Submitted in Comp & Geosci (Elsevier)

Morphotectonic analysis of Bhilangana river basin in Lesser and Higher Himalaya (Uttarakhand, India) & tectonic implications

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Abstract: Sustainable development in the Garhwal Himalaya needs the terrain's landform/geomorphic analysis. This study aims to assess the tectonic activeness of the Bhilangana River basin through morphotectonic analysis of its 12 sub-watersheds. ArcGIS 10.8 software is employed to generate map and calculate morphometric parameters. The longitudinal profiles of the sub-watersheds are analyzed, incorporating additional information e.g., lithology, sinuosity index, stream length index, knickpoints and major thrusts to interpret the effect of geology and tectonics on stream profile. Using SPSS statistics software, Hierarchical clustering is conducted to analyze the linear parameters, while the Index of Active Tectonics (IAT) considers relief and areal parameters. Normalized longitudinal profiles were subject to R^2 curve fitting analysis. Sub-watersheds 2, 8, and 9 are active tectonically, whereas 3 and 7 are comparatively less influenced by tectonic activity. A watershed crossed by a fault is not necessarily tectonically active and landslide-prone.

Words: 143

Keyword: Collisional tectonics; morphometry; tectonic modeling; tectonic stability

"…historical geographers concerned with land development in marginal areas have felt pressed to investigate the interaction between land use and geomorphic processes." – Douglas (1987)

1. Introduction

Physical geographic/geomorphologic studies have crucial impacts on society **(e.g., Tadaki et al. 2012; Goudie 2017)**. Geomorphic studies can categorize lands/terrains as per tectonic activeness. Such studies are important since settlement dynamics can change depending on natural calamities such as landslides and earthquakes (**Mandasari et al. 2016**). Generally speaking, tectonically highly active areas are either to be avoided for settlement/engineering constructions, or be paid special attention for any construction works. Especially in mountains, such an input is crucial. Active tectonic study is at present a rather non-expensive approach in this direction **(e.g., Biswas et al. 2022)** and is widely practiced worldwide by geoscientists. To be specific, United Nations Educational, Scientific & Cultural Organization (UNESCO) recognizes Himalaya as a terrain of enormous importance, conducted studies **(e.g., Bhasin et al. 1984)** and established (geo)parks **(Singh et al. 2021).**

Student of recent tectonic activity in collisional terrains matters since such geological terrains are of several engineering constructions e.g., hydel power plants, dams, tunnels and sometimes as locations for hydrocarbon exploration (**Goffey 2010**). Himalaya is an active mountain chain (**Mukherjee et al., 2015**), where several engineering constructions works have been undertaken. For dam construction, it is therefore important to demarcate tectonically active locations near the major streams, and avoid those locations as construction sites. Faults have already been delineated in the Himalaya based on fieldwork and remote sensing studies (e.g.

Nakata 1989). However, not every portion of the fault along its length are equally active **(Horton 1996)**. Therefore, mere presence of exposed/blind faults in a terrain is not sufficient to comment about its activity and hence active tectonics. Active faults can allow continuous very slow slip leading to ongoing microseismicity **(e.g., Pudi et al. 2021)** or a sudden slip (the stick-slip mechanism) leading to devastating earthquakes **(e.g., Gupta 2023).** River channel geometries and networks are sensitive to recent tectonics. Hence morphometric studies of drainage basins has gained global attention.

Index of Active Tectonics (IAT) is a reliable and widely used method for assessing the level of recent tectonic activity in any region **(e.g., Ghosh and Sivakumar, 2018; Biswas et al., 2022a, b; Dasgupta et al., 2022, Gupta and Biswas 2022; Kumar et al., 2022; Raha et al.., 2023; Dhawale et al., 2023; Mondal et al., 2023)**. It provides a semi-quantitative measure of the relative degree of tectonic activeness by considering various morphometric parameters. Cluster analysis is a statistical technique that focuses on finding natural groups or clusters within a dataset. The goal is to group individuals or objects together based on their similarities, using a suitable criterion **(Hashemi and Mehdizadeh 2014).** The hierarchical classification technique is a useful tool to interpret geologic data. The longitudinal profile is a commonly used tool in geology to analyse and understand the characteristics of landforms, particularly in fluvial or river systems. It refers to a graphical representation of the elevation changes along the course of a river or stream. The profile provides information about the gradient, slope and shape of the channel over its entire length. These help in understanding the tectonic, climatic and erosional processes.

The Garhwal area covering parts of Lesser and Greater Himalaya in Uttarakhand state (India) is of great importance for (eco)tourism **(e.g., Nigam 2002; Chaudhary et al. 2022)**. Negative impacts of tourism in mountains is well known **(e.g., Singh and Kaur 1986)**, therefore the Garhwal region deserves scientific study of its landforms. **Ramya and Devadas (2019)** performed Technique for *Order Preference by Similarity to Ideal Solutions* (TOPSIS) and multicriteria study on Garhwal area to locate best feasible area for development. However, their work missed input of active tectonics. The present work fills up this gap in knowledge.

We apply several morphometric approaches **(**IAT, cluster analysis and rivers' longitudinal profile analyses) to understand different degrees of stabilities of the watersheds of the Bhilangana river within the Greater and the Lesser Himalaya in the Uttarakhand Garhwal Indian western Himalaya. Seismicity and landslide information have been compared with this study.

1. Study Area

The study area is located in the Tehri Garhwal district of Uttarakhand.

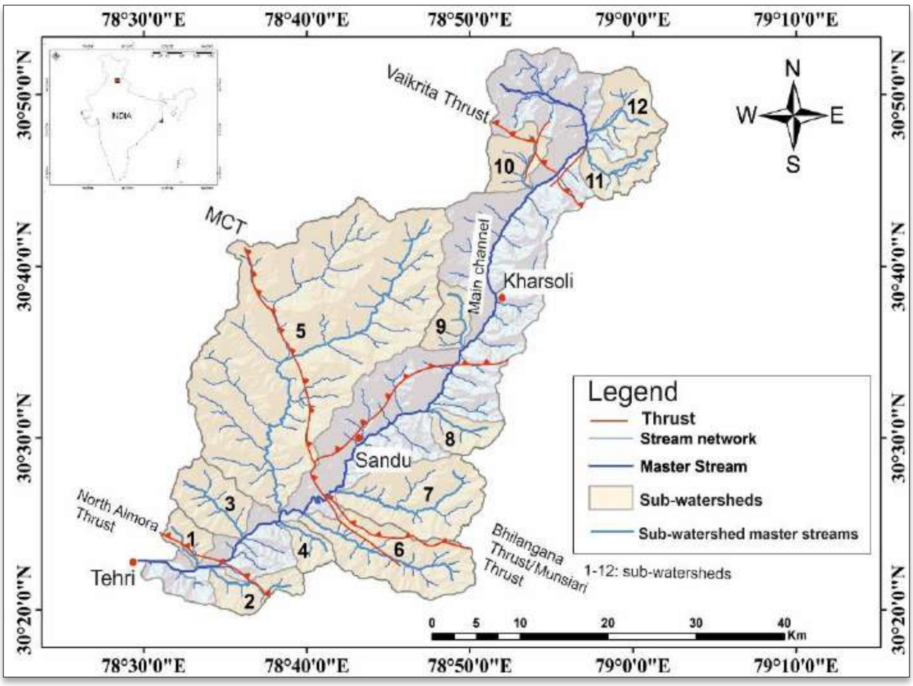


Fig. 1. *Map of the Bhilangana basin showing stream network and twelve delineated sub-watersheds. Major thrust lines are plotted as per* ***Valdiya (2016) and GSI Misc. Publ. (2002, 2019).***

Geologically, the study area comprises of Lesser Himalayan and Greater Himalayan regions. In **Fig. 1** regions north of the Main Central Thrust (MCT) is the Greater Himalaya, and the region south to it is the Lesser Himalaya. The GH in the Garhwal sector consists of mainly Neoproterozoic rocks that had a dual source from northern portion of south China and the southern Gondwana terranes (**Imayama et al., 2023**). The Lesser Himalaya in the Garhwal region consists of paleo to Mesoproterozoic low-grade metamorphic rocks, usually quartzites, slates, limestones and schists (**Bose and Mukherjee 2019**). **Appendix** presents structures and geochronology of faults in the study area. The Uttarakhand Himalaya is prone to frequent earthquakes and landslides due to its active tectonics. The study area comes within the IV and V earthquake zones **(Internet ref 1).**

The study area is drained mainly by the Bhilangana river and its tributaries. There are several incidences of landslides and earthquakes in the Bhilangana basin **(Fig. 2).** The Bhilangana watershed is studied in detail to find the morphotectonic characteristics of the region. ArcGIS 10.8 software is used to prepare maps and extract data for calculating morphometric parameters.

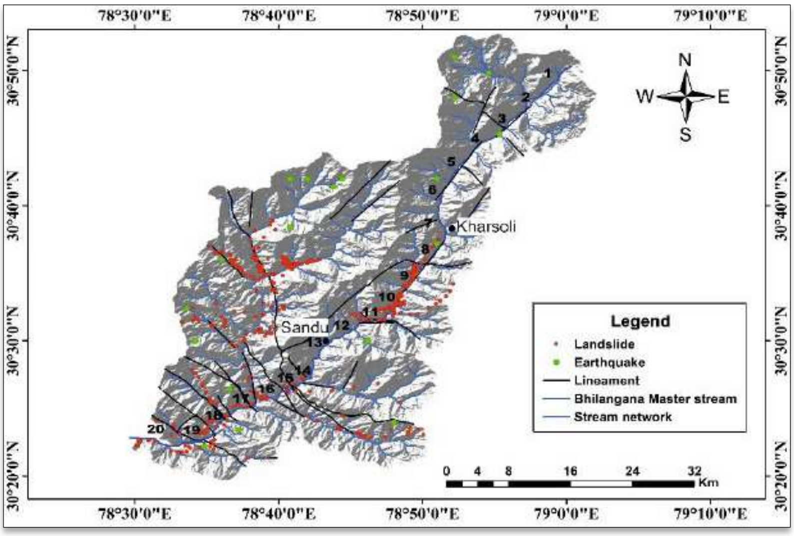


Fig.2. *The overlay map showing the past landslides, earthquakes and lineaments in the Bhilangana basin. Landslide and lineament data have been taken from Bhukosh, Earthquake data is taken from USGS. The map is made using ArcGIS 10.8.*

The main objective of this study is to find the tectonic activeness of the Bhilangana basin. The Bhilangana watershed is further divided into twelve sub-watersheds for detailed analysis of relief and areal parameters. The master stream of each sub-watershed **(Fig. 1)** is divided into segments to study in detail the linear parameters. IAT is calculated from each sub-basin.

2. Geoscientific aspects of the Bhilangana basin

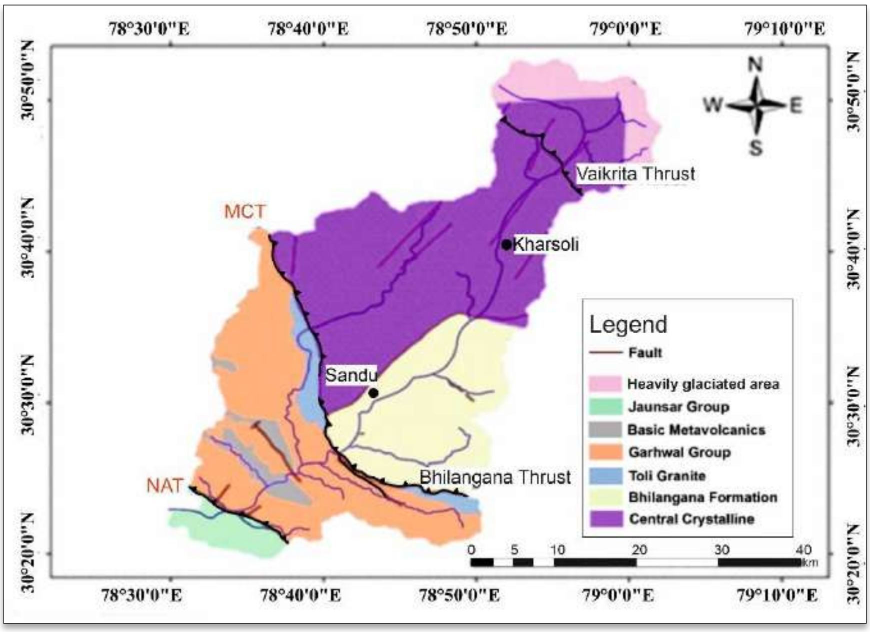


Fig. 3. *Geologic map of the study area. Prepared by using ArcGIS 10.8.*

2.1. Previous (geomorphologic) works on Bhilangana river basin

Several researchers have worked on the Bhilangana river basin focussing on structural and tectonics in the region **(Fig. 3)** **(Table 1).** These works so far concluded only on depositional models and tectonics.

