REVIEW PAPER

Analysis of tectonic deformation on channel morphology through quantitative geomorphic indices and DEM derived drainage system

Ankita Sharma[1] · Dhirendra Singh Bagri[1]

Abstract

Drainage basin dynamics of any river is controlled by geomorphic attributes which include both surface and subsurface characteristics of a watershed. These characteristics comprise erosional and deformational processes affecting the hydrological and morphological conditions of the watershed. Similarly, the tectonic setup of the watershed influences the terrain topography and geomorphology as well. The paper deals with the evaluation of DEM-derived parameters related to morphometry and tectonic setup in the Asan watershed, Doon Valley, Uttarakhand. The assessment of active tectonics in the study area is based on the parameters related to the morphometry and morphotectonic characters of the watershed. These terrain attributes are determined using Cartosat-1 DEM (10 m) using GIS to investigate the structural setting. The parametric evaluation concerning morphometric analysis helps to understand their significance in watershed prioritization and management while the tectonic analysis helps to determine the structural setup and identifying the hazard-prone area, if persists, in the watershed. The study area falls downhill of tectonically active Lesser Himalaya and Siwaliks, make it an ideal location to determine the degree of relative tectonic activity in the area. The average of measured attributes is used to evaluate the combined classification of the Relative Active Tectonic Index (R_i). The outcome reveals that the watershed is tectonically active that experienced a differential rate of tectonism and have a consistence relationship between structural disturbances and basin geometry.

Keywords Morphometry · Geomorphic indices · Watershed · DEM · GIS · Relative active tectonic index

Introduction

The active Himalayan mountain chain is subjected to various deformational processes because of tectonic uplift, weathering and denudational processes (Valdiya 2003; Perez-Pena et al. 2010). The geomorphological setup of a particular watershed is strongly affected by the deformational processes occurring within them. It is strongly dependent upon the tectonic activities occurring into it, which influences the drainage system, terrain topography and landscape development. Tectonic geomorphology describes the formation of geomorphic features which is the results of the relationship between the tectonic and surficial processes (Burbank and Anderson 2001). In controlling river behaviour and the development of drainage network, tectonism plays a significant part (Holbrook and Schumm 1999; Sinha-Roy 2001; Valdiya and Narayana 2007). This can be described both qualitatively and quantitatively (Hare and Gardner 1985; Keller and Pinter 2002). The drainage network in active regions is susceptible to tectonic features viz., faults, folding and tilting. River and streams are the significant landforms that are very sensitive to tectonic movement as these affected by incision, diversion and asymmetry in a tectonic environment (Cox 1994). Watersheds behave as the fundamental unit of the fluvial landforms and act as an ideal entity to understand the tectonic activity in the area (Strahler 1964). Geomorphological quantitative studies of the basin relate with the study of morphometric and morphotectonic attributes of tectonic geomorphology. The geomorphic feature gives quantitative information about the tectonic processes

✉ Ankita Sharma
  ankita.geors@gmail.com

  Dhirendra Singh Bagri
  bagri.ds@gmail.com

[1] Hemvati Nandan Bahuguna Garhwal University/IIRS-ISRO, Dehradun, India

that occur in the region, its history, rate and magnitude. In terms of landscape evaluation and tectonics in concern, the use of Remote Sensing (RS)/Geographic Information System (GIS) are extensively used by several authors (Ramírez-Herrera 1998; Keller et al. 1996; Molin et al. 2004; Perez-Pena et al. 2010) and it is proved to be a significant tool in the generation of updated and precise information for characterization of drainage basin parameters (Singh et al. 2014). These parameters are further validated using field visit, toposheets, aerial photograph and satellite images.

The purpose of this paper is to evaluate the parameters related to surface hydrology and topography concerning structural imbalance which is a significant scientific aid for water resources management. The morphological characteristics and associated structural impact are analysed in the 12 delineated sub-watershed of the Asan River. The stretch of the Asan watershed comprises of some major structural features like Main Boundary Thrust, Santaugarh thrust, Mahajaun thrust, Bhauwala thrust and Nun River fault falls in the northern portion while Tons fault and Asan fault lies in the central portion of the watershed. In the present work, 16 morphometric parameters and 5 geomorphic indices are evaluated which is individually based on the analysis of the drainage network. These parameters incorporated to determine the Relative Active Tectonic Index which corresponds to the presence of relative tectonism in the watershed. This similar methodology is adopted through various researchers (Hamdouni et al. 2008; Mahmood and Gloaguen 2012; Shukla et al. 2013; Anand and Pradhan 2019) for their different areas of interest. This integrated approach may prove significant in the conservation of resources in a sustainable manner.

