

Original Research

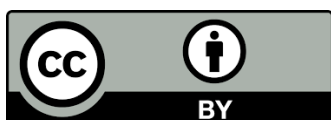
Evaluation of Active Tectonic Features of Nandakini River Basin, Lesser Himalaya, India by Using Morphometric Indices: A GIS ApproachPawan Kumar Gautam ^{†,*}, Anoop Kumar Singh [†]Department of Geology, University of Lucknow, Lucknow – 226007, U.P., India; E-Mails: 89pawangautam@gmail.com; anoop1818@gmail.com[†] These authors contributed equally to this work.^{*} **Correspondence:** Pawan Kumar Gautam; E-Mail: 89pawangautam@gmail.com**Academic Editor:** Leonel J. R. Nunes**Special Issue:** [Environmental Risk Assessment and Risk Management](#)*Adv Environ Eng Res*

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Received: July 11, 2022**Accepted:** January 03, 2023**Published:** January 30, 2023**Abstract**

Tectonic geomorphology has been evidenced as an essential tool to define and measure recent tectonic deformation. The Nandakini River originates from Nanda Ghunti glacier at 6886 m in Lesser Himalaya. It covers about ~551 km² basin area, with a fourth-order stream. It confluences with the Alaknanda River near Nand Prayag (at elevation 852 m), Chamoli district of Uttarakhand. The drainage pattern is predominantly dendritic in the study area. The morphotectonic indices are measured to know the tectonic activity of the drainage basin. Morphometric indices reflecting hypsometric Integral is 1.07, indicating a deeper incision and a slight erosion. The basin elongation ratio is 0.17, suggesting that the area is tectonically active. The drainage basin asymmetric factor (44) suggest tilting. In addition, the drainage basin shape (3.27) indicates the basin is tectonically strong, the transverse topographic symmetry factor (0.31) indicates the asymmetric nature, the valley floor width to valley height ratio is 0.54 shows the deep, narrow valleys, and Active V-shaped incision. Stream longitudinal profile showing the area tectonically influenced. The Sinuosity Index of 1.12 suggests that low sinuous nature. The Stream length-gradient Index is 10.64, indicating high tectonic activity in



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valleys and basin areas. The transverse profile helps to understand the tilting of the basin. The Surface profile shows irregularity, and the linear trend of the profile shows the tilting of the basin. River carrying capacity with large boulder-size sediment indicates youth stage and tectonically active environment. The morphotectonic indices suggest that the drainage basin was affected by the regional structures and the present tectonics.

Keywords

Lesser Himalaya; Nandakini River basin; morphotectonic indices; GIS

1. Introduction

The major rivers of Northern India originated from the great Himalaya [1]. During the last decades, geoscientists have paid much attention to understanding the tectonic design of the Kumaun-lesser Himalaya in particular and the Himalaya in general [2-13]. The Himalaya are amongst the most excellent and identifiable structures of tectonic forces extending 2,900 km along the boundary between India and Tibet. The structural (tectonic) Himalayas can be divided from north to south, the Eastern Himalayas, the Central Himalayas, and the Western Himalayas as follows [14].

The Himalayan region is tectonically and seismically active; therefore, investigations of neotectonic evidence mainly affect geomorphology [1, 15-17]. The continuous north-western motion of the Indian Plate at a velocity of about 5 cm/year indicates about 2500 km of post-collision shortening has occurred due to Indian and Eurasian plate collision during 50-55 Million years [18-22]. The Himalayan region's rugged topography is reshaped by neotectonic activity, such as thrusts/faults, resulting in geomorphic changes along the banks of all major rivers [11, 23]. The present study area falls in the central part of the Himalayan belt in the Garhwal Himalaya. It is important for studying the distinctive features of the Himalayan fold-and-thrust belt [24]. The Garhwal Lesser Himalaya is cut by various thrusts/faults, e.g., MBT, MCT, HFT, Munsiri Thrust (MT), Ramgarh Thrust (RT), Tons Thrust (TT)/Berinag Thrust (BT) and STDS. This middle latitudinal domain, tectonically bounded at the top by the MCT and base by the MBT, comprises mainly Precambrian clastic sediments and meta-sedimentary rocks [25, 26]. The MCT zone has the largest width of about 80 km in the Kumaun and Garhwal regions [27]. The Garhwal Lesser Himalayan area is situated on the west side of the Himalayas and surrounded by Main Central Thrust (MCT) in the north, and Main Boundary Thrust (MBT) in South and South West, Srinagar Thrust in the east, west, and center of the network. Most of the higher magnitude earthquakes (Magnitude Scale-5.5) in the Himalaya occurred around the (MCT) due to the thrust-flawed separation zone and the northern Indian plate. Different aspects of seismo-tectonic and seismicity have been studied using local seismological and strong resistance networks [9, 28-32]. Gharwal Himalayas is situated near the central part of the Himalayan origins. Therefore, the region is affected by the Himalayan tectonic as compared to the areas close to EW in the direction. Many geomorphological features describe tectonically active regions on the earth to know the recent tectonic processes during 100 Ka [33]. There has been evidence of neotectonics and reactivation of faults and thrusts throughout the North West Himalayas [34]. Tecto-geomorphology analyzes landforms created by tectonic processes or the various applications of geomorphic concepts to solve tectonic problems [35]. Topographic-based

geomorphic indices are developed as essential techniques for recognizing areas with rapid deformity of the tectonic [35, 36]. It deals with active Cenozoic deformation's tectonic and geomorphological process interactions [37]. Drainage basins is a dynamic system that may possess records of formation and evolution since its most tectonic-geomorphic processes to occur within its limits [38]. Thus, landscape expansion results from the evolution of drainage basins [39]. Geomorphic features of drainage basins and stream networks can be represented adequately using Digital Elevation Models (DEM) and Geographical Information Systems (GIS) [12, 40-42]. These tools allow the rapid, accurate, and scientifically provable of fluvial channels and landscape characterization [43-51]. The Nandakini basin lies between MBT and MCT at the northern Baijnath klippe, which is regarded as one of the active thrusts in the Indian Himalaya [52-58]. The geomorphic indices are a dominant tool for appraising the effect of active tectonics [32]. This study aims to evaluate the tectonic zones using morphometric indices. The objective will be to help prepare and manage probable disasters like landslides and select suitable sites for settlements and transportation.

2. Study Area

Nandakini river originates from Nanda Ghunti glacier at 6886 m altitude in the Lesser Himalaya. It joins in Alaknanda River at 852 m altitude near Nand Prayag, Chamoli district of Uttarakhand. Geographically it lies between 30°10' to 30°22' N latitude and 79°18' to 79°47' E longitude. The geographical area of the Nandakini basin is ~551 km² (Figure 1). The study area is characterized by several geomorphic features like long ridges, rugged topography, steep slopes, stepped river terraces, and dense forests.

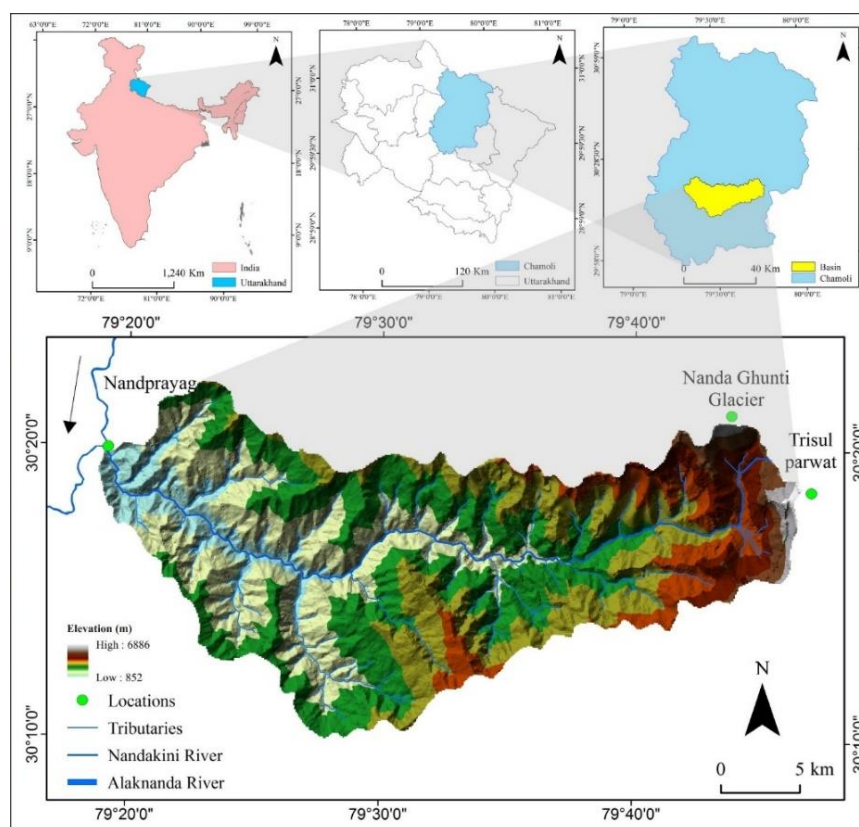


Figure 1 Location map of the Study area.