Table 1. *Details of previous work mostly on morphotectonics of the Bhilangana basin.*

Sl.no	Authors	Key conclusions	Approaches
1.	**Bahuguna et al. (1982)**	Cyclic straining in the hangingwall during the emplacement of thrust sheets developed the Central Crystalline	Tectonic activeness along the MCT

		Duplex.	
2.	**Rao (1993)**	Foreland-directed migration of the depo-centres.	Magnetic polarity and stratigraphy of NW Himalaya
3.	**Taloor et al. (2021)**	Bhilangana and Mandakini drainage basins in the Garhwal region underwent increasing tectonic activity since 5 Ma.	The study includes GIS-based morphotectonic investigation in the Bhilangana and Mandakini basins of the Garhwal Himalaya.
4.	**Chauhan et al. (2022)**	The boundary of the MCT zone in the south is represented by the Bhilangana Thrust. Bhilangana Formation experienced three ductile periods of deformation.	Fieldwork
5.	**Bisht et al. (this work)**	The main channel watershed and two sub-watersheds are active tectonically.	Basin-scale and linear scale morphometric study of the Bhilangana basin

2.2. Morphometric analysis

Morphometric studies of watersheds involve analysis of linear, areal and relief parameters using several basin-scale and linear parameters (second and third columns of **Table 2**). Results are then correlated with the known geoscientific dataset **(Section 6).**

2.3. Seismicity

The Main Central Thrust (MCT) zone, known for its seismic activity, has witnessed major earthquake epicenters with M > 5 concentrated within its 50 km width (**Paul et al., 2005**). These earthquakes are closely associated with thrust sheets and their imbricate zones **(Kayal, 2003)**. Uttarakhand has experienced significant earthquakes in the past, such as the 1991 Uttarkashi earthquake (M 6.8) and the 1999 Chamoli earthquake (M 6.8), which caused extensive devastation along major tectonic discontinuities. Concerningly, the state has not witnessed a higher magnitude earthquake for over 200 years, indicating a possible build-up of strain known as the seismic gap (**Bilham et al., 1998**).

2.4. Landslides & other disasters

The Garhwal Himalaya is prone to natural calamities such as landslides and flash floods. These are often triggered by factors such as heavy rainfall, steep slopes, geologic and tectonic conditions and fragile terrain. High hazard zones for landslides are primarily located in steep slopes, areas with high rainfall intensity, and areas with loose or erodible soils. (**Sati and Rawat 2014). Rana et al. (2020)** conducted a study specifically targeting the assessment of debris flow susceptibility in the Bhilangana river basin. They employed bivariate statistical analysis and frequency ratio modeling to investigate this susceptibility. The research findings indicated that factors such as slope, lithology and rainfall intensity played crucial roles in the occurrence of debris flows within the valley. How far active tectonics leads to landslide in Garhwal sector has not been well-researched.

3. Data & Methodology

3.1. Data

We utilize ASTER DEM version 3 data with a spatial resolution of 1 arc second (~ 30 m horizontal resolution). The WGS 1984 reference system is adopted. The study area is located within the UTM zone 44. Seismic data from the past century, with M > 3, are obtained from the United State Geological Survey (USGS) Earthquake catalogue **(Internet ref-2)** to create the overlay maps.

3.2. Morphometric parameters

Morphometric parameters **(Table 2)** are quantitative measures used to analyse the geometric and topographic characters of the watersheds. We calculate relief, areal and linear parameters to assess the tectonic implications of each watershed. Calculations are performed using the software ArcGIS 10.8 (2020).

We divide the Bhilangana basin into 12 sub-watersheds (**Fig. 1**), and each were analysed to identify the tectonic influence on particular regions. Relief and areal parameters are computed for 12 sub-watersheds of Bhilangana basin. Using the Editor Tool in ArcGIS 10.8, the main Bhilangana river's master stream and the 12 sub-watersheds are traced. The main Bhilangana master stream of ~ 77.2 km is divided into 20 equal segments, while the sub-watershed master streams are divided into five equal segments. However, sub-watershed 5, representing the watershed of the Balganga river (the largest tributary to the Bhilangana river), is divided into 10 equal segments due to its long channel. Linear parameters are then calculated for each segment (fourth column in **Table 2**).

Table 2. *Details of geomorphic indices, equations, implication and relation with active tectonics. Results of this work have also been stated.*

Sl. No.	Parameters	Equations and meaning of symbol	Reference	Relation with active tectonics	Results of this study
Basin scale parameters					
1	Relief Ratio (R_h)	$R_h = R\ L_b^{-1}$ R: relief, L_b: basin length. R_h provides information about the steepness or gradient of a landscape.	Schumm (1956), Shukla et al. (2014)	R_h represents the degree of rock resistance and indicates the overall steepness of an area. Factors such as erosion rate, tectonic influence and the (non) resistant character of rock can affect R_h magnitude. Higher values of Rh are associated with	R_h ranges from 0.05 to 0.24 for the 12 sub-watersheds. Sub-watersheds 2, 5, 6, and 7 fall into Class 3 (0.05-0.10), while sub-watersheds 1, 3, 4, 8, 9, 11 and 12 belong

				hilly regions characterized by resistant rocks, while lower values indicate less resistive rocks and flatter regions. A higher R_h value suggests a steeper watershed and potentially greater tectonic influence.	to Class 2 (R_h = 0.11-0.17). Sub-watershed 10 belongs to Class 1 (R_h = 0.18-0.24). Sub-watershed 10 has highest R_h = 0.24, indicates greatest overall steepness. Sub-watersheds 1, 3, 4, 8, 9, 11 and 12 have moderate R_h (0.11-0.17) suggesting a significant tectonic influence within a larger number of sub-watersheds. Sub-watersheds 2, 5, 6, and 7 exhibits low R_h, (0.05-0.10) indicating a relatively lower degree of rock resistance.
2	Ruggedness number (Hd)	Hd = R * D R: relief in km, D: drainage density. It Provides	Schumm (1956)	Hd represents the combined effect of slope steepness and length, indicating the extent of instability	Hd ranges from 0.58 to 0.87 in the 12 sub-watersheds.

		information on the shape of a watershed, specifically whether it is elongated, circular or irregular.		of the land surface. High Hd suggests a region that is more susceptible to degradation processes and characterized by dissected hills with intrinsic structural complexity. (Schumm,1956; Strahler, 1957).	Sub-watersheds 10 and 12 belong to Class 3 (Hd = 0.78-0.87), while sub-watersheds 1, 3, 4, 5, 7, 8 and 9 belong to Class 2 (Hd = 0.68-0.77). Sub-watershed 2, 6 and 11 belong to Class 1 (Hd = 0.58-0.67). Sub-watersheds 5, 11, 9, 10, and 12 are classified as highly to moderately tectonically active, indicating a potential greater tectonic influence compared to other sub-watersheds. However, seven sub-watersheds 1-4, and 6-8 exhibit low values of Hd (0.36-0.65), suggesting that they do not strongly reflect a greater tectonic

					influence.
3	Hypsometric Integral (HI)	HI = (Ele_{avg} – Ele_{min}) (Ele_{max} – Ele_{min})$^{-1}$ Ele_{avg}: mean elevation of the basin above msl, Ele_{min}: elevation of the lowest point of the basin, Ele_{max}: elevation of the highest point the basin	Strahler (1952), Zhang et al. (2019)	HI denotes the developmental stage of a watershed and reflects the intensity of activity within the geological terrain (Duan et.al. 2022). HI's higher values indicate a basin with a deep incised valley and minimal erosion on plateaus. This suggests a relatively youthful landscape with limited erosion. Low HI indicates severe erosion, suggesting an older landform with extensive erosion (Dehbozorgi, et.al.2010).	HI ranges from 0.3 to 0.57 in the Bhilangana watershed. Sub-watersheds 3, 4 and 5 are classified into Class 3 (HI = 0.3-0.38); sub-watersheds 1,2,6,8,10 and 12 are grouped into Class 2 (HI = 0.39-0.47); sub-watersheds 7, 9 and 11 into Class 1 (HI = 0.48-0.57) Sub-watersheds 7, 9, and 11 with HI = 0.48 -0.57 exhibits a youthful stage of landscape. Sub-watersheds 1, 2, 6, 8, 10 and 12 also demonstrate moderate HI values (0.39-0.47), aligning with the concept of a youthful landscape. In contrast, sub-watersheds 3, 4, and 5 exhibit low

					HI = 0.3-0.38, which indicate a significant level of erosion.
4	Drainage Density (D)	$D = \Sigma L.A^{-1}$ ΣL: total length of streams, A: drainage basin area.	Horton (1945),	D represents the degree of stream channel development within a watershed. D is often used as an indicator of tectonic activity. Higher D is associated with regions experiencing greater tectonic activity, while lower D suggests less tectonic influence.	D = 0.46-0.61, for all the sub-watersheds in this study. The values are classified into three Classes; Class 3: D = 0.46-0.50 (sub-watershed 1, 5, 7 and 10), Class 2: D = 0.51-0.55 (sub-watersheds 3 and 6) and Class 1: D = 0.56-0.61 (sub-watershed 2, 4, 8, 9, 11 and 12). The majority of the sub-watersheds exhibited higher drainage density, indicating a greater degree of tectonic activity. This is exemplified by six sub-watersheds grouped in

					Class 1 with drainage density values ranging from 0.56 to 0.61. Sub-watersheds 3 and 6 demonstrated moderate drainage density values ranging from 0.51 to 0.55, suggesting a noticeable but relatively less pronounced influence of tectonic activity. Conversely, sub-watersheds 1, 5, 7, and 10 exhibited the least tectonic influence among the 12 sub-watersheds, as reflected by their lower drainage density values.
5.	Elongation Ratio (R_e)	$Re = 1.128\sqrt{\frac{A}{L_b}}$ A: signifies the area of the basin, L_b: length of basin.	Brice (1964)	Re is inversely correlated with tectonic activity. Low R_e indicates a higher level of tectonic influence and vice versa. It provides insights into the shape of a basin, with lower values indicating	Re ranges from 0.58 to 0.87 in the 12 sub-watersheds. Sub-watersheds 10 and 12 belong to Class 3 (Re = 0.78-0.87),

				elongated basins and higher values representing more circular basins.	while sub-watersheds 1, 3, 4, 5, 7, 8 and 9 belong to Class 2 (Re = 0.68-0.77). Sub-watershed 2, 6 and 11 belong to Class 1 (Re = 0.58-0.67). Three sub-watersheds- 2, 6 and 11 exhibits Re = 0.58 -0.67 indicating elongated basin shapes. Seven sub-watersheds demonstrate moderate Re = 0.68-0.77 suggesting a somewhat elongated shape and implying a certain degree of tectonic influence. Sub-watersheds 10 and 12 display circular basin shapes with Re = 0.86 and 0.87, respectively.
6.	Circularity Ratio (R_c)	$Rc = \frac{4\pi A}{P^2}$ p: perimeter of river basin, A: area of the basin.	Hack (1957); e.g., Lee & Tsai (2009)	High values of R_c indicate the circular shape of the basin and consequently the mature stage of landscape evolution.	Rc for Bhilangana sub-watersheds = 0.37-0.68. Class 3 (sub-watershed 1,