Study area

The Asan watershed is situated in latitude 30° 14′ 14″ N to 30° 29′ 54″ N and longitude 77° 39′ 42″ E to 78° 05′ 30″ E, Dehradun district, Uttarakhand State, India. Asan River is the tributary of Yamuna River flowing northwest of Doon valley. The Asan River is originated from Chandrbani (spring water) in Dehradun city and joining Yamuna River at Dhalipur and forms one of the prominent watersheds i.e. Asan watershed in Doon Valley at foothills of Siwalik ranges. It is flowing through the central portion of the area from northeast to southwest direction. The location map of the watershed is given in Fig. 1. It covers an area of 712.34 km^2 (Table 7). The length and width of the Asan watershed is approximately 40 km and 18 km respectively. The physiographical feature of the watershed is the sharp rise in the height of the Lesser Himalayan range, locally known as the Mussoorie hill in the north (2188 m above Mean Sea Level) and Siwaliks in the south. The outlet of

the watershed along the mainstream in the western direction of the watershed is having a minimum elevation of 345 m above Mean Sea Level. The annual average rainfall over the watershed ranges from 1274 to 1766.7 mm (Sharma et al. 2020). The maximum portion of rainfall in the watershed is drained eastwards by the Song-Suswa river system and joined by streams such as Bindal, Rispana, Jakhan etc. and westwards by the Tons, Suarna, Sitala etc. Small seasonal streams emerging from the Siwalik Hills are dry during most of the year.

Geological and structural setting

Geologically, the Asan watershed forms an asymmetrical synclinal valley. Asan River flows along the axis of a synclinal valley. The physiographic units of the watershed are striking in NW-SE to ENE-WSW. The length and width of the Asan watershed is approximately 40 km and 18 km respectively. On the north, the valley floor is bounded by Main Boundary Thrust with Lesser Himalaya and in the south, it is bounded by Mohand Thrust with Lower Siwaliks. The Majhaun Thrust (Thakur et al. 2007) activated during the initial stage of the Bhauwala Thrust. Thakur and Pandey 2004, described Asan Fault as out-of-sequence thrusts (OOST) as they displaced the Asan River. The Santaurgarh thrust (Raiverman et al. 1983; Sinha and Sinha 2016) the Bhauwala thrust (Singh 1998), the Asan and Tons Faults (Thakur and Pandey 2004) are the other structural features present on the watershed shown in Fig. 2. The Asan, Majahaun Faults and Bhauwala, Santaugarh Thrusts have approximately followed the E-W trend. Several large fans descend from the foothills of the Mussoorie hills were mapped by Nossin (1971). Moreover, the entire watershed is covered by a system of springs (Jasrotia et al. 2013). The northern and southern part of the watershed is characterized by rough mountainous terrain having rocks predominantly of sedimentary and metamorphic origin.

