geol Soc Am Bulletin 106: 571–581

Farooq S, Sharma I, Khan MN (2015) Geomorphic evidence of active tectonics in eastern Kumaon Himalaya as deciphered from the morphometry of Ramganga River basin. Int J Advancement Earth Environ Sci 3(1):30–39

Gansser A (1964) Geology of the Himalaya. Wiley-Interscience, New York, p 289

Heim A, Gansser A (1939) Central Himalaya. Mem Soc Nat 73:1–245

Jhonson, M. R. W. (1986). The structural evolution of the Kumaun Lesser Himalaya. In current trends in geology. IX Himalayan thrust and associated rocks (Eds. P. S. Saklani). 27-39p

Keller EA, Pinter N (1996) Active tectonics: earthquakes, uplift and landforms. Prentice Hall, New Jersey

Kothyari GC (2014), Morphometric analysis of tectonically active Pindar and Saryu River basins: Central Kumaun Himalaya, Zeitschrift für Geomorphologie, (published online)

Kothyari GC, Pant PD (2008) Evidence of active deformation in the northwestern part of Almora in Kumaun Lesser Himalaya: a geomorphic perspective. Jour Geol Soc Ind 72:353–364

Malik JN, Shah AA, Naik SP, Sahoo S, Okumura K, Parta NR (2014) Active fault study along foothill zone of Kumaun Sub-Himalaya:

influence on landscape shaping and drainage evolution. Curr Sci 106(2):229–236

Morisawa M (1985). River - Forms and Process. Longman, London

Mueller JE (1968) An introduction to the hydraulic and topographic sinuosity indexes. Annals Assoc Am Geographers 58(2):371–385

Pant CC, Paul A (2007) Recent trends in seismicity in Uttaranchal. J Geol Soc, India 70(4):619–626

Pathak V, Pant CC, Darmwal GS (2013) Geomorphological and seismological investigations in a part of western Kumaun Himalaya, Uttarakhand, India. Geomorphology 193:81–90

Pike RJ, Wilson SE (1971) Elevation-relief ratio, hypsometric integral and geomorphic area-altitude analysis. Geol Soc Am Bull 82(4): 1079–1084

Powar KB (1980) Stratigraphy of Lesser Himalayan sediments of Nainital-Almora area, Kumaun Himalaya. In: Valdiya KS, Bhatia SB (eds) Stratigraphy and correlations of Lesser Himalayan formations, Hindustan Pub. Corp, Delhi, pp 49–58

Saklani, P.S. and Bahuguna, V.K. (1983). Main Central Thrust zone and associated imbricated structures in Chhatera area, Garhwal Himalaya. In: Saklani, P.S. (Ed.), Himalayan Shears, p1–9

Schumm SA, Dumont JF, Holbrook JM (2002) Active tectonics and alluvial rivers. Cambridge University Press, United Kingdom

Schumm SA (1956) Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey. Geol Soc Am Bulletin 67(5):597–646

Strahler AN (1952) Hypsometric (area-altitude) analysis of erosional topography. Bull Geol Soc Am 63:1117–1142

Tarboton DG (1997) A new method for the determination of flow directions and contributing areas in grid digital elevation models. Water Resour Res 33(2):309–319

Tarboton DG (1998) Terrain analysis using digital elevation models

Valdiya KS (1980) Geology of the Kumaun Lesser Himalaya: Dehra Dun. Wadia Institute of Himalayan Geology, India

Valdiya KS (1998). Dynamic Himalaya, University Press Hyderabad

Valdiya KS (2001a) Reactivation of terrain-defining boundary thrusts in central sector of the Himalaya: implication. Curr Sci 81(11):1418–1430

Valdiya KS (2001b) Tectonic resurgence of the Mysore plateau and surrounding regions in cratonic Southern India. Curr Sci 81(8):1068–1089

Valdiya KS (2010) The making of India: geodynamic evolution. Macmillan Publishers, India