		R_c of basin gets influenced by the geological structures, stream length, frequency, slope and climate.		R_c provides insights into the geometric shape and compactness of watersheds.	3,4,7,8 and 9) has Rc = 0.58-0.68, Class 2 (sub-watershed 5, 6, 10 and 12) has Rc = 0.48-0.57, Class 1 (sub-watershed 2 and 11) has Rc = 0.37-0.47.
7.	Basin Shape (Bs)	$Bs = \frac{Bl}{Bw}$ Bl: measured length from headwater to the point on the mouth of the basin, Bw: width at the widest point on the basin.	Bull and McFadden, (1977), Ramirez-Herrera (1998)	Bs quantifies the shape of a basin or watershed. Higher BS values suggest a more elongated basin, which can be indicative of tectonic control or deformation. Lower BS values indicate a more circular basin shape, suggesting a lesser influence of tectonics.	It ranges from 1.07 to 2.71 in the Bhilangana sub-watersheds. The values are grouped into three Classes, Class 3 (Bs = 1.07-1.61) represented by sub-watersheds 3,9, 10 and 12; Class 2 (Bs = 1.62-2.1) represented by sub-watersheds 1,4,5,7,8 and 11; Class 1 (Bs = 2.2-2.71) represented by sub-watersheds 2 and 6. Sub-watersheds 2 and 6 exhibit a remarkable tectonic influence, as

					they are grouped in Class 1 (2.2-2.71). These sub-watersheds reflect the profound impact of tectonic activity on the landscape. Similarly, sub-watersheds 1, 4, 5, 7, 8 and 11, classified under Class 2 (1.62-2.1), also demonstrate a significant tectonic influence. In contrast, sub-watersheds 3, 9, 10 and 12, grouped in Class 3 (1.07-1.61), suggest a relatively lesser degree of tectonic influence. These sub-watersheds indicate a more subdued tectonic activity in shaping the basin's landscape.
8.	Asymmetry Factor (AF)	$AF = \left(\frac{A_r}{A_t}\right) * 100$ A_r: area of the basin to the right of the main channel facing	Hare & Gardner (1985); Cox, (1994), Keller &	AF is an important indicator to measure how much a river basin is tilted owing to tectonic activity. Tectonic activity	In the Bhilangana sub-watersheds its value varies between 3.12

		downstream; A_t: is the total area of the basin.	Printer (2002)	causes the main stream to change course, sloping away from the basin's midline. AF refers to a quantitative measure of the asymmetry or skewness of a river basin or watershed. Tectonic activity, such as faulting or uplift, can result in asymmetrical basin shapes.in areas with active tectonics, the presence of faults or uplifted blocks can cause differential erosion, leading to an asymmetrical basin. The longer side of the basin may correspond to the side that has experienced greater uplift or tectonic activity. AF ≈ 50% indicates minimal or no tilting perpendicular to the drainage. AF significantly different from 50%, either higher or lower, suggests substantial tilting and active tectonic influence. The normalized value |Af-50| can also be used. Values closer to zero indicate a more symmetrical basin with low levels of active tectonics and	to 26.7. The sub-watersheds are classified into three Classes namely Class 3 ranging from 3.12 to 10.9 (sub-watersheds 3, 6 and 7); Class 2 ranging from 11 to 18.9 (sub-watersheds 2,5,11 and 12); Class 1 ranging from 19 to 26.7 (sub-watersheds 1,4,8,9 and 10). In the Bhilangana watershed, most of the sub-watersheds exhibit asymmetry. Sub-watersheds 1, 4, 8, 9 and 10 are grouped in Class 1 (AF = 19-26.7), representing the highest degree of asymmetry. Sub-watersheds 2, 5, 11 and 12 come under Class 2 (AF =

				no tilting.	11-18.9), indicating a moderate level of asymmetry. Sub-watersheds 3, 6, and 7 are categorized in Class 3 AF = (3.12-10.9), signifying relatively lower levels of asymmetry.
Linear parameters					
Sl. No.	**Parameters**	**Equations and implication**	**Reference**	**Relation with active tectonics**	**Results of the study**
9.	Sinuosity Index (SI)	$SI = \frac{CL}{Vl}$ CL: channel length between two points on a river, Vl: valley length.	Brice (1964)	SI represents the degree of meandering or curviness of a river or stream channel. It is a quantitative measure that compares the actual length of the channel to the straight-line distance between its endpoints. $SI < 1.05$ indicates a straight channel. $SI > 1.05$-1.5 indicates increasing meandering. Straight and sinuous pattern of channel indicate vertical incision due to active tectonics.	In the Bhilangana watershed, most of the stream segments show sinuous (winding) pattern with SI = 1-1.25. Low SI values possibly indicate that the region is tectonically active and the stream is in a youthful stage, such as sub-watersheds 2, 5 and 7.

10.	Stream – length Gradient index (SL)	$SL = \frac{h_1 - h_2}{[\ln(d_2) - \ln(d_1)]}$ 'h_1' and 'h_2' represent height of the first and second point from the source, respectively. 'd_1' and 'd_2' represent the distance of first and second point from the source, respectively.	Hack (1973)	Higher SL values specify the crossing points of major faults and lineaments. Lower SL denotes fractures and small-scale lineaments. K_{Sn} indicates underlying tectonic and erosional processes that shape the landscape. It provides insights into the rate of rock uplift. Higher K_{Sn} reflects steeper river channels and more rapid erosion These characteristics are often associated with regions experiencing tectonic activity or uplift.	The Bhilangana master stream shows a significantly high SL indicating high relief and active tectonics.
11.	Normalised Steepness Index (K_{Sn})	$S = K_{Sn}A^{-\Theta}$ Slope S and drainage area A for each segment is calculated separately.	Hack (1957)	K_{Sn} indicates underlying tectonic and erosional processes that shape the landscape. It provides insights into the rate of rock uplift. Higher K_{Sn} reflects steeper river channels and more rapid erosion These characteristics are often associated with regions experiencing tectonic activity or uplift.	In the Bhilangana sub-watersheds, K_{Sn} is calculated for each segment. Generally, a decreasing trend in K_{Sn} is observed from the source to the mouth of the river. However, there are specific segments where an increase in K_{Sn} is observed. These segments

					directly correlate with areas undergoing tectonics.
12.	Channel Concavity (ɵ)	$S = ksA^{-\theta}$ S: channel slope; ks: steepness index, a: concavity index.	Hack (1957)	Concavity (ɵ) magnitudes classified into four types: (i) low concavity (ɵ < 0.4)- related to short, steep drainage dominated by debris flow, (ii) moderate concavity (ɵ = 0.4-0.7)- associated with actively uplifting bedrock channel, (iii) high concavity (ɵ = 0.7-1)- related to decrease in the uplift, and (iv) extremely high concavity (ɵ > 1)- transition from incisive to depositional conditions.	ɵ derived from slope area analysis, for the entire Bhilangana watershed is 0.366. When calculated the for individual sub-watersheds, θ is ≤ 4. These low values can indicate rapid uplift rates and ongoing active tectonics, the influence of debris flow, or a downward increase in rock strength. Sub-watershed 11 displays θ = 0.29, which can be attributed to the presence of a prominent knick point representing river hanging valley.
13.	Long Profile	Linear function y= ax+b Logarithmic function $y =$	Cox	Long profile denotes the break of slope	Sub-watersheds 1-

	analysis	$aln[x + b]$ ‘y’: elevation (H/H0); H: elevation of each point, H0: elevation of the source, x: length of the river (L/L0); L: distance of the point from the source, L0: total length of the stream), ‘a’, ‘b’- coefficients derived independently from each profile.	(1994)	and formation of knick points due to tectonics and lithology from source to mouth.	8 have highest R^2 in exponential curve fitting. In SW 9 and 11, linear curve fitting R^2 values are highest and it indicates the channel to be very active.

3.3. IAT analysis

The values of each parameter in column 2 in **Table 2** from the 12 sub-watersheds of Bhilangana basin are categorized into three Classes according to their tectonic implications. Each value is assigned a numerical code: 1 (corresponding to Class 1, indicating the highest tectonic influence), 2 (Class 2, moderate tectonic influence), and 3 (Class 3, least tectonic influence). The values for each sub-watershed are then averaged to obtain an IAT value. Subsequently, these IAT values are classified into three Classes based on the level of tectonic activity.

3.4. Dendrogram & hierarchical clustering

Hierarchical clustering on linear parameters was conducted using IBM's SPSS Statistics software (2018) to generate dendrograms. The concavity indices of 12 sub-watersheds were used to create this dendrogram based on the similarities in their values, reflecting potential tectonic influence. Additionally, SI, SL and K_{sn} for each segment of the master stream in the 12 sub-watersheds were combined. To ensure comparability, the linear parameter values, which initially had different ranges, were normalized within the range of 0 to 1 using the software's normalization function. This step helped align the values and facilitate meaningful comparisons during the clustering process. The linear parameters are considered for hierarchical clustering and visualising the results of clustering through dendrograms. The hierarchical clustering using Ward's method for concavity index**.** The optimum distance considered for clustering is 20.

3.5. Longitudinal profiles

In this study, the longitudinal profiles of each master stream in each sub-watershed were created using a combination of ArcGIS 10.8, GPS visualizer, Google Sheets and CoralDraw software. The elevation and distance data were sourced from a digital elevation model (DEM). The traced master streams were interpolated over the DEM layer and converted to a *Keyhole Markup Language* (KML) file in the ArcGIS 10.8 software. This file was then uploaded to GPS visualizer to obtain detailed elevation and distance measurements at various points along the stream.

The data obtained from GPS visualizer were sorted and rearranged in Google Sheets to generate the longitudinal profiles. These profiles were then imported into the CoralDraw. In CoralDraw, important information such as geological contacts, knick points and structural / geomorphic features intersecting the profiles, as well as the SI and the SL were marked and included in the profiles.

3.6. R^2 curve fitting of normalised longitudinal profiles

The normalised longitudinal profile is a representation of the elevation changes along the length of a river or stream, where the elevation and distance values are normalized or scaled relative to a reference point. The normalised long profiles were fitted with equations 1-4.

$$y = ax + b \quad \text{(eqn 1)}$$

$$y = ae^{bx} \quad \text{(eqn 2)}$$

$$y = a \ln x + b \quad \text{(eqn 3)}$$

$$y = ax^{b} \quad \text{(eqn 4)}$$

Here ‘y’ represents the elevation, expressed as the ratio of the elevation at each point (H) to the elevation at the source (H_0). The variable ‘x’ represents the length of the river, expressed as the ratio of the distance from the source (L) to the total length of the river (L_0). The coefficients a and b are determined from each profile. The coefficient of correlation (R^2) is used to evaluate the degree of best fit (Lee and Tsai., 2010). The equation that exhibits the highest R^2 value provides the best fit to the data. The tectonic influence on the master streams of the sub-watersheds can be inferred by comparing the R^2 value of the linear equation 1 with the highest R^2 value obtained from the other equations 2-4. A smaller difference between these R^2 values indicates a greater impact of recent tectonic activity.