Data and methodology

In tectonic geomorphology, Digital Elevation Model (DEM) is used for better analysis of topographic parameter and database generation. Significant information about the characteristics of the rock formation, their storage capacity and yield of the watershed has been extracted from quantitative analysis of morphometric parameters (Singh et al. 2012). HEC-GeoHMS extension in ArcGIS v. 10.3 software was used to delineate the watershed and extraction of drainage channels. Details of the data used in the present study are shown in Table 1. Thereafter, parametric formulas and related methodologies are shown in Tables 2 and 3.
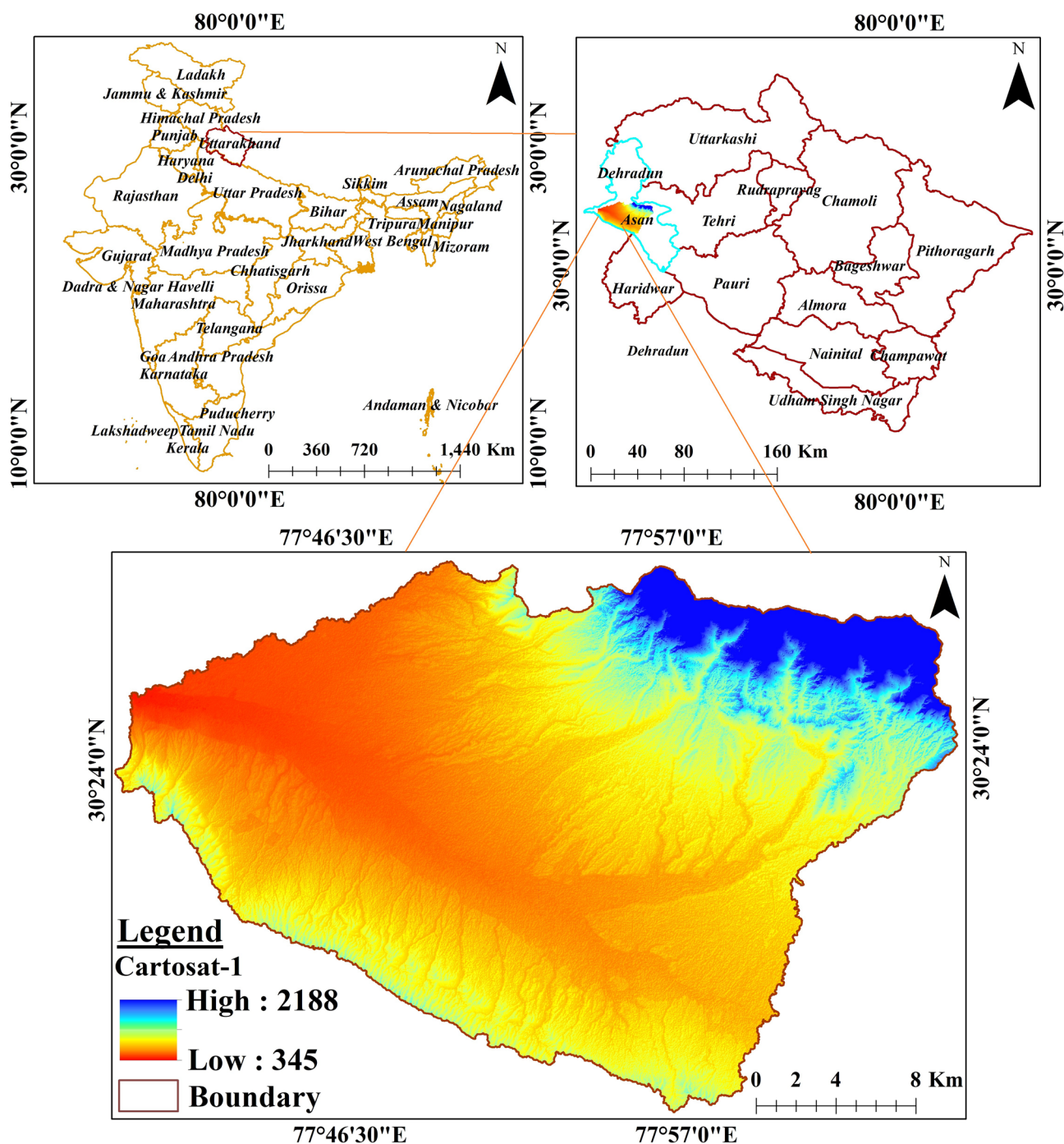
Fig. 1 Location map of the study area and the DEM used

The following procedure is followed to carry out the work:

(a) The SOI toposheets are geometrically rectified and geo-referenced by taking ground control points (GCPs) by using UTM projection and WGS 84 datum. Further, all four geocoded toposheets are mosaic using ERDAS Imagine 9.1 image processing software.