2.1 Climate

The study area comes under temperate climates. The climate here is mostly cold and sub-humid, with frigid winters from December to February and mild hot from March to May. Rainfall in the region is highly variable and depends on the altitude. Monsoon starts in June with westerly winds and receives about 1100 to 1305 mm rainfall [59]. The area receives maximum rainfall between June to September and post-monsoons during October and November. Rain swiftly decreases at the end of September and less in November. Very occasionally, some area experience snowfall in January.

2.2 Geological Settings

The basin is surrounded by hills and deep valleys that effectively disrupt and are associated with a complex geological setting. Most of the basin, the Baijnath klippe, in the west, the klippen represent the eroded remnants of the Ramgarh and Munsiri thrust sheets, which are correlated with the thrust units underlying the Vaikrita thrust. As per structure, the Lesser Himalaya Zone reflects a duplex thrust system consisting of horses of Berinag, Chakrata–Rautgara, and Deoban Formations overlain by the crystalline Ramgarh along the Ramgarh Thrust as roof thrust and the MHT as the floor thrust [24, 60]. The MCT, representing a shear zone, brings the HHC to overlain by Lesser Himalaya. [13] states, the HHC, and the Vaikrita Group underlain by the Munsiri and Ramgarh nappes (Table 1, Figure 2).

Table 1 Geology of Study area [13].

Vaikrita group
-----Vaikrita thrust (MCT II) -----
MCT Zone
-----Munsiri Thrust (MCT I) -----
Berinag thrust hanging wall
-----Ramgarh thrust-----
Berinag thrust footwall
Baijnath klippe
Berinag thrust hanging wall

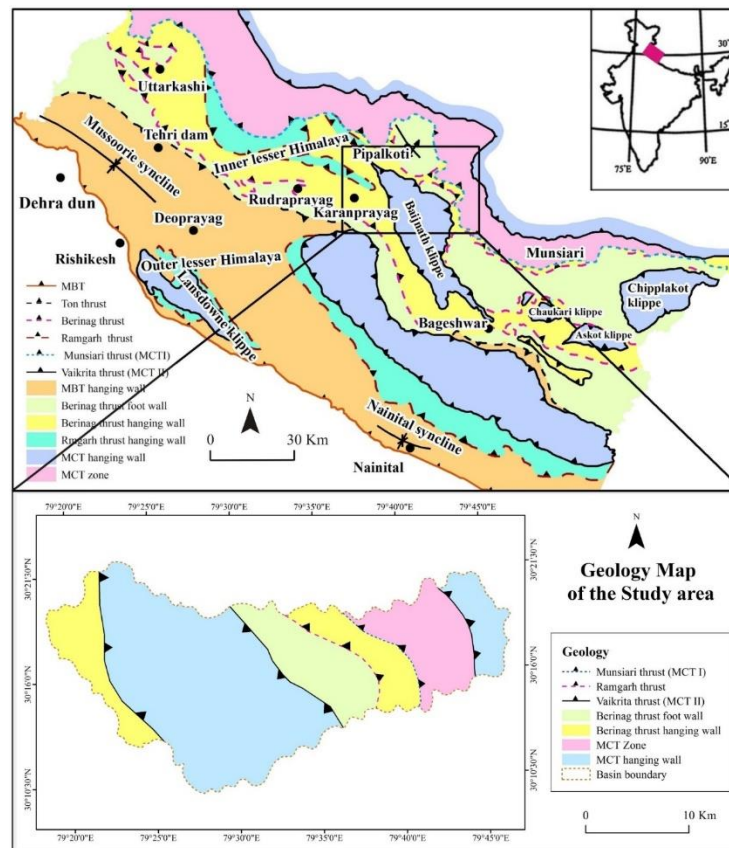


Figure 2 (a) Tectonic map of the Uttarakhand (black rectangle indicates the area of study [61]. (b) Geological map of the Nandakini River Basin [13].

Munsiri thrust along the Alaknanda River, where a window through the Berinag thrust hanging wall has exposed underlying dolomites and black schists of the Deoban and Mandhali formations [61]. The north of NAT and BT (Berinag Thrust) in the Lesser Himalaya and up to the Higher Himalaya show maximum deformation [62]. The bedrock refers to the Central Crystalline [8] composed primarily of medium-grade to high-grade metamorphic a derivative of pelitic, semi-pelitic, and psammitic sediments, which are interlayer sporadically with the meta basics and, to a lesser range (i.e., in the Dhak and Jharkula regions), calcareous rocks. In the south, the Central Crystalline' is overlain by the Garhwal Group through the MCT [13, 61].

2.3 Seismicity

The micro-seismicity recorded instrumentally by the Wadia Institute of Himalayan Geology network shows the clustering of events along a transitional physiographic region between the High and Lesser Himalaya and along the Main Central Thrust zone (MCT) [63]. The widespread occurrence of small and moderate earthquakes along MCT and subsidiary thrusts between the MBT and MCT [64]. Uttarakhand was struck by two Mild Earthquakes, the 1991 Uttarkashi earthquake, and the 1999 Chamoli earthquake. There is a historical account of the 1803 earthquake causing severe damage and destruction primarily in Garhwal and moderate-to-minor effect in the adjoining areas of Kumaun. The 1991 Uttarkashi earthquake occurred over a low-angle reverse fault southern of the Vaikrita Thrust (MCT–II). Nearly to 700 died, and a considerable effect was inflicted on the property. Monitored through a series of aftershocks and micro-seismicity (1979 to 1980 and 1984

to 1986), Show the focus at Bhatwari, to the north, at 10-km depth. The epicenter, below the MCT-II, is at the same level [65, 66]. Based on aftershocks distribution, the Uttarkashi Fault, a bedrock-mapped fault, was interpreted as the causative fault [67]. The 1999 Chamoli earthquake, with a magnitude (of 6.4), devastated the Chamoli and neighboring villages, inflicting about 500 casualties. The Chamoli earthquake indicates reverse faulting with plane dipping NNE at a low, 15-20° angle. The epicenter lies within the regional micro-seismicity belt located south of the Vaikrita Thrust in the Main Central Thrust (MCT) zone. Displacements may be controlled by tectonically enhanced erosion balanced by displacement within the hanging wall of the Vaikrita Thrust/MCT [68]. The aftershocks recorded by the WIHG network lie below the MCT at 7-17 km depth over the inferred ramp region [66]. The earthquake catalog suggests that Mw 6.3 (Uttarkashi, 1991) and Mw 6.6 (Chamoli, 1999) are the highest magnitude earthquakes in this part during the last three decades [69].

3. Methodology

The study has been completed based on the following data sets:

- a. Survey of India (SOI) Toposheets (53N/7, 53N/8, 53N/11, 53N/12 and 53N/15) of 1:50,000 scale of the years 1964 and 1967.
- b. SRTM Digital Elevation Model (DEM) data (<http://srtm.csi.cgiar.org/srtmdata>), along with GIS software, is used to analyze and extraction of morphotectonics and drainage networks.

The basin area has been manually outlined from (SOI) toposheets, and other morphometric metric calculations and maps have been prepared in Arc Map 10 GIS software. The methodology adopted for computing and numerical formulas of Morphometric indices including Drainage network, Bifurcation ratio (R_b), Circularity ratio (R_c), Hypsometric Integral (H_i), Basin elongation ratio (R_e); Drainage basin symmetry such as Asymmetric factor (A_f), Drainage basin shape (B_s), Transverse topographic symmetry index (TTSF), Valley floor width to valley height index (V_f), Sinuosity Index (S_i); Stream length-gradient Index ($SLGI$) included $SLG_{segment}$, SLI_{total} and $SLG_{anomalous\ points}$; Tectono-geomorphologic: Stream longitudinal profile (L_s) and Transverse profile (T_p) are used to interpret the tectonic relationship of the basin (Figure 3). The drainage network was analyzed following the [70] and stream orders following the [71] method.