4. Results

4.1. Drainage pattern

The angles between each tributary and the main Bhilangana master stream were measured to determine the drainage pattern **(Fig. 4) (Table 3).**

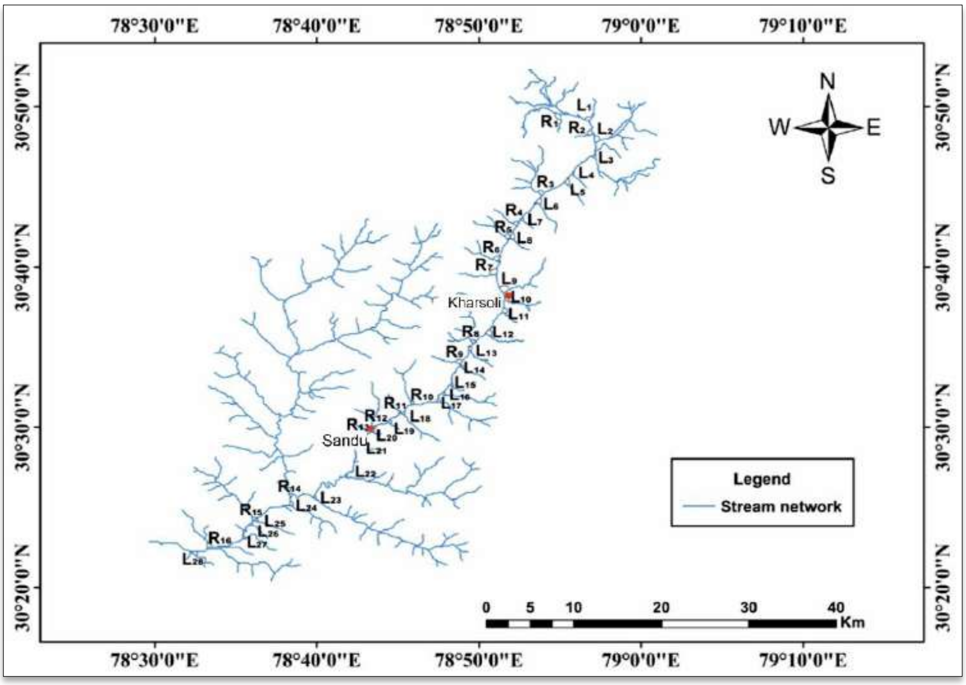


Fig. 4. *Showing the drainage pattern in the study area and the marked left and right bank tributaries whose joining angles are measured. Rectangular drainage pattern observed.*

Table 3. *Stream joining angle between Bhilangana master stream and its right bank tributaries (R1 to R16); Bhilangana master stream and its left bank tributaries (L1 to L28). Values highlighted in red: joining angles of 85-90°. Rectangular drainage pattern indicated.*

Master stream and right tributaries joining angle (in degrees)	**Master stream and left tributaries joining angle (in degrees)**	
$R_1 = 98$	$L_1 = 99$	$L_{17} = 80$
$R_2 = 93$	$L_2 = 75$	$L_{18} = 83$
$R_3 = 91$	$L_3 = 81$	$L_{19} = 86$
$R_4 = 92$	$L_4 = 89$	$L_{20} = 66$
$R_5 = 91$	$L_5 = 93$	$L_{21} = 93$
$R_6 = 46$	$L_6 = 60$	$L_{22} = 75$
$R_7 = 96$	$L_7 = 84$	$L_{23} = 91$
$R_8 = 98$	$L_8 = 89$	$L_{24} = 100$
$R_9 = 92$	$L_9 = 94$	$L_{25} = 62$
$R_{10} = 88$	$L_{10} =93$	$L_{26} = 39$
$R_{11} = 135$	$L_{11} = 103$	$L_{27} = 92$
$R_{12} = 114$	$L_{12} = 85$	$L_{28} = 42$
$R_{13} =94$	$L_{13} = 137$	

$R_{14} = 67$	$L_{14} = 135$
$R_{15} = 65$	$L_{15} = 130$
$R_{16} = 85$	$L_{16} = 72$

4.2 Relief & Areal parameters

The relief parameters have been computed for the 12 sub-watersheds (**Table 4**) of the Bhilangana basin. The resulting values are presented in **Table 4.**

Table 4. *Relief and areal parameters for the 12 sub-watersheds and main channel watershed (MCW). Each Class is assigned a specific colour code (similar approach in Biswas et al, 2022a, b).*

Sub watershed	R_h	Hd	HI	D	R_e	R_c	R_f	Bs	A_f
SW 1	0.11	0.36	0.46	0.48	0.69	0.62	0.37	1.64	26.70
SW 2	0.09	0.47	0.44	0.52	0.64	0.44	0.32	2.55	14.44
SW 3	0.11	0.56	0.35	0.51	0.76	0.68	0.46	1.49	6.02
SW 4	0.12	0.47	0.38	0.58	0.68	0.60	0.36	1.62	22.81
SW 5	0.07	1.25	0.30	0.47	0.68	0.48	0.37	1.79	17.17
SW 6	0.05	0.47	0.42	0.51	0.58	0.48	0.26	2.71	3.23
SW 7	0.08	0.55	0.57	0.46	0.73	0.63	0.42	1.67	3.13
SW 8	0.12	0.50	0.45	0.54	0.72	0.60	0.41	1.82	23.85
SW 9	0.16	0.71	0.51	0.60	0.74	0.58	0.43	1.45	21.65
SW 10	0.24	0.88	0.39	0.49	0.86	0.56	0.58	1.29	25.31
SW 11	0.17	1.02	0.57	0.61	0.65	0.37	0.33	1.96	13.84
SW 12	0.15	0.68	0.47	0.55	0.87	0.54	0.59	1.07	17.26
MCW	0.19	1.72	0.39	0.54	0.59	0.6	0.28	2.34	11.2
CLASSIFICATION									
Class 1	0.18-0.24	0.96-1.25	0.48-0.57	0.56-0.61	0.58-0.67	0.37-0.47	0.26-0.37	2.2-2.71	19-26.7

Class 2	0.11-0.17	0.66-0.95	0.39-0.47	0.51-0.55	0.68-0.77	0.48-0.57	0.38-0.48	1.62-2.1	11-18.9
Class 3	0.05-0.10	0.36-0.65	0.3-0.38	0.46-0.50	0.78-0.87	0.58-0.68	0.49-0.59	1.07-1.61	3.12-10.9

4.3. Linear parameters

SI, SL, K_s and ϴ are examined along the main Bhilangana channel and each sub-watershed. The linear parameters are then calculated for each segment. Similarly, the master stream of each sub-watershed is divided into five equal segments to study and compare the values of the linear parameters. However, the Balganga sub-watershed (SW 5) is divided into ten equal segments due to its longer channel compared to the master streams of other sub-watersheds (**Fig. 5, 6**). **Table 5** presents SI, SL and K_{sn} for the Bhilangana master stream.

The SI values for different segments of the Bhilangana river range from 1.04 to 2.03. The SL values exhibit significant variation 92.5 to 2388.75. Similarly, the normalized K_{sn} also demonstrate wide-range: ~ 0.81-136.51.

Table 5. *SI, SL and Ksn for the 20 segments of the Bhilangana master stream.*

Segment	Sinuosity Index (SI, unitless)	Stream length gradient Index (SL unitless)	Normalised steepness Index (K_{sn}, unitless)
1	1.26	300.8	54.6063
2	1.15	1207.35	136.5106
3	1.13	985	70.3962
4	1.06	1785.7	76.1048
5	1.06	1000.8	35.6682

6	1.06	1031.8	22.3844
7	1.04	1332.5	29.3925
8	1.07	1804.5	34.3644
9	1.07	2039.15	35.1472
10	1.08	2730.3	36.3523
11	1.26	1902.6	32.7489
12	1.18	1690.5	23.7146
13	1.11	2388.75	25.6803
14	1.21	1728	16.0777
15	2.03	1596.45	41.0565
16	1.46	1209	20.7661
17	1.18	259.05	6.1545
18	1.07	192.5	1.8601
19	1.09	92.5	0.8057
20	1.09	624	3.6599

The range of θ for the entire Bhilangana stream and its 12 delineated sub-watersheds is -0.295 to 0.401 **(Table 6).**

Table 6. *Concavity index* **(**θ**)** *values of Bhilangana watershed and its 12 sub-watersheds. Maximum and minimum values are in bold and underlined, respectively.*

Subwatershed	MCW	SW 1	SW 2	SW 3	SW 4	SW 5	SW 6	SW 7	SW 8	SW 9	SW 10	SW 11	SW 12
θ	0.36	0.11	0.18	0.31	0.27	0.25	**0.40**	0.38	0.08	**0.006**	0.21	0.29	0.06

The master streams of twelve sub-watersheds shows the SI ranging from 0.98 to 1.63 **(Table 7)**; SL varying from 92.45-1935.85 **(Table 8)**; the K_{sn} ranging 0.0011-195.0939 **(Table 9)**.

Table 7. *SI of sub-watersheds of the Bhilangana basin. Maximum and minimum values are in bold and underlined, respectively.*

Segments of sub-watersheds	1	2	3	4	5
SW 1	1.09	**1.15**	1.11	**1.07**	**1.07**
SW 2	1.12	**1.63**	1.33	1.16	**1.03**
SW 3	1.09	**1.17**	1.09	**1.01**	**1.01**
SW 4	0.98	1.1	1.08	**1.12**	**1.06**
Segments of Sub-watersheds	1	2	3	4	5
SW 5	**1.08**	1.15	1.33	**1.26**	1.12
Segments of Sub-watersheds	6	7	8	9	10
SW 5	**1.46**	1.18	1.52	1.22	**1.11**
SW 6	1.15	**1.16**	1.13	1.12	**1.10**
SW 7	1.38	**1.16**	**1.39**	1.26	1.18
SW 8	1.13	1.17	**1.09**	1.11	**1.28**
SW 9	**1.26**	**1.08**	1.23	1.11	**1.08**
SW 10	1.04	**1.11**	**0.99**	1.04	1.07
SW 11	**1.50**	1.20	1.15	**1.07**	1.09
SW 12	1.11	**1.31**	1.29	**1.10**	**1.10**

Table 8. *SL of sub-watersheds of the Bhilangana basin. In each row, maximum values are in bold and minimum values are underlined.*

Segments of Sub-watersheds	1	2	3	4	5
SW 1	**94.85**	267.00	259.00	**565.25**	518.40
SW 2	**129.55**	273.75	396.50	570.50	**571.50**
SW 3	**210.40**	396	461.25	**500.5**	379.8
SW 4	**148.75**	250.65	335	362.95	**450.9**
Segments of Sub-watersheds	1	2	3	4	5
SW 5	**391.1**	719.85	771.75	1009.75	**1069.2**
Segments of Sub-watersheds	6	7	8	9	10

SW 5	**882.2**	817.7	826.5	837.25	<u>817</u>
SW 8	**116.95**	300.90	479.75	494.90	**687.15**
SW 9	**122.80**	340.20	503.50	918.05	**1113.30**
SW 10	**323.65**	560.40	738.75	827.75	**1012.95**
SW 11	**92.45**	263.40	1281.75	**1935.85**	1083.15
SW 12	**182.90**	329.10	447.25	723.80	**1190.70**

Table 9. *K_{sn} of sub-watersheds of the Bhilangana basin.*

Segments of sub-watersheds	1	2	3	4	5
SW 1	1.0498	0.9779	0.5629	0.9166	0.6834
SW 2	2.6924	2.5110	1.6963	1.8106	1.0401
SW 3	35.9461	28.6242	19.8451	10.1814	6.9586
SW 4	14.0558	10.6772	6.8996	5.1149	3.5465
Segments of sub-watersheds	1	2	3	4	5
SW 5	13.3159	9.1161	7.1208	6.4238	4.4905
Segments of sub-watersheds	6	7	8	9	10
SW 5	6.1207	2.7963	3.2645	2.5385	1.3222
SW 6	88.3504	142.7507	163.9420	195.0939	141.7325
SW 7	121.0899	39.5882	34.6818	26.0200	20.1585
SW 8	0.7067	0.6552	0.5232	0.4310	0.4880
SW 9	0.2212	0.1760	0.1787	0.2084	0.1925

4.4. R^2 curve fitting

Nine out of 12 profiles exhibit the best fit with the exponential eqn 2, while three profiles fit with the linear eqn 1. The power function eqn 4 demonstrates the poorest fit in all cases.