(b) The contributing streams of the watershed generated through the following geoprocessing techniques of watershed delineation: Cartosat-1 DEM (10 m) > Filled
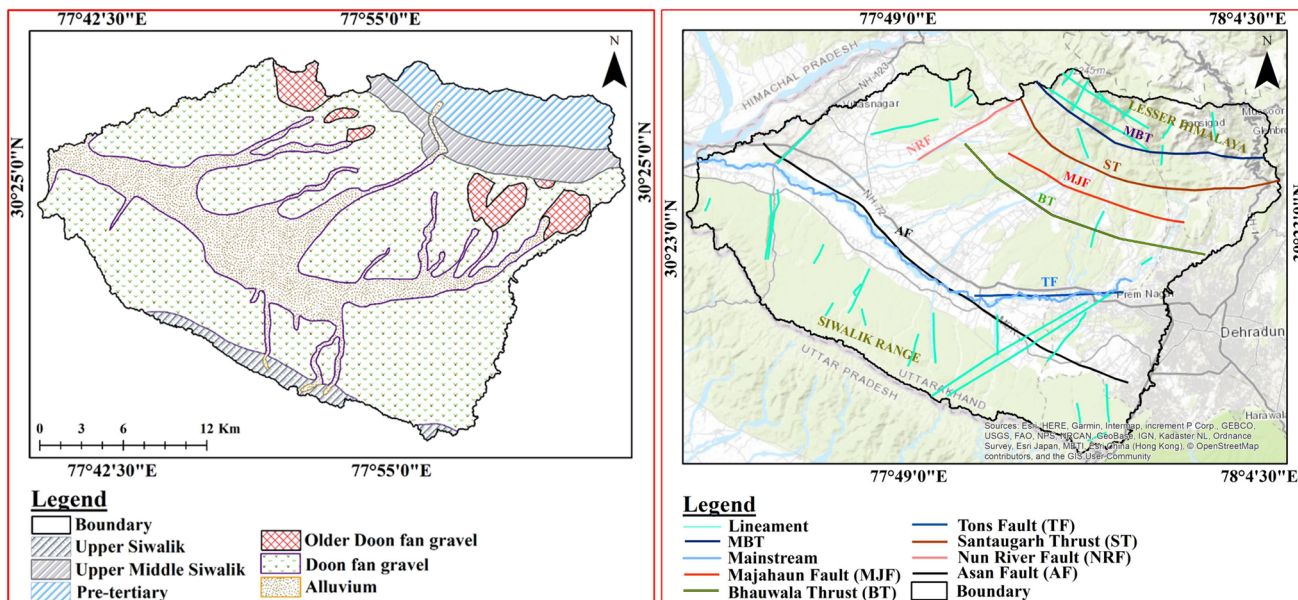
Fig. 2 Geological and Structural map of the Asan watershed (Sinha et al. 2013)

Table 1 Detailed data information about the present work

Type of data/software	Details of data	Sources
Toposheet	53F/11, 53F/15, 53F/16 and 53 J/3 on scale (RF)- 1:50,000	Survey of India (SOI), Dehradun, India
Cartosat-DEM	Spatial Resolution-10 m	National Remote Sensing Centre (NRSC), India

DEM > Flow Direction > Flow accumulation > Stream network generation > Watershed extraction.

(c) The systematic description of quantitative morphometric parameters of stream network is evaluated using the standard mathematical equation given by Smith (1939), Strahler (1952, 1964 and 1968), Horton (1945), Schumm (1956). The parameters include Stream order (S_u), Stream length (L_u), Stream Number (N_u), Bifurcation ratio (R_b), Mean Bifurcation Ratio (R_{bm}), Area (A) Perimeter (P), Basin length (L_b), Drainage density (D_d), Stream frequency (F_s), Drainage texture (D_t), Length of overland flow (L_g), Elongation ratio (R_e), Basin relief (H), Relief ratio (R_h), Ruggedness number (R_n) are mentioned in Table 2.

(d) Geomorphic indices used here known to be useful in calculating active tectonic studies are adopted from Mueller (1968), Hack (1973), Bull and McFadden (1977) Cox (1994), Bull (2007) This methodology has been previously tested as a valuable tool by Cuong and Zuchiewicz (2001), Hamdouni et al. (2008), Perez-Pena et al. (2010), Mahmood and Gloaguen (2012), Sarma et al. (2015).Parameters like Drainage basin asymmetry (A_f), Hypsometric Integral (H_i), Basin shape index (B_s), Valley floor width to height ratio (V_f), Stream length gradient index (S_L-index)are calculated using mathematic equations given in Table 3.