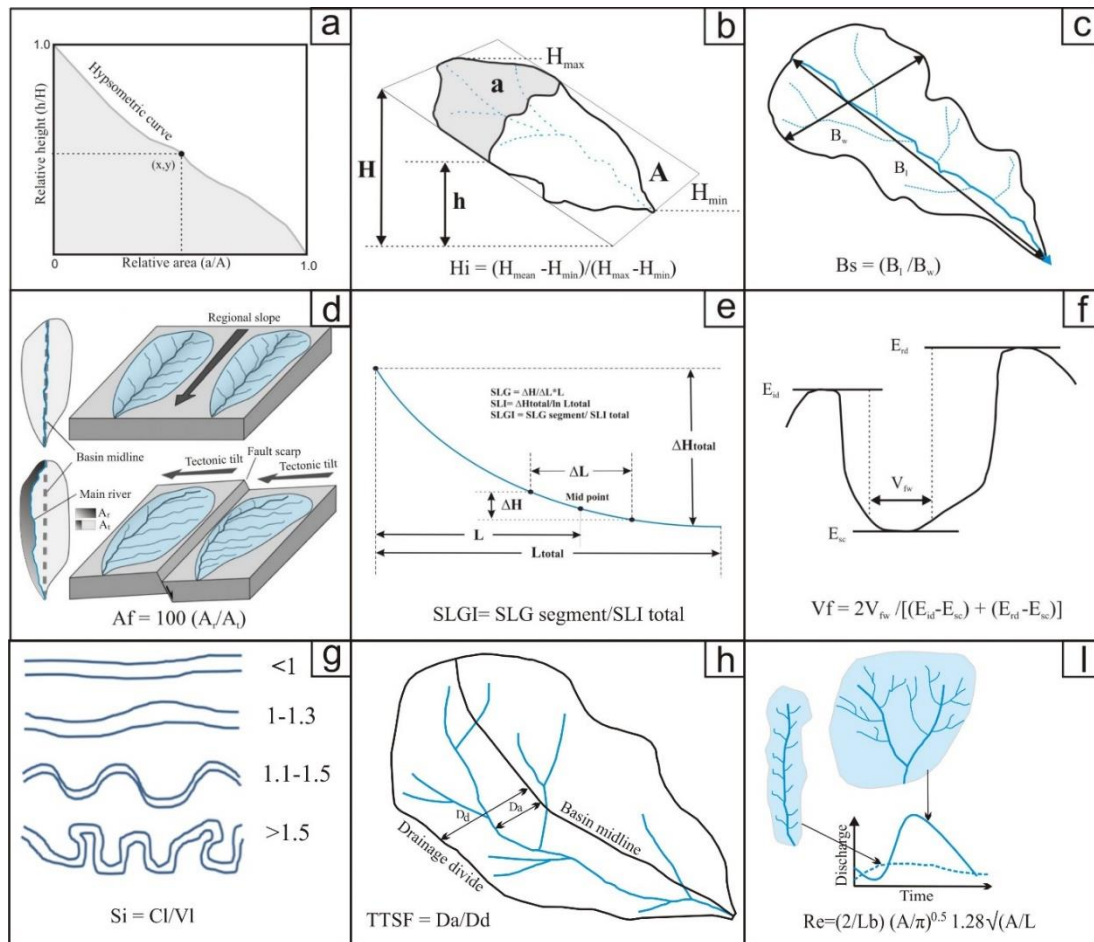


Figure 3 Geomorphic indices applied in this study modified after [34, 36, 72-76] are (a) Hypsometric curve. (b) HI: hypsometric integral. (c) BS: drainage basin shape. (d) AF: asymmetry factor. (e) SLGI: stream length-gradient. (f) VF: valley floor width-to-height ratio. (g) Sinuosity Index (S_i). (h) Transverse topographic symmetry factor (TTSF). (i) Basin elongation Ratio (R_e).

3.1 Bifurcation Ratio (B_i)

Normally bifurcation ratio ranges from 3.0 to 5.0 for basins in which the geological features (e.g., active faults) do not alter the drainage pattern where climate, subsurface rock type, and topography are more or less homogeneous [71]. The lower values of ' R_b ' reflect less structural disruptions and less disturbed drainage, whereas the higher values imply high structural complexity and low permeability of the terrain. It is calculated by the formula

$$R_b = \frac{N_u}{N_u + 1} \quad (1)$$

N_u is the total number of stream order ' u ', and ' $N_u + 1$ ' are the Number of segments of the higher-order.

3.2 Circularity Ratio (R_c)

It is calculated by the formula

$$R_c = \frac{4\pi A}{P^2} \quad (2)$$

where A and P is an area and perimeter of the basin respectively.

3.3 Hypsometric Integral (H_i)

High H_i values indicate that most topography is high relative to the mean representing a youthful topographic stage. Low H_i values represent a mature stage of development [77] (Figure 3a, 3b). A hypsometric basin Integral shows the correlation between the basin area and the altitudes of the basin. H_i is calculated by the following formula

$$H_i = \frac{(H_{\text{mean}} - H_{\text{min}})}{(H_{\text{max}} - H_{\text{min}})} \quad (3)$$

where H_{mean} = mean elevation value, $H_{\text{max.}}$ = maximum elevation value and $H_{\text{min.}}$ = minimum elevation.

3.4 Basin Elongation Ratio (R_e)

It is used for determining the shapes of the drainage basin. Tectonic effects influence the elongated shape of the basin, and it reflects on a drainage basin [36].

$$R_e = \left(\frac{2}{L_b}\right) \left(\frac{A}{\pi}\right)^{0.5} \quad (4)$$

where R_e = Elongation Ratio, A = Area of the Basin (km^2), L_b = Basin length.

3.5 Drainage Basin Shape (B_s)

The B_s index describing a drainage basin elongation ratio is defined as

$$B_s = \frac{B_l}{B_w} \quad (5)$$

where B_s = drainage basin shape ratio, B_l = length of the basin, and B_w = width of the basin.

3.6 Asymmetry Factor (A_f)

The asymmetry factor (A_f) proposed by [78] is the ratio of area to the right of the basin A_r (facing downstream) to the total area of the basin. At normalized by multiplying the ratio with 100. The asymmetry factor is sensitive to tilting perpendicular to the trunk of the stream [78]. The asymmetry factor is useful in determining relative tectonic upliftment for basin areas.

The asymmetric factor (A_f) is defined as

$$A_f = 100 \left(\frac{A_r}{A_t}\right) \quad (6)$$

The 'A_f' value (>50) indicates a tilting to the left bank, and the value (<50) shows a significant tilting of the drainage basin to the right side of the channel either because of active tectonics or lithological influence [72].

3.7 Stream Length-Gradient (SLGI)

It is one of the indexes suggested by the following formula for tectonic force assessment.

$$SLG_{\text{segment}} = \left(\frac{\Delta H}{\Delta L} \times L \right) \quad (7)$$

where 'SLG' = Stream length gradient, ' $\Delta H/\Delta L$ ' is the Stream slope or gradient of the basin, ' ΔH ' = height difference between two contours in the drainage basin, ' ΔL ' = length of the stream in between these two contours and 'L' = total length of the channel from the midpoint of the segment to the head of the channel.

$$SLI_{\text{total}} = \frac{\Delta H_{\text{total}}}{L_{\text{total}}} \quad (8)$$

where ' ΔH ' is a difference in heights between the headwaters and the mouth and 'L' is a total length of the channel from the midpoint of the segment to the head of the channel.

$$SLGI_{\text{anomalous points}} = \frac{SLG_{\text{segment}}}{SLI_{\text{total}}} \quad (9)$$

where 'L' is a total length of the channel from the midpoint of the Selected extend to the channel's highest point.

3.8 Valley Floor Width-To-Height Ratio (V_f)

In estimating the basin floor width and valley height, we analyzed 'V_f' in different sections. Those basins, which have been the proximity to the structures but have U-shaped valleys, have been influenced by the erosion of the main river channel. The low values are confined to regions with less erosion, deep, narrow valleys, and V-shaped, Active Incision. The Valley floor width to valley height ratio is defined as

$$V_f = \frac{2V_{fw}}{((E_{ld} - E_{sc}) + (E_{rd} - E_{sc}))} \quad (10)$$

3.9 Sinuosity Index (S_i)

The sinuosity index has been defined, and all sections for investigating the channel Sinuosity parameters of the river were measured using the procedure [74]. Based on the channel sinuosity index [74, 79] proposed a classification of channel pattern as straight (<1), Low sinuous (1-1.3), High sinuous (1.3-1.5), and Meandering (>1.5) (Table 2). The overall length of the channel and the main channel length are computed using the given equation for each reach and are defined as

$$S_i = \frac{C_l}{V_l} \quad (11)$$

Table 2 Summary of Morphotectonic parameters in the study area.