In **Table 10**, the highest R^2 value indicating the best fit is underlined. Additionally, the difference between the highest R^2 value and the R^2-value obtained from the linear equation was calculated and displayed in italics. These differences indicate tectonic activity. Smaller the difference, more intense is the tectonic activity, and vice versa. The sub-watersheds were then ranked based on the obtained differences. A higher rank was assigned to sub-watersheds with smaller differences, as indicated in the last column in **Table 10**.

Table 10. *R^2 curve fitting values and the related analysis for normalized longitudinal profile for the Bhilangana sub-watersheds. Highest R^2 values of each master stream are in bold.*

Sub watershed	Linear R^2	Exponential R^2	Logarithmic R^2	Power R^2	Highest R^2- Linear R^2	Rank
SW 1	0.99	**0.996**	0.824	0.769	*0.006*	3
SW 2	**0.986**	**0.986**	0.827	0.758	*0*	1
SW 3	0.947	**0.984**	0.907	0.848	*0.037*	8
SW 4	0.947	**0.968**	0.905	0.859	*0.021*	6
SW 5	0.912	**0.982**	0.921	0.833	*0.07*	9
SW 6	0.918	**0.949**	0.941	0.88	*0.031*	7
SW 7	0.955	**0.977**	0.885	0.812	*0.22*	10
SW 8	0.989	**0.997**	0.825	0.788	*0.008*	4
SW 9	**0.997**	0.99	0.763	0.721	*0*	1
SW 10	0.964	**0.98**	0.875	0.836	*0.016*	5
SW 11	**0.952**	0.93	0.619	0.589	*0*	1
SW 12	0.987	**0.99**	0.839	0.814	*0.003*	2

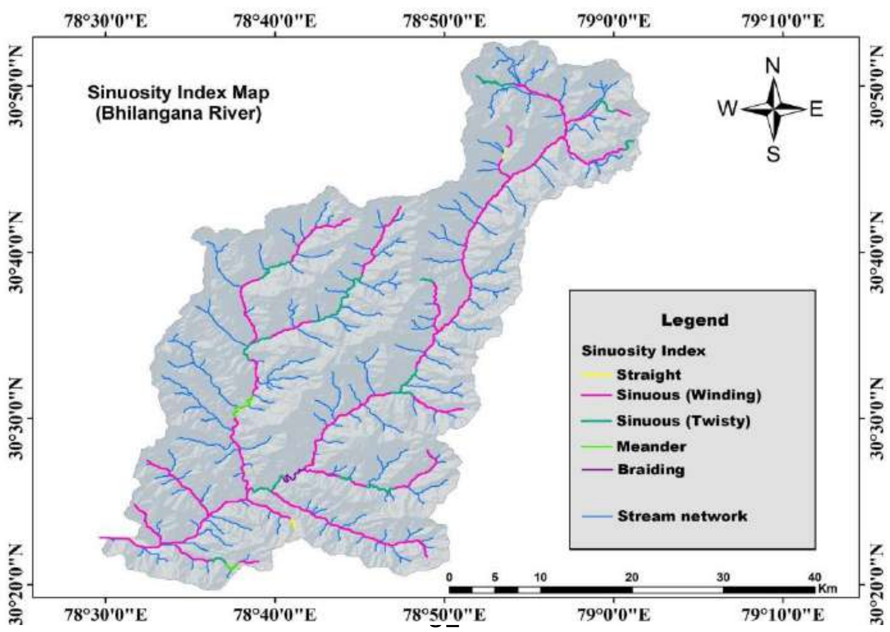


Fig. 5. *Spatial map of SI along the channels.*

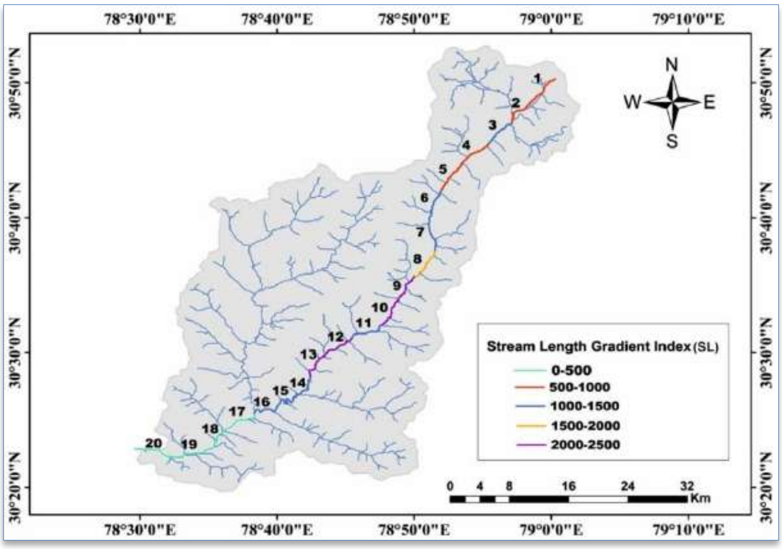


Fig. 6. *Map showing the SL Index Classification for Bhilangana master stream.*

5.1. IAT analysis

Table 11 presents the IAT classification of the 12 sub-watersheds of the Bhilangana River. Three classes of sub-watersheds are also presented **(Fig. 7).**

Table 11. *IAT Classification for the 12 sub-watersheds of the Bhilangana River. The parameter values are color coded based on the assigned Class. The IAT Classification and the corresponding sub-watersheds are labelled to indicate their relative tectonic influence. SW: Sub-watershed, MCW: Main channel watershed.*

Sub watersheds	Rh	Hd	HI	D	R_e	R_c	R_f	Bs	Af	IAT
	Unitless									
SW 1	2	3	2	3	2	3	1	2	1	2.11
SW 2	3	3	2	1	1	1	1	1	2	1.67
SW 3	2	3	3	2	2	3	2	3	3	2.56
SW 4	2	3	3	1	2	3	1	2	1	2.00
SW 5	3	1	3	3	2	2	1	2	2	2.11

SW 6	3	3	2	2	1	2	1	1	3	2.00
SW 7	3	3	1	3	2	3	2	2	3	2.44
SW 8	2	3	2	1	2	3	2	2	1	2.00
SW 9	2	2	1	1	2	3	2	3	1	1.89
SW 10	1	2	2	3	3	2	3	3	1	2.22
SW 11	2	1	1	1	1	1	1	2	2	1.33
SW 12	2	2	2	1	3	2	3	3	2	2.22
MCW	1	1	2	2	1	3	1	1	2	1.7
IAT CLASSIFICATION										
Class 1	1.30 - 1.75	High tectonic activity (2, 11 and MCW)								
Class 2	1.76 - 2.20	Moderate tectonic activity (SW 1, 4-6, 8 and 9)								
Class 3	2.21 - 2.65	Low tectonic activity (SW 3, 7, 10 and 12)								

5.1.3 Spatial representation of IAT Index

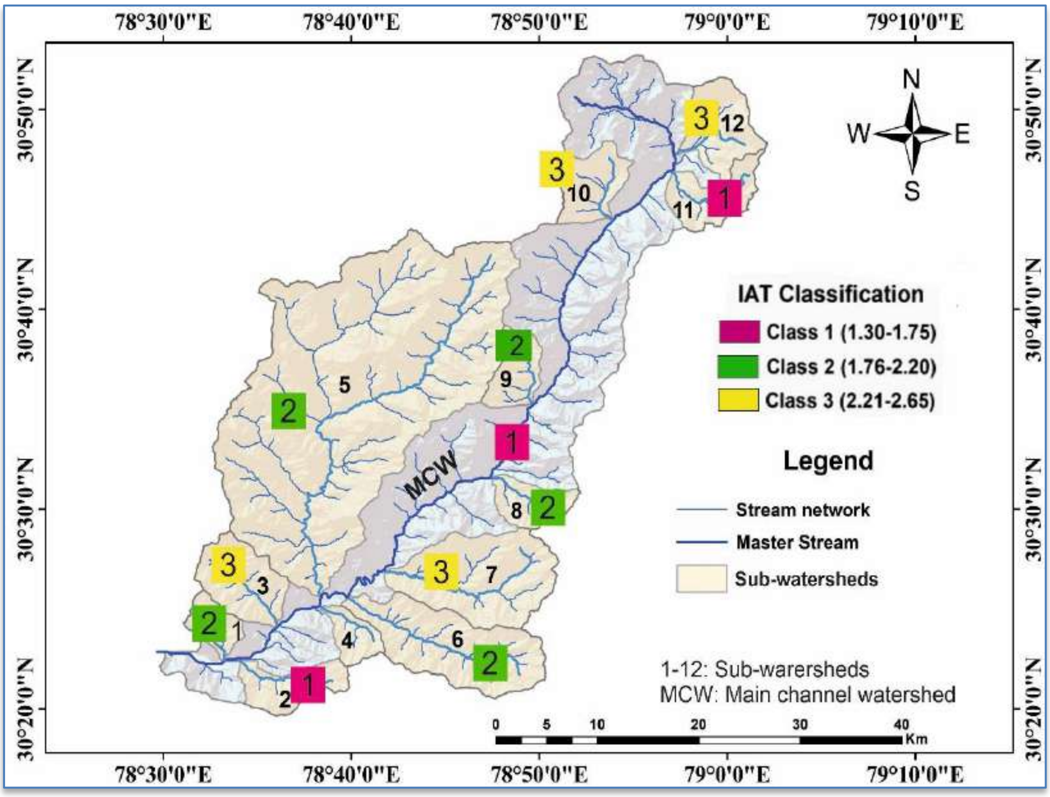


Fig. 7. *IAT classification for the Bhilangana sub-watersheds.*

In the present study, river morphology was identified as per **Table 12**.

Table 12. *Classification of SI. This classification is prepared on the basis of the present data.*

Classification		Range
Straight		≤ 1
Sinuous	Winding	1-1.25
	Twisty	1.25-1.5
Meandering		1.5-2.0
Braided		>2.0

5.3. Dendrogram Analysis

The sub-watersheds highlighted in the red box in **Fig. 8.** exhibit the highest influence of SL, SI and θ, suggesting a substantial number of sub-watersheds to be tectonically active.