Parameters	Method/Formula	References	Value & inference	Result & Interpretation
Morphometric indices				
Circulatory ratio	$R_c = 4\pi A/P^2$, where A = Basin area, (km/km) ² , P = Perimeter of the basin	[77]	$R_c = 0.40-0.50$, indicates strongly elongated and highly permeable homogeneous geological materials	0.38, Sub elongated
Hypsometric integral	$H_i = (E_{mean} - E_{min}) / (E_{max} - E_{min})$, where E_{mean} = Mean elevation, E_{min} = Min elevation, E_{max} = max elevation	[80]	$H_i > 0.5$, Deep incision and slight erosion, $0.4 < H_i < 0.5$, Equilibrium and an intermediate stage of incision and erosion, low relief and severe erosion	1.07, Deep incision and slight erosion,
Basin elongation Ratio	$R_e = (2/Lb) (A/\pi)^{0.5}$ $1.28\sqrt{A/L}$, where A = Basin area, L = Basin Length and π is 'Pi' value, i.e., 3.14,	[36]	$R_e < 0.50$, Tectonically Active $R_e = 0.50-0.75$, Slightly Active $R_e > 0.75$, Inactive Settings	0.17, Tectonically Active
Drainage basin symmetry				
Asymmetric factor	$A_f = 100(A_r/A_t)$, where A_r = Right-hand side area of drainage looking downstream and A_t = Total area of a drainage basin	[72]	AF = 50, Stable setting Environment $50 < AF > 50$, Suggest Tilt	44, Tilt
Drainage basin shape	$B_s = B_l/B_w$, where B_l is the distance from the river mouth to headwater, and B_w is the maximum width of the drainage basin	[36]	>2.3 = Tectonically Strong, $1.5-2.3$ = Tectonically Moderate, <1.5 = Tectonically Weak	3.27, Tectonically Strong

Transverse topographic symmetry factor	$TTSF = D_a/D_d$, where D_a = Distance from the midline of the drainage basin to the midline of active channel and D_d = Distance from basin midline to basin divide [72]	$T = 0$, Symmetric Basin $T > 0$, Asymmetric Basin	0.31, Asymmetric Basin
Valley floor width to valley height ratio	$V_f = 2V_{fw}/((E_{ld}-E_{sc}) + (E_{rd}-E_{sc}))$, where V_{fw} = Width of valley floor, E_{ld} and E_{rd} = Elevation of the left and right valley divides respectively and E_{sc} = Elevation of the valley floor [36]	Low values <1.0 Deep, Narrow Valleys, 'V' shaped, Active Incision High values >1.0 Broad Valleys, 'U' shaped	0.54, Deep, Narrow Valleys, 'V' shaped, Active Incision
Sinuosity Index	$S_i = C_i/V_i$, where C_i = channel length, V_i = Valley length [74]	<1 = straight 1-1.3 = Low sinuous 1.3-1.5 = High sinuous >1.5 = Meandering	1.12, Low sinuous
Stream Length Gradient Index (SLGI)			
SLG segment	$SLG = (\Delta H/\Delta L * L)$, where SL = Stream length gradient, $\Delta H/\Delta L$ is the Stream slope or gradient of the basin, ΔH = height difference between two contours in the drainage basin, ΔL = length of the stream in between these two contours and L = total length of the channel from the midpoint of the segment to the head of the channel. [81]	High values-High tectonic activity, rocks, Low values-Low tectonic activity, less resistant, soft rocks	1285.73, High tectonic activity
SLI total	$SLI = (\Delta H_{total}/\ln L_{total})$, where ΔH is a difference in heights between the headwaters and the mouth and L is a total length of the channel from the midpoint of the segment to the head of the channel. [81]		120.80

SLGI anomalous points	SLGI = (SLG _{segment})/(SLI total), where L is a total length of the channel from the midpoint of the Selected extend to the channel's highest point.	[81]	Values >2-High tectonic activity Values <2-Low tectonic activity	10.64, High tectonic activity
<i>Tectono-geomorphologic</i>				
Longitudinal profile	Relation b/w height and distance	[81]	Smooth = Equilibrium condition no tectonically influenced. Topographical undulation = Disequilibrium condition suggest tectonic disruption of the bed	Topographical undulation, Disequilibrium condition suggest that river tectonically
Transverse profile	Relation b/w height and distance	GIS analysis		Topographical undulation

The Nandakini River is estimated to be 57 km long, and the river segments were demarcated into 30 sections into a series of equal-length reaches. Each have a length of 1.9 km.

3.10 Transverse Topographic Symmetry Factor (TTSF)

The topographical index or transverse symmetry variable was determined as

$$TTSF = \frac{D_a}{D_d} \quad (12)$$

‘D_a’ is the space from the drainage basin's midline to the active belt's midline, and ‘D_d’ is the space from the midline to the basin limit [72].

4. Results and Discussion

4.1 Morphometric Indices

The qualitative morphometric analyses were carried out on the drainage network, the spatial distribution of the drainage basin, and their geometric relationships on topographic profiles by using SRTM DEM, following Strahler's stream ordering system [71]. Evaluation and derivation of morphometric parameters measured and delineated in the Arc-GIS platform [82]. The basic characteristic of stream networks is the stream segment, and the assignment of stream orders is the first stage in the geomorphic analysis [83]. The drainage basin of the Nandakini River (~551 km²) was classified into fourth order by using 117 streams. The majority of streams (91) were found to be of the 1st order, occupying about 77.78% of the whole watershed, whereas, 2nd, 3rd, and 4th order

streams occupy 17.1%, 4.3%, and 0.9%, respectively. The drainage is predominantly dendritic (Table 3, Figure 4).

Table 3 Morphometric parameters as measured in Nandakini Basin. U = Stream Order, N_u = Stream Number, L_u = Stream Length, L_{sm} = Mean Stream Length, R_l = Stream length Ratio, R_b = Bifurcation Ratio.

U	N_u	L_u	% (N_u)	% (L_u)	Log N_u	Log L_u	L_{sm}	R_l	R_b
I	91	140	77.78	52.24	1.96	2.15	1.54	0.46	4.6
II	20	64	17.09	23.88	1.3	1.81	3.2	0.48	4
III	5	31	4.27	11.57	0.7	1.49	6.2	1.06	5
IV	1	33	0.85	12.31	0	1.52	33		
4	117	268	100	100	3.96	6.96	10.98	0.67	

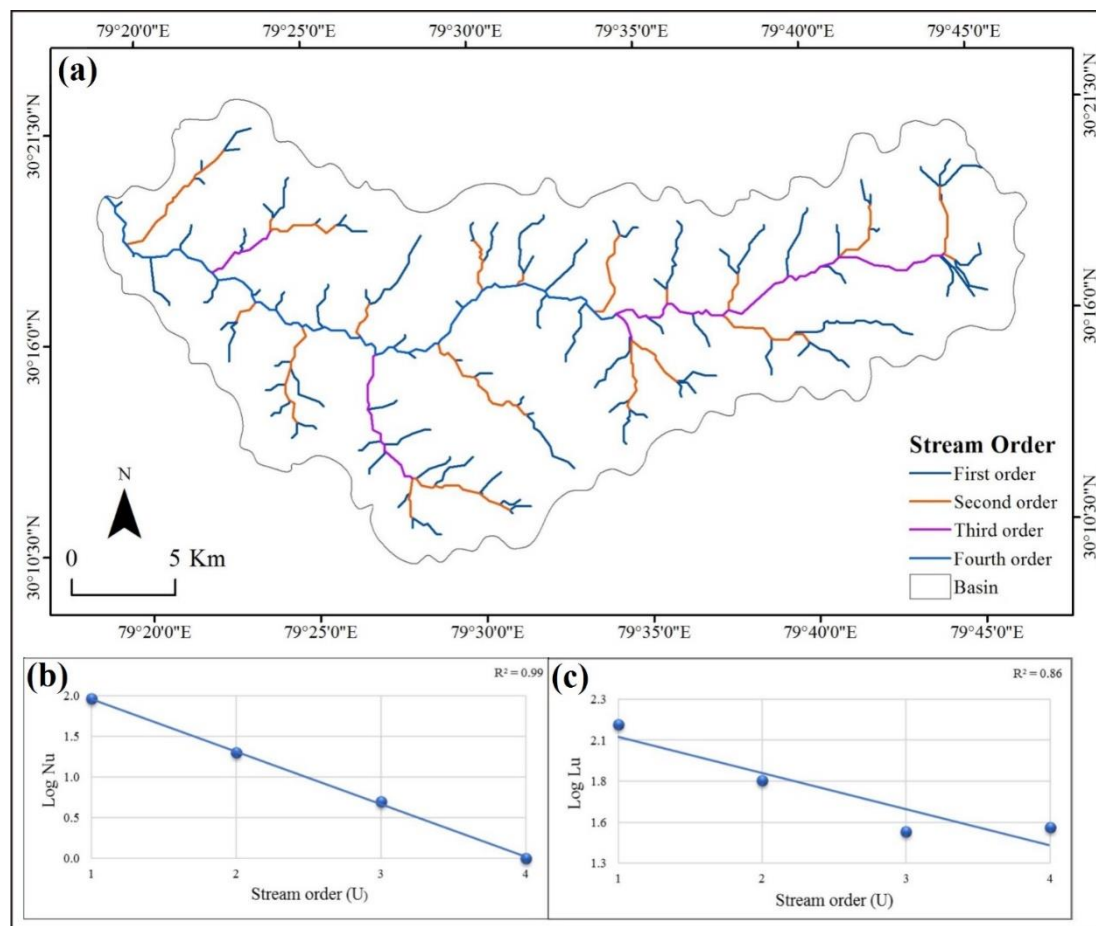


Figure 4 (a) Drainage map of the Basin, (b) Bivariate plots of Regression of logarithm of number of streams versus stream order and (c) Regression of logarithm of stream lengths versus stream order [70].

4.1.1 Bifurcation Ratio (R_b)

In Nandakini Basin, the 1st, 2nd, 3rd, and 4th order are 4.55, 4 and 5 (Table 2, Table 3). Which shows the basin is lithologically and structurally controlled.

4.1.2 Circularity Ratio (R_c)

The circularity ratio is defined as the ratio of the basin area and the circle area with the perimeter as of the basin area [71, 77]. [77] has characterized the basin of the circularity ratios that range from 0.40 to 0.50, which shows sub-elongated and highly porous homogenous geologic materials [84-86]. The basin's circularity ratio value (0.38), which subbed elongated and in mature stage topography, supported a dendritic pattern of the drainage network, high discharge of runoff, and low permeability condition (Table 2).

4.1.3 Hypsometric Integral (H_i)

[87] proposed a dimensionless parameter hypsometric integral as a tool for measuring landscape evolution. Hypsometric analysis (or area-altitude analysis) studies the distribution of horizontal cross-sectional area of a landmass concerning 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 the geological period. Hypsometric integral proves beneficial in calculating and comparing various sub-basins in a watershed having different area elevation values irrespective of scale. It is related to drainage basins' geomorphic and tectonic development in terms of their structures and processes [35, 71, 87]. The hypsometric contour curve 6886, 3484, 2800, 2360, 1937, 852, and the H_i value for this basin is calculated at 1.07. This indicates a deeper incision and a slight erosion (Table 2, Table 4).

Table 4 Hypsometric Integrals [80].

S. No.	Range	Inferences
1	$H_i > 0.5$	Deep incision and slight erosion
2	$0.4 < H_i < 0.5$	Equilibrium and an intermediate stage of incision and erosion
3	$H_i < 0.4$	low relief and severe erosion

Which indicate the Deep incision in the region [35] as (Figure 5).

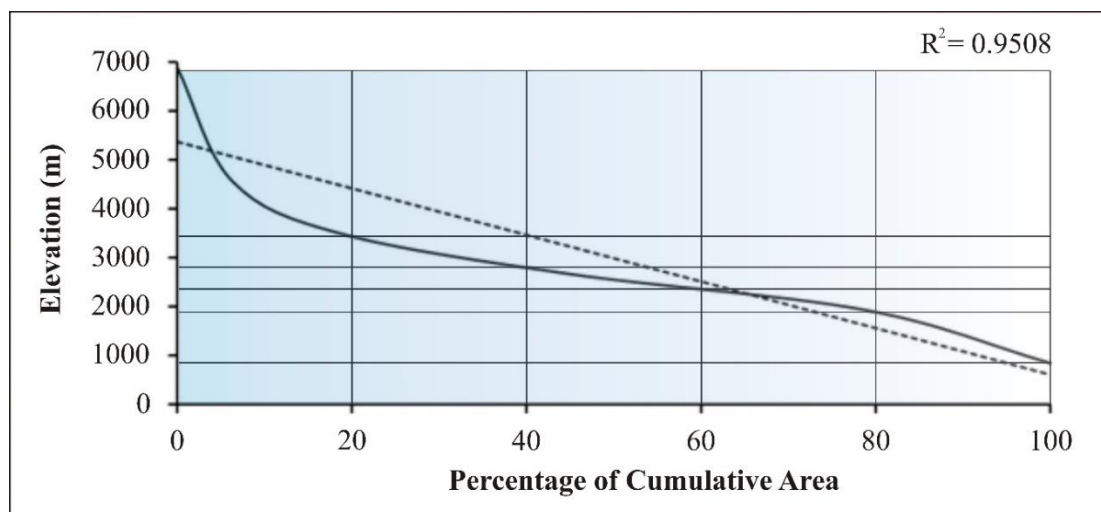


Figure 5 Hypsometric integral of the Basin [35, 56].

4.1.4 Basin Elongation Ratio (R_e)

The ' R_e ' for the Nandakini river basin is 0.17, referring to the tectonic disturbance in the basin area (Table 2).

4.2 Drainage Basin Symmetry

4.2.1 Asymmetry Factor (A_f)

Calculating the asymmetry factor for tectonic frequency determination of discharge of the stream to the major watercourse [72]. This index also defines the directions of neo-tectonic. The asymmetry factor explains the tectonic tendency of the channel discharge to the significant watercourse activity and is responsible for elevating and substituting separate blocks versus broad inclination [78]. The asymmetry factor is the higher level of neo-tectonic action tilts [88] (Table 2), resulting in basins (Figure 6).

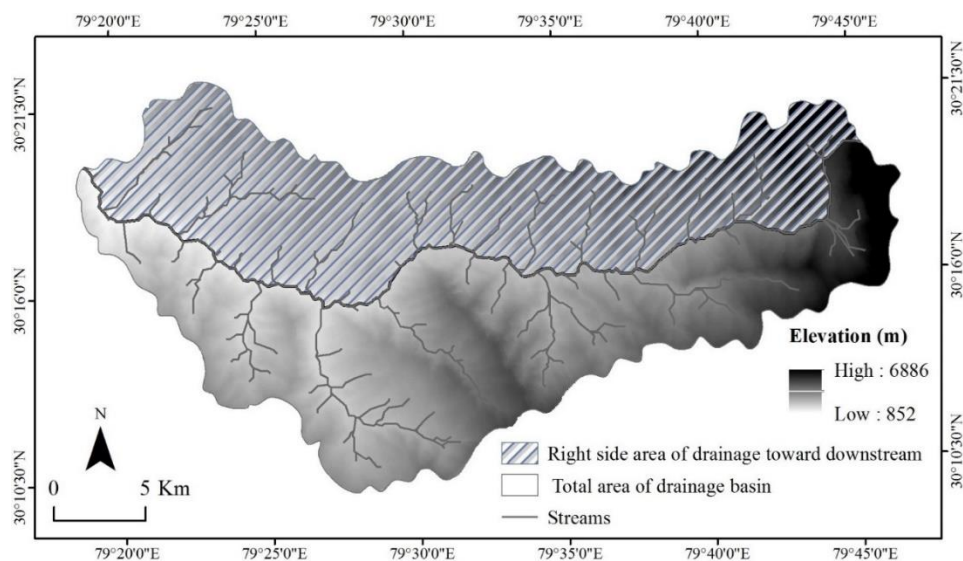


Figure 6 Block diagram of basin drainage asymmetry factor [72].

4.2.2 Drainage Basin Shape (B_s)

Basin shape is an important parameter because it influences and controls the geometry of the stream network [89]. It influences tectonic processes. Extended basins frequently define tectonically active areas and sub-circular forms without structural deformation or deformation level [36]. The Drainage basin shape for the basin is 3.27 (Table 2), which indicates the basin is tectonically active. The shape of a drainage basin is controlled by tectonic processes [90].

4.2.3 Transverse Topographic Symmetry Factor (TTSF)

It refers to Trunk River deviation from the basin mid-line. Its values range from (0-1), with a value similar to '0' indicating symmetric basin or ranges and a value greater than or less than '0' suggesting asymmetric basin or tilting [8, 72, 79]. The values of 'TTSF' for all the drainage basins have been calculated at different segments of the basins (Figure 7a). The Average value of TTSF of the drainage basins is 0.31, indicating asymmetric basins influenced by neotectonics (Table 2, Table 5).

Table 5 Segments selected for computation of Transverse Topographic Symmetry Factor (TTSF).