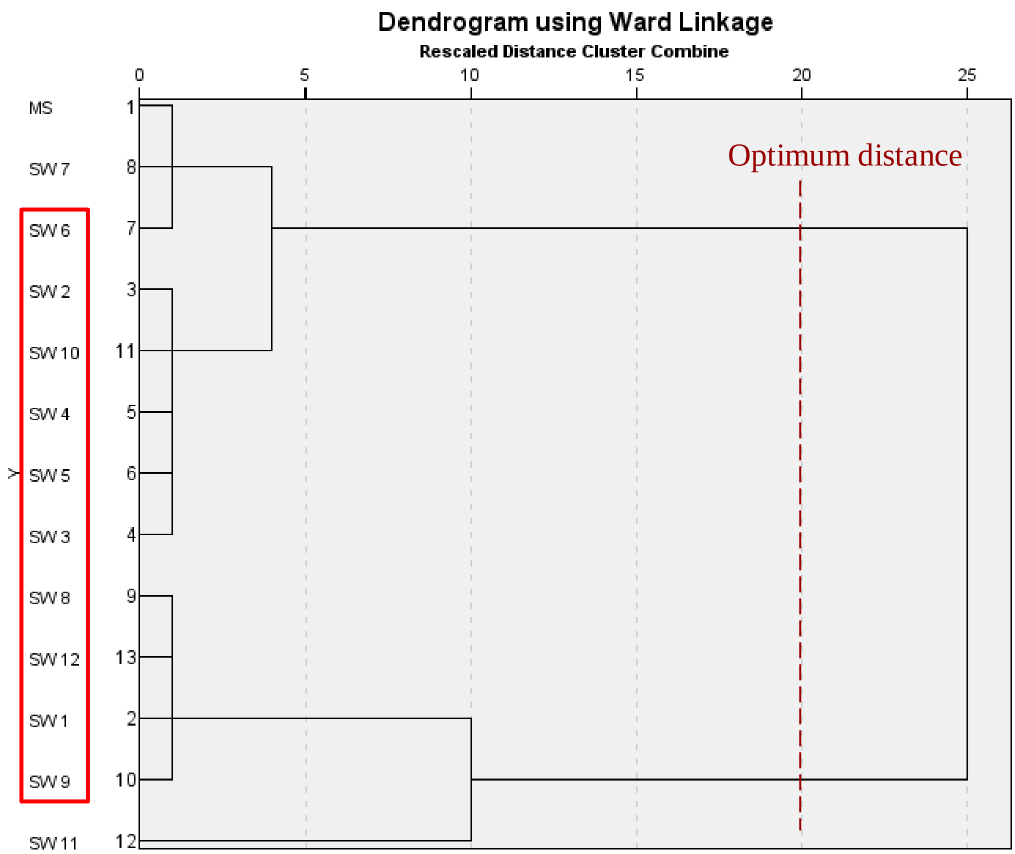


Fig. 8. *Sub-watershed wise dendrogram analysis.*

The segments of sub-watersheds highlighted in the red box (**Fig. 9**) exhibit the highest influence of the combined linear parameters. The spatial map **(Fig. 10)** presents the results of the clustering analysis for better understanding. The analysis reveals that the highlighted segments along the master streams are more susceptible to tectonic activity in watersheds 6-9.

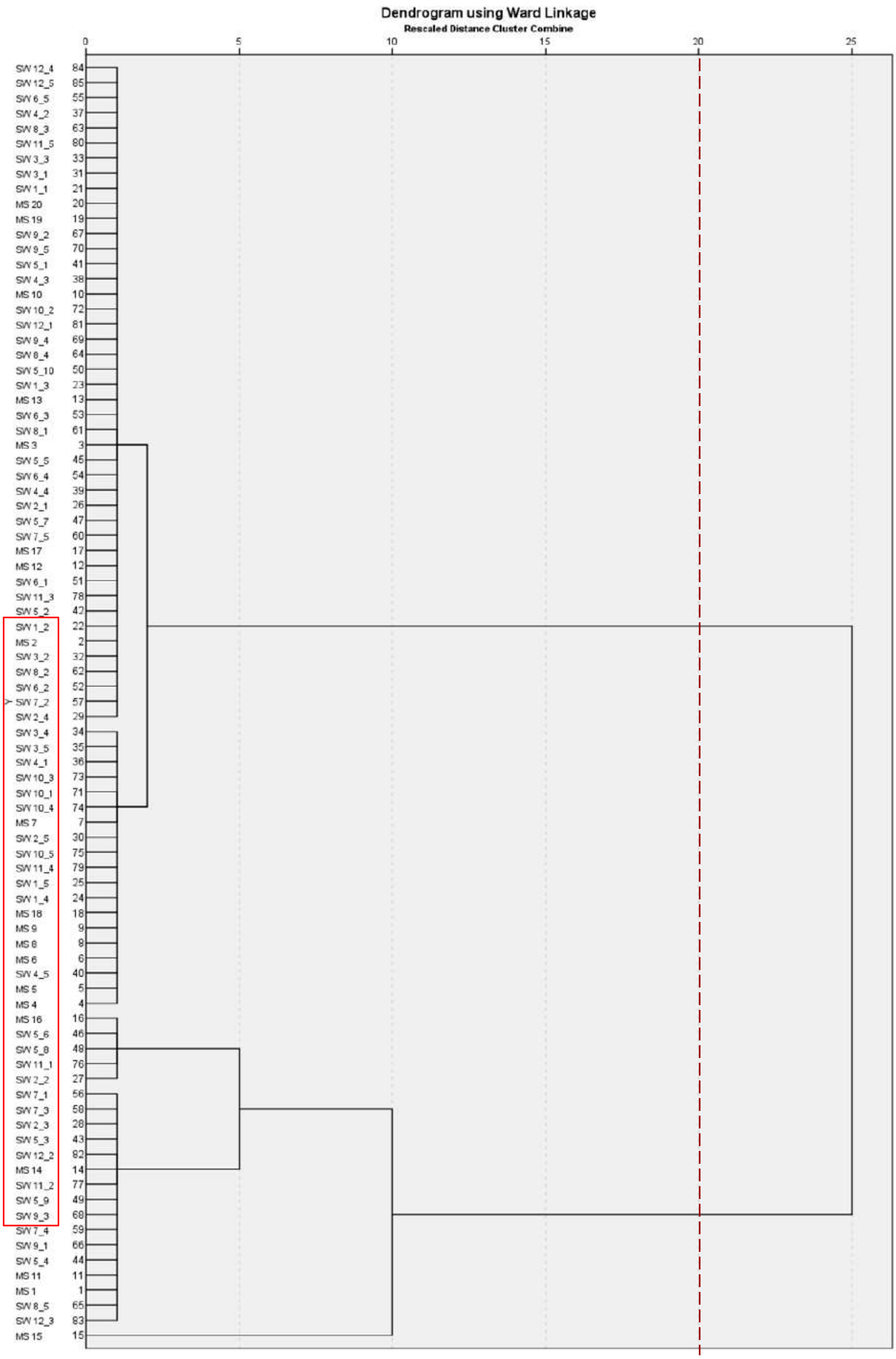


Fig. 9. *Dendrogram showing clustering considering the SI, SL and K_{sn}.*

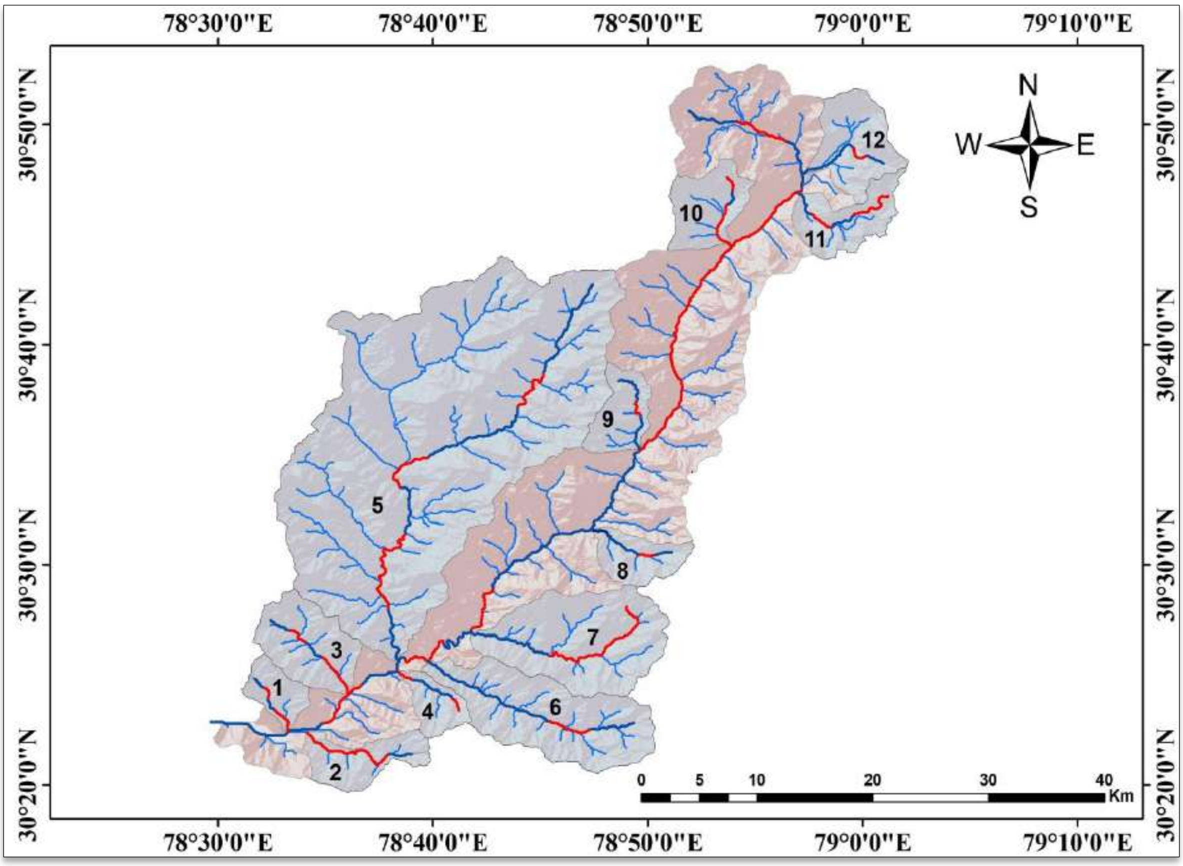


Fig. 10. *Cluster analysis of SI, SL and K_{sn}. The master stream segments in red colour show the regions of maximum tectonic impact of these parameters.*

5.4. Longitudinal profiles

The longitudinal profile of main Bhilangana master stream along with the master streams of the 12 sub-watersheds is prepared **(Fig. 11)**. The longitudinal profiles marked by important values provide a close insight of changes in stream flow pattern along the course of stream. This also helps in analysing specific locations with respect to the local structure and tectonics. The knick points, lithologic contacts, geomorphic and structural lineaments, SI and SL for each segment of master streams of different watersheds are marked along within the long profiles **(Figs. 11-13).**

Fig. 11 shows the longitudinal profile of the Bhilangana master stream. The stream is traversed by many structural and geomorphic lineaments impacting the values of SI and SL index. Three major knick points have been identified. The other one seems to be formed because of tectonic impact as it lies in the close to the Vaikrita Thrust. The SL values for most of the segments are high reflecting a greater slope within smaller length suggesting slope instability in the region. The SI of most of the segments are close to that of straight channel suggesting youth stage of stream development and in some cases the stream follows a tectonic feature. It is interesting to observe that in the seventh segment the SI index value is 1.001 (almost straight channel) and is dissected by three structural lineaments which indicates a tectonically disturbed region. The last three segments show a low SL index as the slope is very gentle and here Bhilangana river impounds the Tehri reservoir.