Segment No.	D _a (km)	D _d (km)	TTSF (km)	Location Latitude	Longitude	Inference
1	2.02	2.29	0.88	30°19'49.92"	79°45'21.327"	Asymmetric Basin
2	1.12	5.05	0.22	30°18'2.751"	79°42'39.342"	Asymmetric Basin
3	1.04	4.43	0.23	30°16'47.494"	79°36'45.111"	Asymmetric Basin
4	0.46	7.7	0.06	30°15'14.78"	79°34'6.128"	Asymmetric Basin
5	0.72	6.79	0.11	30°15'6.8"	79°30'50.607"	Asymmetric Basin
6	3.91	8.95	0.44	30°15'49.49"	79°28'17.509"	Asymmetric Basin
7	0.49	9.61	0.05	30°16'0.218"	79°26'1.995"	Asymmetric Basin
8	1.35	8.6	0.16	30°17'38.497"	79°24'3.178"	Asymmetric Basin
9	1.87	6.05	0.31	30°18'37.324"	79°21'36.263"	Asymmetric Basin
10	3.93	5.35	0.73	30°18'59.479"	79°20'43.251"	Asymmetric Basin
Average	1.69	6.48	0.31			

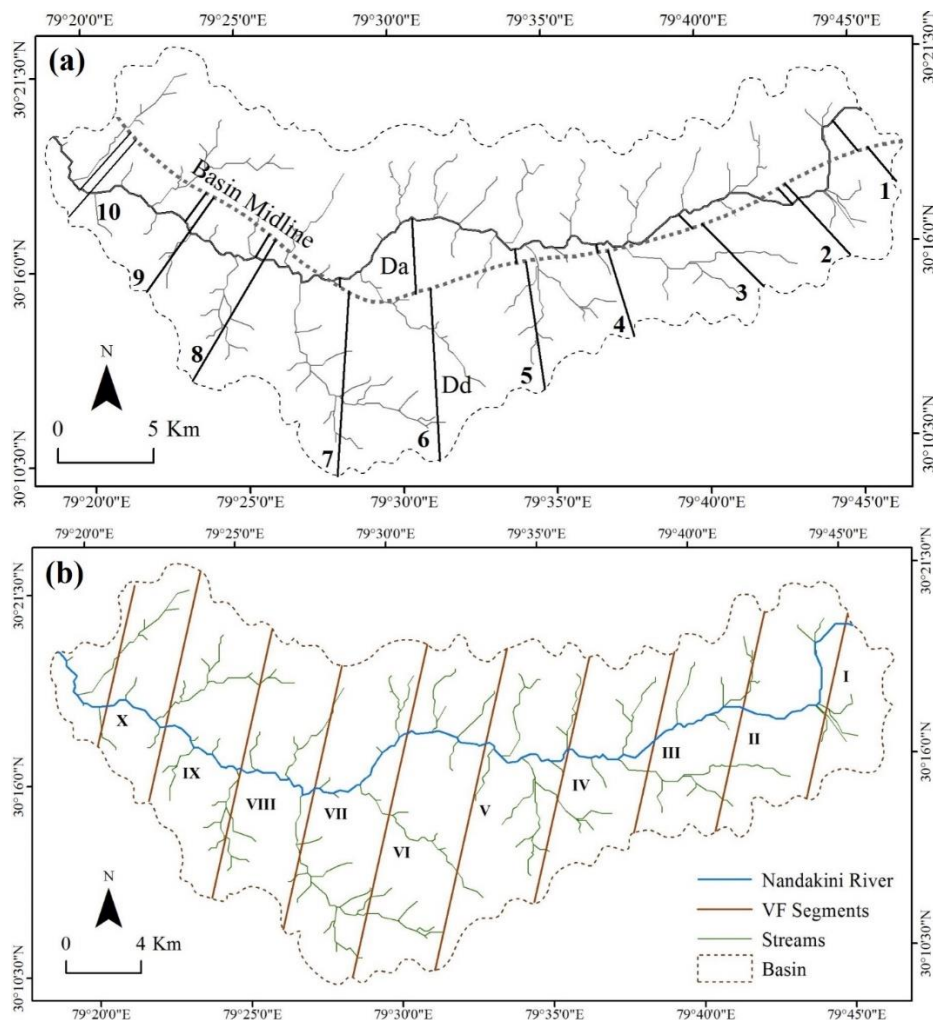


Figure 7 (a) The Transverse Topographic Symmetry Factor (TTSF) is calculated by $T = D_a/D_d$, where D_a = distance from midline of the drainage basin, D_d = distance from basin midline to the basin divide and (b) Valley floor to valley width ratio (V_f).

4.2.4 Valley Floor Width to Valley Height Ratio (V_f)

The Calculating ' V_f ' index in this analysis, by ten cross-sections on the mainstream and sub-streams in the highlands of 467.72, 570.28, 1032.02, 780.58, 468.35, 627.69, 1120.96, 1027.45, 1162.36 and 652.05 that show the valley floor heights, they are drawn perpendicular to the stream. The necessary calculations have been performed on them. The average ' V_f ' of the basin is 0.54 (Table 2, Table 6), suggesting low values indicative of less erosion, deep, narrow valleys, and V-shaped (Figure 7b, Figure 8).

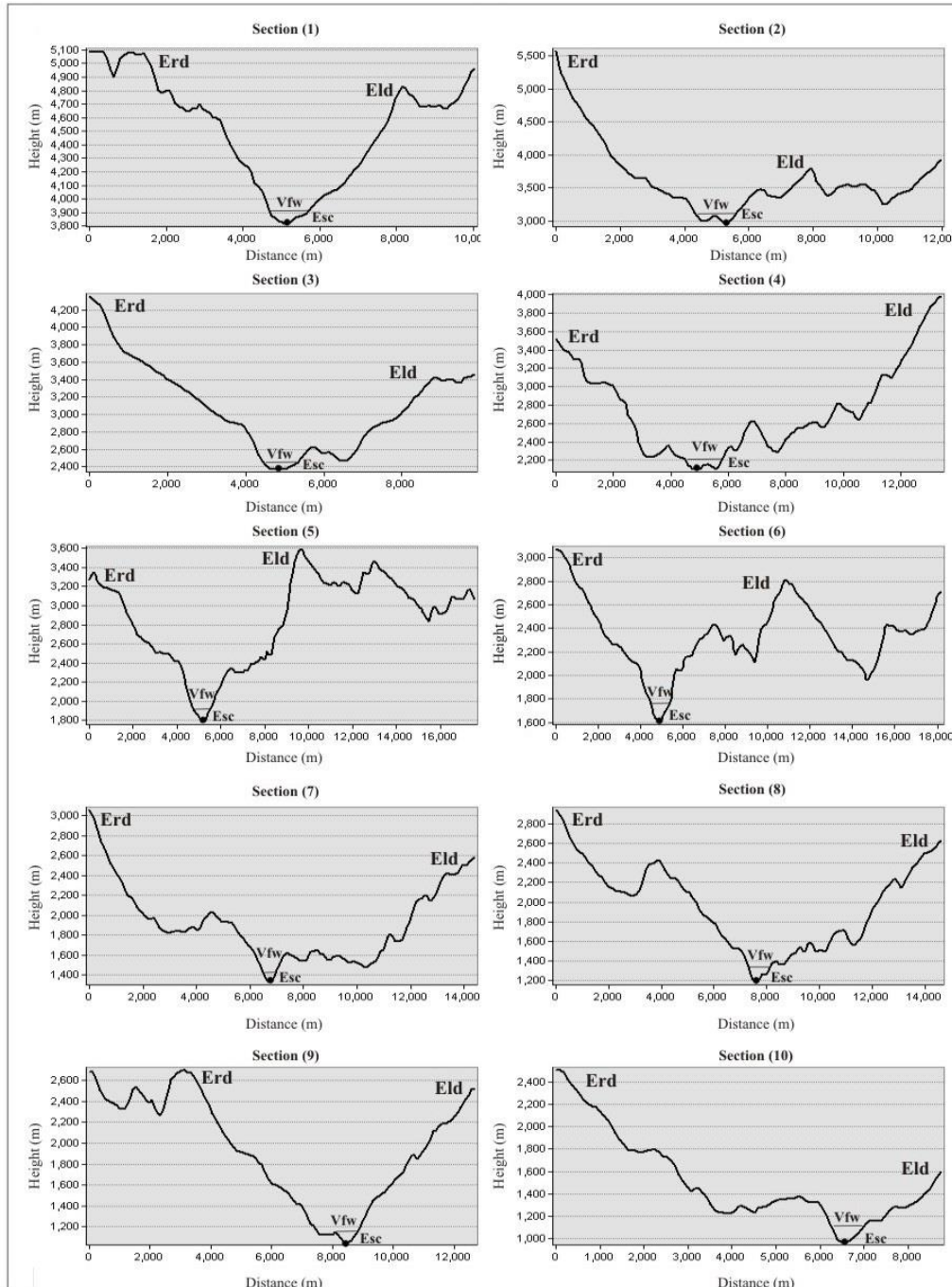


Figure 8 The cross-section for Valley floor width to valley height ratio (V_f).

Table 6 Segments selected for valley floor to valley width ratio (V_f).

Segment No.	Eld (L) m	Erd (R) m	Esc (F) m	(Vfw) m	VF (m)	Inference
1	4958.69	5091.58	3816.62	467.72	0.39	Average V_f = 0.54, deep, narrow valleys, 'V' shaped, Active incision
2	3918.62	5576.38	2950.61	570.28	0.32	
3	3456.48	4357.37	2371.33	1032.02	0.67	
4	3982.77	3522.63	2104.00	780.58	0.47	
5	3072.00	3274.53	1784.60	468.35	0.34	
6	2708.34	3073.38	1605.41	627.69	0.49	
7	2582.00	3058.58	1329.26	1120.96	0.75	
8	2629.02	2939.00	1184.90	1027.45	0.64	
9	2463.71	2684.00	1053.24	1162.36	0.76	
10	1595.13	2509.34	965.24	652.05	0.60	

4.2.5 Sinuosity Index (S_i)

Channel sinuosity is a key parameter in understanding the role of active tectonics. Along with active faults where erosion rates are high due to the pulverized rock material, the river erodes its valley linearly, forming strath terraces. Channel sinuosity values are lower in regions with relatively high tectonic effects. The range of the S_i value varies from 0.99 to 1.50. The average sinuosity of 1.12 is called low sinuosity (Figure 9). The channel sinuosity is controlled by channel gradient, sediment load, resistance to lateral erosion of a river, stage of valley development, and the structural characteristics of the area through which it flows [90-93].

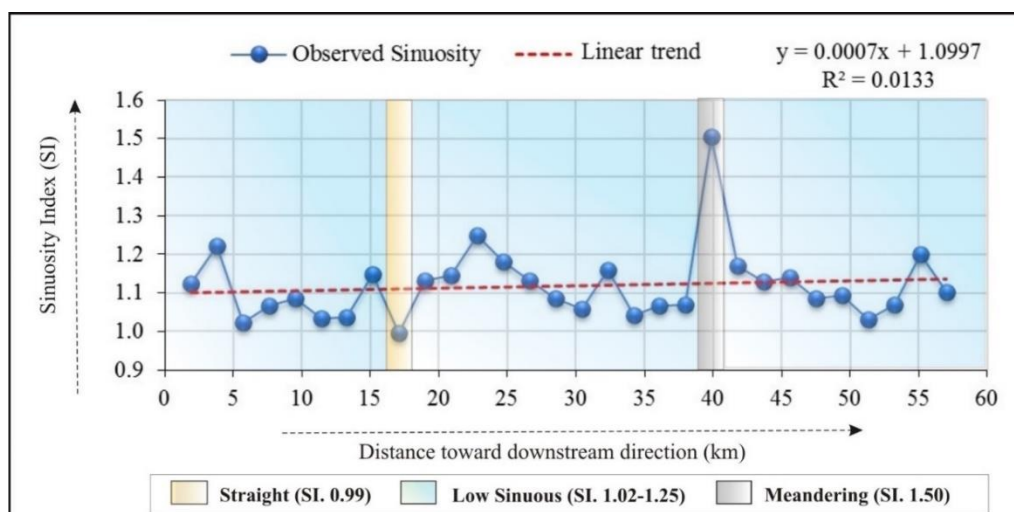


Figure 9 Calculated the Sinuosity Index of the basin which is divided into straight, Low and Meandering zones.

In this study, three zones of the Sinuosity Index have been observed based on [74], namely as straight, low sinuous zone, and high sinuous zone. The measured, observed sinuosity and linear fit curve for channel following straight (S_i -0.99) at 17 km. The low sinuosity zone (S_i -1.02 to 1.25) referred to low sinuosity [94]. The sinuosity of the river is 1.25 which also shows the braided nature [95]. Mostly the river has low sinuosity. Sinuosity increases when the outer bend of the bank erodes

more rapidly than the inner bend [96]. The alluvial theory of meanders relates this lateral erosion imbalance to hydraulic valves [80, 97, 98].

Similarly, [99] revealed that remarkable sinuosity changes relate to changes in river discharge and sediment load at the tributary interflow. Even the smallest topographical changes influence the sinuosity of low gradient rivers [100]. The meandering zone ($S_i-1.50$) shows the meandering zone at 40 km from the source. Most meandering streams show substantial changes in sinuosity over time, reflecting not only the geomorphic history but also active tectonics. Stream variations and other influences on valley slopes [42, 101]. The straight and low sinuosity zone shows the high peak zone (V) shape valley. Mostly the river has low sinuosity.

4.3 Stream Length Gradient Index (SLGI)

4.3.1 $SLG_{segment}$

[81] defined the tectonic activity and nature of the rocks. The $SLG_{segment}$ for the basin is 1285.73, which is recommended for High tectonic activity (Table 2).

4.3.2 SLI_{total}

The stream length gradient ratio is studied to analyze tectonic influence, rock resistance, and topography. The roughly equivalent tectonic activity in the basin was assessed [34, 102]. The SLI_{total} for the basin is 120.81.

4.3.3 $SLGI_{anomalous\ points}$

The tectonic activity is relatively high, and vice versa [73, 81]. Most of the SLGI anomalous points are situated in the locations where the change in slope gradient on the longitudinal profiles or where the rivers take right-angled turns. The SLGI for the Nandakini River basin is 10.64 (Table 2). A high value of the SLG represents the hard bedrock of stream and reflects.

4.4 Tectono-Geomorphologic Investigations

Based on the integrated application of satellite imagery and digital data, a take-out of reliable information on the geomorphologic evolution of the basin was carried out. We attempted to evaluate the effect of tectonic deformation along the Nandakini River valley, indicating the geologic complexity setting.

4.4.1 Longitudinal Profile (Ls)

A curvature that shows the relationship between heights versus distance downstream of a channel. Longitudinal channel profiles may indicate instability due to climatic, rock-type, and tectonic factors [103]. Hence, it is one of the geomorphic indexes used to identify areas with intense tectonic deformation [35, 73]. The river is evident in the cyclic evolution of the basins due to local neotectonic control [104]. The longitudinal river profiles contain the uplift and tectonic records [72]. This profile starts at 4955.22 m height at the head, and after reaching the maximum, the profile further shows the decline and ends its journey at 965.23 m height at the mouth. The longitudinal

profiles of the streams show a sudden change in slopes, graded profile, a considerable amount of incision, and deposition along their profiles, showing tectonically instability (Figure 10).