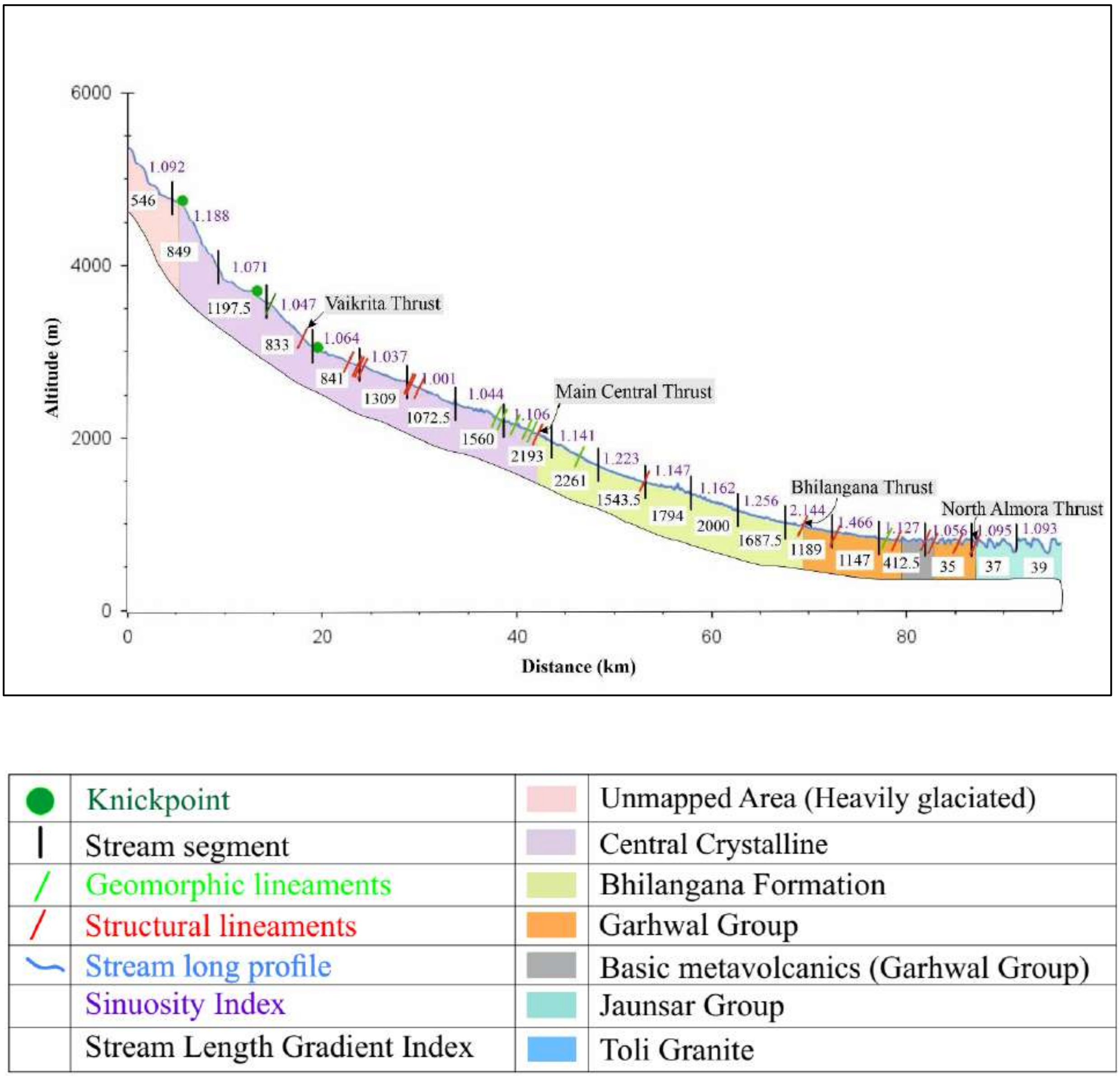


Fig. 11. *Longitudinal profile of Bhilangana master stream along with marked knick points, major thrusts, SI and SL index. Numbers in violet present SI values. Numbers in black represent SL values. Geomorphic and structural lineaments and lithologic contacts.*

The longitudinal profiles of sub-watersheds 1-6 are shown in **Fig. 12**.

In sub-watershed 1, SI = 1.07-1.15 indicate very low sinuosity character indicating tectonic control in the region. The North Almora Thrust (NAT) passes through the region. A knick point is observed close to the NAT. The SL value increases abruptly after the knickpoint downstream till the mouth of the river indicating steeper slope.

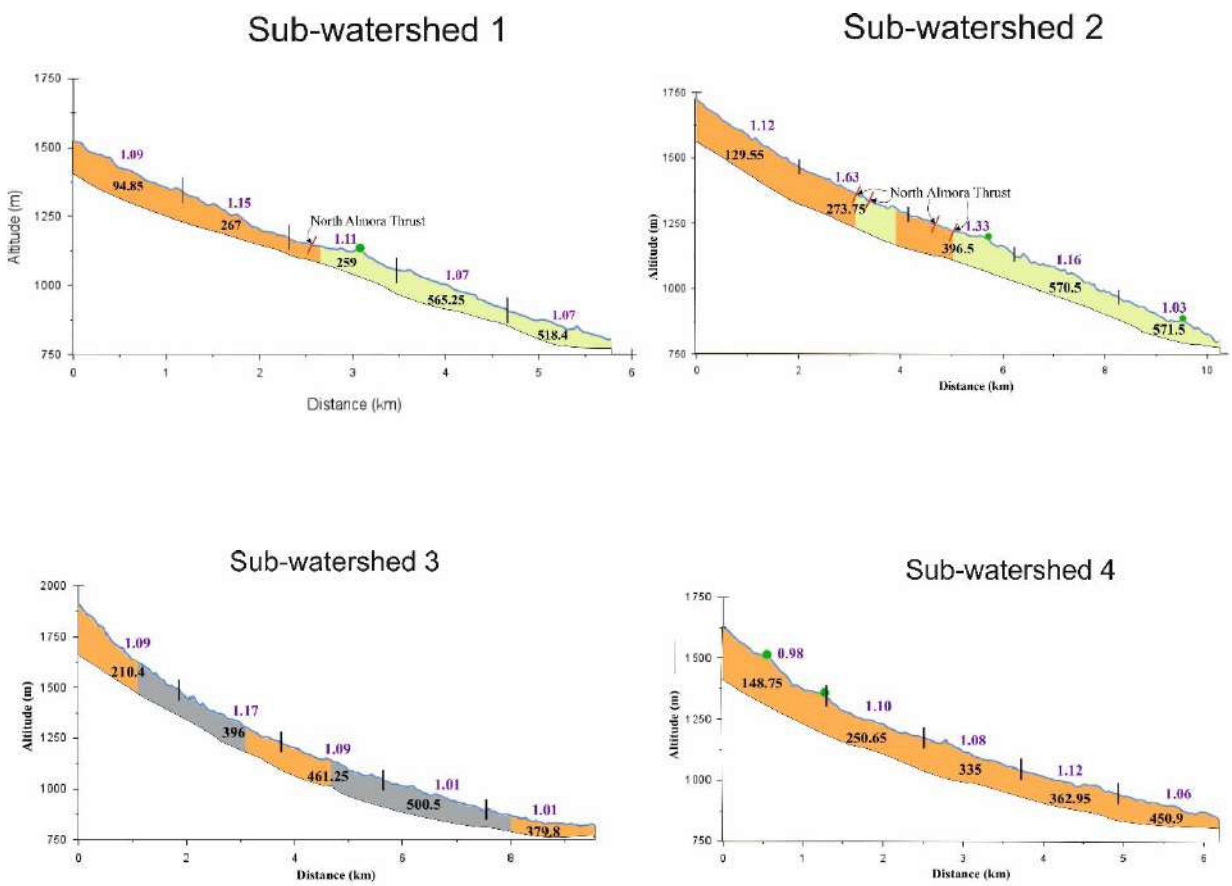
Sub-watershed 2 is traversed by NAT at several locations suggesting a possible strong tectonic influence in the region. The alternating meandering, sinuous to less curved channels also confirm the tectonic influence. The knickpoint position is justified by the presence of NAT. The SL value increases suddenly after the stream passes through NAT suggesting a greater vertical incision and uplift of the region. The sub-watershed has strong tectonic influence, which is also supported by the IAT's Class 1-3 analysis.

The sub-watershed 3 shows a normal concave profile without the presence of any major knickpoints and lineaments. The SI index shows a low sinuous character, which indicates the flow through steeper channels (youth stage of river). The river incision increases downstream as indicated by the increasing SL values. No major tectonic influences are found in the region as confirmed by IAT's Class 1-3 analysis.

In sub-watershed 4, two major knick points are located at the upstream reaches of the stream. In segment 1, SI = 0.98 suggests high tectonic activity. The lithology is uniform along the stream course, which eliminates the possibility of differential erosion by the stream. SL values show a gradual increase downstream after the knickpoint.

Sub-watershed 5 is marked by the presence of major thrust- the MCT. The knickpoint in segment 2 seems to be formed due to tectonic uplift as there is a local fault present in the close vicinity **(Fig. 3)**. After that, the SL increases greatly. The non-uniform stream course from low sinuous to high sinuous to meandering, then again sinuous pattern also indicates a tectonic influence. The IAT's Class 1-3 analysis also shows the tectonic influence in the region.

Sub-watershed 6 shows a knickpoint upstream near the source of the stream, which is marked by a high SL value and a low sinuous character as per the SI values. indicating upliftment in the region. The stream shows an overall moderate SL value and low sinuous character.