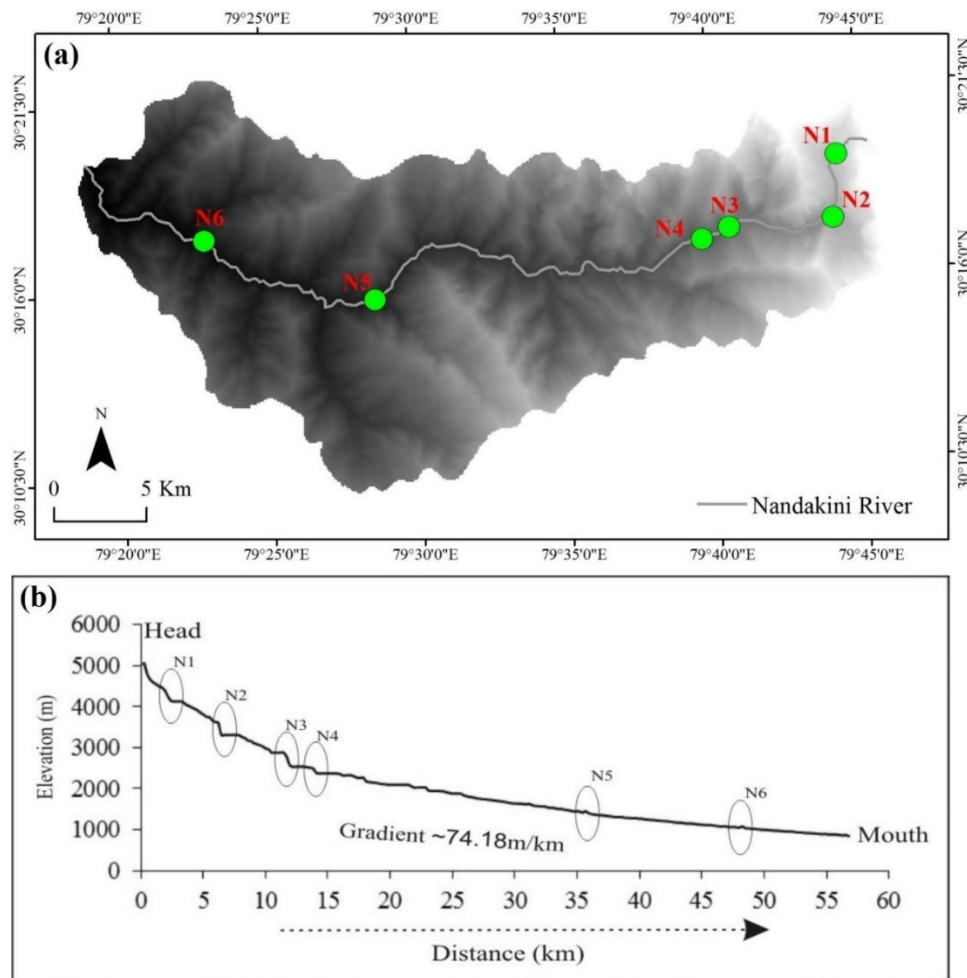


Figure 10 (a) Longitudinal profile of the Nandakini River. (b) Illustrates a concave up profiles and distribution of the knickpoints. From knickpoints (N1–N4), it flows on steep slope in a highly faulted zone and thrusting, whereas (K5–K6) indicate the resistance of hard rock formation. In the final stage, the river shows stiff resistance rock.

4.4.2 Transverse Profile (Tp)

It is prepared using 90 SRTM DEM and section as NTP-1, NTP-2, NTP-3, NTP-4, NTP-5, NTP-6, NTP-7, NTP-8, NTP-9, and NTP-10. These segments are running parallel to each other along E-W in direction. These profiles are taken across the river within the basin. Each profile shows irregularity, tilting, and undulation. The Profile NTP-1, NTP-2, NTP-3, NTP-4, NTP-8, NTP-9 and NTP-10 tilting toward left valley side while Profile NTP-5, NTP-6, NTP-7 tilting right valley side (Figure 11). Its entire journey profile cuts the tributaries and geomorphic features at various locations. The transverse profiles of the river show a cross-section of the channel and valley of a river in the path of the river at some point. A river cross profile varies as it shifts from the head to the mouth due to changes in the energy of the river and the processes the river carryout.

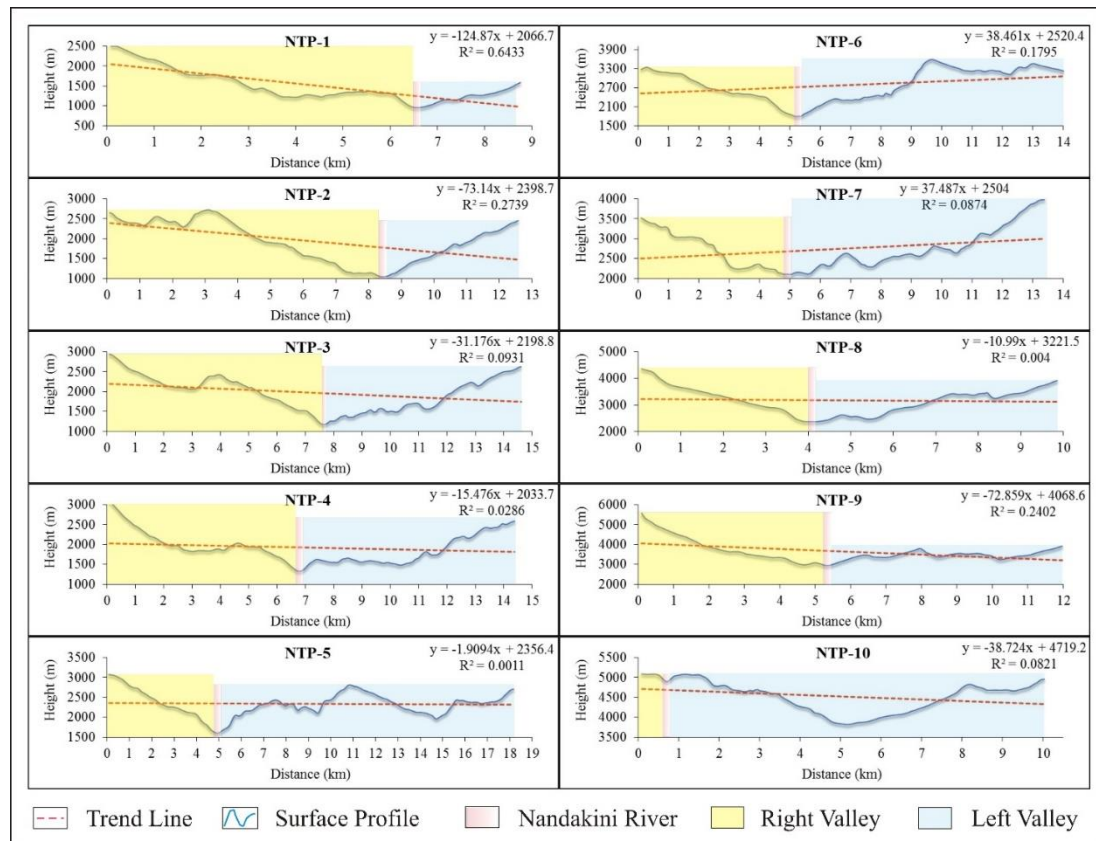


Figure 11 Transverse profile of the Nandakini River basin. Section within five profiles following NTP1 to NTP10. In which blue colour shows the right bank, yellow colour shown left bank, Pink colour showing the main channel. The surface profile showing irregularity and the linear trend of profile showing the tilting of the basin.

The valley and narrowing channel deep in the upper course because of the large amount of vertical and little lateral erosion. In the upper course, the sides of a river valley are very steep, term “V-shaped valley” for these valleys. Due to an increase in lateral erosion, the valley decreases in width in the middle section. Due to increasing vertical erosion, its depth does not change significantly. The land in the valley to the side of the channel is recognized as the river's floodplain. The mouth of the valley is narrow again due to a sudden decrease in slope. The upper course of the basin tilts toward the right side, while the lower course tilts toward the left side. This tilting of the profile shows the subsurface tectonic activity. It has been found that the valley increases in the middle course, and the valley may become narrow again in the lower course. Such transverse profiles were prepared to understand the structure of the valley and its width from the origin of the mouth and recent tectonic activities.

5. Conclusions

In this research, efforts have been made to discuss the tectonic-geomorphic signatures of the Nandakini basin, which is subject to neotectonic activity. Through qualitative and quantitative morphometric analyses with an emphasis on topography, I demonstrate the role of surface processes and topographic adjustment on landscape development in the study area. The morphometric parameters indicate a transient response of the landscape to disequilibrium initiated

by active tectonics. The circularity ratio reveals that the basin is sub-elongated, whereas the asymmetric basin factor indicates the effect of active tectonics or substantial lithological control in the study area. The Nandakini terrain points to the youthful topography. The hypsometric integral data suggest that the basin has experienced unevenness and respond to Deep incision and slight erosion due to the active tectonics in the area. Further, the presence of high-elevation surfaces to the tectonic disturbances in the area. R_e , B_s , SLGI is 0.17, 3.27, and 10.64, respectively, reporting that the area is tectonically active. TTSF is 0.31 implies the asymmetric nature. The river profile showing topographical undulation, tilting, and disequilibrium condition suggests that the river is tectonically influenced. The geomorphic features include unpaired fluvial terraces with tilting, rugged topography and boulders size sediment, V-shaped valleys, active river terraces, river meandering, and lake depositions, landslides, and mudflow indicate active tectonism. From knickpoints N1 to N4, the river flows on the high slope in the highly faulted zone showing action by the tectonic activity. Abrupt break in slope, sinuous to meandering course of the river, youthful topography, and elongated shaped basin add to the evidence of neotectonic. The higher rate of rock weathering, particularly of schists in the vicinity of the active supplementary faults, disintegrated rocks and numerous landslides, is additionally responsible for the landscape revolution. The drainage basins are significantly elongated in shape, and sediment carrying capacity is high and tilted. Most river valleys are narrow and deep, indicating active incision due to tectonic activity.

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Author Contributions

Pawan Kumar Gautam wrote and edited the manuscript. He also prepared the necessary maps. Anoop Kumar Singh made corrections to the manuscript.

Competing Interests

The authors have declared that no competing interests exist.

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