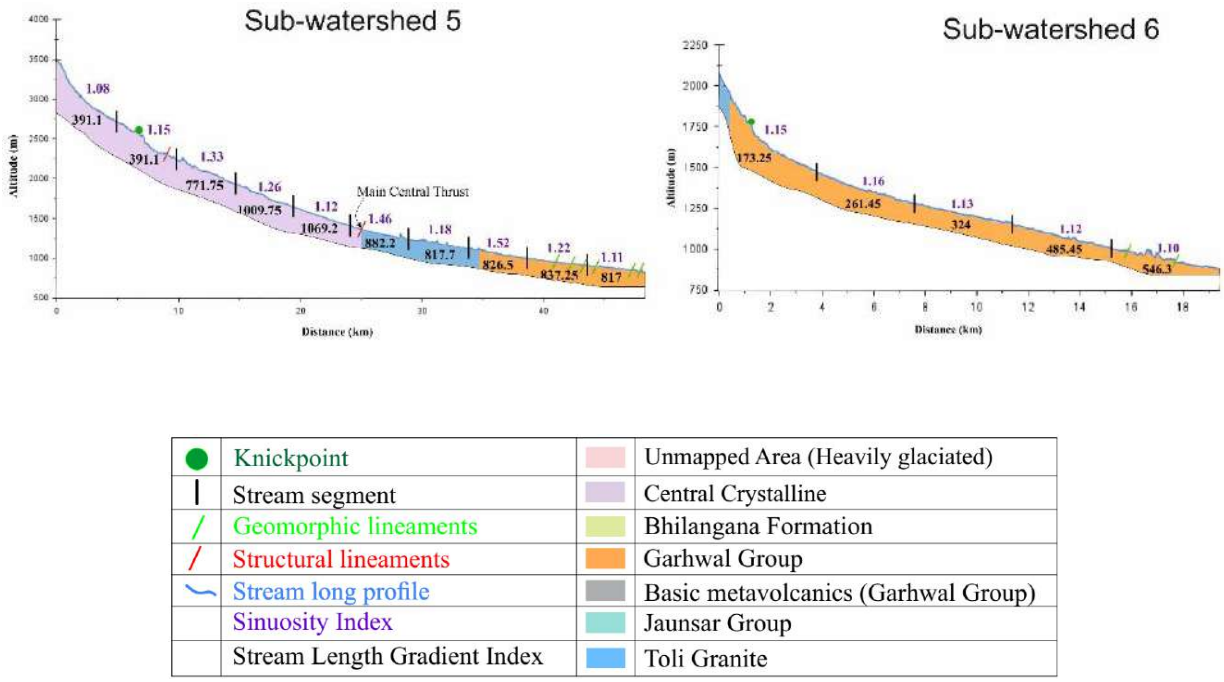


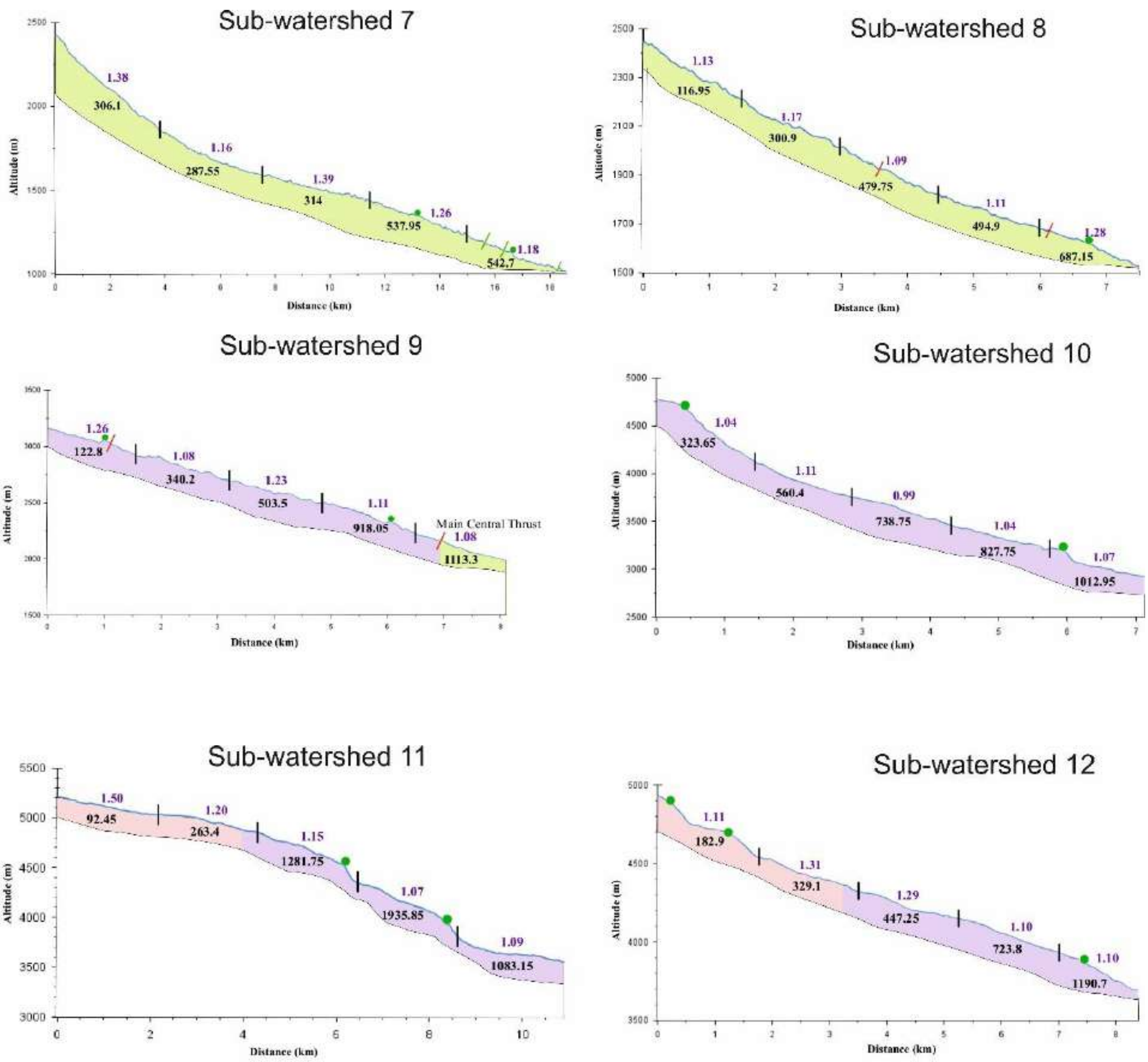
Fig. 12. *Longitudinal profile of sub-watersheds 1-6. The long profile is marked with lithologic contacts, geomorphic lineaments, structural lineaments, knick point, SI and SL value for each segment and major thrusts passing through the streams.*

The sub-watershed 7 shows a concave profile along the consecutive three segments with θ = 0.382 indicating a normal stream course. The knickpoints in segment 2 in sub-watershed 7 and segment 1 in sub-watershed 8 are not tectonically active. The SL index of segment 2 (SL = 391.1) and segment 1 ((SL = 343.29) show relatively lower values than the other sub-watersheds. The IAT's Class 1-3 analysis also confirm the basin to be least active tectonically at present.

The sub-watershed 8 shows an almost straight channel profile. The stream channel shows low SI = 1.10-1.16 for most of the course. The knickpoint in the last stream segment along with increased SL index and presence of fault suggest some tectonic influence downstream. The IAT's Class 1-3 analysis shows that the sub-watershed has moderate tectonic influence.

In sub-watershed 9 the stream profile shows a very low θ = 0.00686. The knickpoints are closely associated with the presence of faults. The major thrust fault, MCT, passes through the stream channel resulting in increased SL index suggesting upliftment. The stream shows low sinuosity character. Overall there is a tectonic imprint upon the region, which reflects the study of stream characteristics. Sub-watershed 10 shows a concave profile between two knick points.

In sub-watershed 11, a convex channel profile is observed with the glacier related geomorphic characteristics. The areal parameter study shows the complex elongated shape of the basin.



●	Knickpoint		Unmapped Area (Heavily glaciated)
|	Stream segment		Central Crystalline
/	Geomorphic lineaments		Bhilangana Formation
/	Structural lineaments		Garhwal Group
~	Stream long profile		Basic metavolcanics (Garhwal Group)
	Sinuosity Index		Jaunsar Group
	Stream Length Gradient Index		Toli Granite

Fig. 13. *Longitudinal profiles of sub-watersheds 7-12. The long profile is marked with lithologic contacts, geomorphic lineaments, structural lineaments, knick point, SI and SL value for each segment and major thrusts passing through the streams.*

5.5. R^2 curve fitting of normalised long profile

The R^2 curve analysis results are presented in **Table 10**. The sub-watersheds are ranked based on the difference in R^2 values between the highest-fit curve and the linear fit. Sub-watersheds (1, 9 and 11) with a linear fit are considered to be more tectonically active as they exhibit a straight channel profile. Most of the longitudinal profiles in the Bhilangana basin fit with exponential best-ft curves, indicating low concavities

The sub-watersheds are ranked from 1 to 10 based on their tectonic activity, with those ranked 1 having the greatest impact and ranked 10 having the least impact. Sub-watersheds 2, 9 and 11 are ranked 1, indicating the highest tectonic influence, which aligns well with the results of the IAT's Class 1-3 analysis.

For sub-watershed 12, the results are however contrasting. While the IAT's Class 1-3 analysis places it under the category of least tectonic influence, it belongs to rank 2 based on the R^2 curve fitting.

The correlation between the IAT's Class 1-3 analysis and curve fitting is quite good for sub-watersheds 2, 3, 4, 6, 7, 8, 9 and 11. However, for sub-watersheds 5 and 10, the correlations are not strong. Results from both analyses may not always align perfectly, as the IAT's Class 1-3 analysis considers relief and areal parameters, while curve fittings work on the linear parameters (e.g., Mandal et al. 2023). A strong correlation between the two indicates a more prominent impact of tectonic activity in the region, while a weaker correlation, as seen in sub-watersheds 5 and 10, suggests that one morphometric parameter (relief, areal or linear) is influencing the watershed more than the other. Considering relief, areal and linear parameters all together, sub-watersheds 2,8 and 9 show higher impact of tectonics. Reactivation of NAT leading to recent geomorphologic developments have been reported **(Kothyari et al., 2020).**

6. Discussions

It will be interesting to compare whether *(i)* tectonically active sub-watersheds are crossed by faults, and whether *(ii)* tectonically active sub-basins are necessarily landslide prone. Watershed 2 falls in Class 2. The region along the main channel comes under Class 1. Watershed 5 (through which MCT passes and comes under Class 2) and the main channel watershed are tectonically active as well as landslide prone. VT passes through watershed 11 and NAT through watershed 2. These two watersheds are tectonically active and come under Class 1. Watershed 7, 10 and 12 under Class 3 are not active tectonically and also (almost) not landslide prone. However, the positive correlation between the presence of faults and tectonic activity or landslides of regions does not always hold true. For example, watershed 3 under Class 3 is tectonically less active yet shows landslides. Also, Bhilangana Thrust passes through sub-watersheds 6 (Class 2) and sub-watershed 7 (Class 3), but these sub-watersheds are tectonically not very active. Therefore, mere present of faults in the study area do not guarantee that the specific terrain is tectonically active. Along the trend of the same fault, there can be significant variation in activation (e.g., **Berryman and Beanland 1991)**. Sustainable development programme of any region in the world therefore must involve morphometric studies after the active faults have been mapped.

7. Conclusions

The morphotectonic analysis of Bhilangana river basin reveals that the region is tectonically active. Detailed analysis of twelve delineated sub-watersheds of the basin on the basis of morphometric parameters; longitudinal profile; curve fitting and clustering suggests the followings:

1. Sub-watersheds 2, 8 and 9 are relatively more active tectonically.
2. Sub-watersheds 3 and 7 are relatively least tectonically active.
3. Sub-watersheds 11 and 12 interpretations are influenced as they lie in heavily glaciated regions with significant erosion.

No unequivocal correlation was found between the presence of faults in sub-watersheds and their recent tectonic activity. Active fault mapping programmes therefore must involve subsequent morphometric studies in different terrains globally.

Acknowledgements: This work was done as a M.Tech. thesis of SB under SM. SB acknowledge MB for morphometric study. *No funding was received for this work.* **Chief Editor + Associate Editor + Reviewers + Proofreaders + Publisher.**

Appendix

In the Himalaya, the Siwalik rocks are delimited by the Himalayan Frontal Thrust by the Main Boundary Thrust (MBT) at north. North to the MBT is the Lesser Himalaya (LH; e Proterozoic phyllites, slates, lower-grade schists and gneisses). The North Almora Thrust, also recognized as the Tons Thrust, Berinag-Tons Thrust and the Srinagar Thrust, is a prominent geologic discontinuity within the LH that separates the LH at north and the LH at south. The northern limit of the LH is the Main Central Thrust (MCT), or the MCT-Lower (MCT_L). The Vaikrita Thrust (VT) is the northernmost strand of the MCT, and is also designated as the MCT-upper (MCT_U). VT has been considered as an out-of-sequence Thrust since it activated ~ 2.5 Ma. North of the MCT is the Central Crystallines or the Greater Himalayan Sequence (GHC; gneisses and higher-grade schists) **(Appendix Table 1).** The zone in between MCT_U and MCT_L is in fact a melange of LH and GHC with a mixed geochemical signal. Within the entire Himalayan orogen. top-to-S/SW shear in the MBT took place between 9-11 Ma back, MCT_L sheared in the same sense from 15 to 0.7 Ma and in the MCT_U from 25 to 14 Ma (compiled from Mukherjee 2015; Martin 2017; Bose and Mukherjee 2019).

Appendix Table 1. *Lithology of the major formations in the study area along with major faults description. (from Valdiya, 2016; GSI Misc.Pub.,2002; 2019).*

AGE	FORMATION	LITHOLOGY
Neo-Proterozoic	Jaunsar Group	Mandhali Formation: Shale, quartzite, limestone, dolomite, conglomerate Chandpur Formation: Phyllites, quartzite, shale, dolomite, tuff with dolerite Nagthat Formation: Quartzite (white, fawn, pink, purple) interbedded with shale, phyllite, conglomerate
North Almora Thrust (NAT)	Marks southern boundary of Garhwal Group, WNW to ESE trend, southerly dipping out-of-sequence thrust	
Meso-Proterozoic	Garhwal Group	Predominantly quartzites and metabasics with phyllite and chlorite schist intercalations

Meso-Proterozoic Proterozoic	Toli Granite Bhilangana Formation	Non-foliated granite with porphyritic texture Biotite gneiss, quartzite schist/gneiss, amphibolite; considered as a tectonic window near Ghuttu village
Main Central Thrust (MCT)	Brought high-grade metamorphic rocks over Lesser Himalayan low-grade metamorphics; bounded in the north by Vaikrita Thrust and Munsiyari Thrust in the south	
Proterozoic	Central Crystalline	Sheared granitic gneisses, porphyritic gneisses, talc schist, mica schist, mylonites, quartzo-feldspathic schist; collectively known as 'Central Himalayan Crystallines', the oldest rocks exposed in Higher Himalaya

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