(e) The numerical values determined for each parameter are categorized into three different classes as Classes 1 to 3. Class 1 (higher class) represent high tectonic activity in the area. The level of tectonism lowers as the subsequent class increases with Class 3 represent the lowest (Table 4).

Results and discussions

The present work is based on the parametric estimation related to morphometry and morphotectonics which are useful in determining the significant information regarding the surficial characteristics, presence of geological structures, differential uplift, erosional control and tectonism and its effect on the channel morphology of the watershed. The calculated values of these parameters are further utilized in assessing the characteristics of a stream network and the structural setup of the area. Furthermore, all the parameters

Table 2 Methodology adopted for morphometric parameters in the Asan watershed

No.	Morphometric Parameters	Formula	References	Explanation	References
1	Stream Order (S_u)	Hierarchical rank of tributaries	Strahler (1952)	–	–
2	Number of Stream of each order (N_u)	Total number of streams of a given order within each watershed boundary	Strahler (1952)	–	–
3	Stream Length (L_u)	Total Length of the streams	Horton (1945)	–	–
4	Bifurcation ratio (R_b)	$R_b = N_u / N_u + 1$ N_u = Total number of stream segments of order 'S_u' N_u+1 = Number of stream segment of next higher order	Schumm (1956)	**≥ 4:** Higher 'R_b'/younger stage **3.5–4:** Moderate 'R_b'/ mature stage **≤ 3.5:** Lower 'R_b'/ older stage	Shukla et al. (2013)
5	Mean Bifurcation Ratio (R_{bm})	Average of bifurcation ratio of all orders	Strahler (1964)	**< 3:** Flat region **3–5:** Least effect of geological structure on the drainage pattern **> 5:** Structurally controlled	Iron (1985)
6	Perimeter (P)	GIS software analysis	Schumm (1956)	–	–
7	Basin Length (L_b)	The longest dimension of the basin	Schumm (1956)	–	–
8	Area (A)	GIS software analysis	Schumm (1956)	–	–
9	Drainage density (D_d)	$D_d = \Sigma L_u/A$ L_u = Total stream length of all orders A = Area	Horton (1932, 1945)	**0–1:** Low **1–2:** Moderate **2–3:** Moderately high **3–4:** High **4–5:** Very high	Adopted class range
10	Stream frequency (F_s)	$F_s = \Sigma N_u/A$ N_u = Total number of stream of all orders A = Area of watershed	Horton (1932, 1945)	**0–1:** Low **1–2:** Moderate **2–3:** Moderately high **3–4:** High **4–5:** Very high	Adopted class range
11	Drainage texture (D_t)	$D_t = \Sigma N_u/P$ N_u = Total number of stream of all orders P = Perimeter	Smith (1939)	**< 2:** Very Coarse **2–4:** Coarse **4–6:** Moderate **6–8:** Fine **> 8:** Very Fine	Smith (1939)
12	Length of overland flow (L_g)	$L_g = 1/D_d*2$ D_d = Drainage density	Horton (1945)	**< 0.2:** Low flow path **0.2–0.3:** Moderate flow path **> 0.3:** High flow path	Chandrashekar et al. (2015)
13	Elongation Ratio (R_e)	$R_e = 2(\sqrt{A/\pi})/L_b$ A = Area of watershed L_b = Basin length π = 3.14	Schumm (1956)	**< 0.7:** Elongated **0.7–0.8:** Less elongated **0.8–0.9:** Oval **0.9–1.0:** Circular	Schumm (1956)
14	Relief (H)	$H = Z-z$ Z = Maximum Height of the basin z = Height of Basin Mouth	Strahler (1952)	–	–
15	Relief ratio/watershed slope (R_h)	$R_h = H/L_b$ H = Basin Relief L_b = Basin Length	Schumm (1956)	**≥ 0.29:** Steep **0.28–0.17:** Moderate **< 0.17:** Gentle	Anand and Pradhan (2019)

Table 2 (continued)

No.	Morphometric Parameters	Formula	References	Explanation	References
16	Ruggedness number (R_n)	$R_n = D_d*(H/1000)$ H=Basin Relief D_d=Drainage Density	Strahler (1968)	**< 1:** Low **1–2:** Moderately low **2–3:** Moderate **3–4:** Moderately high **> 4:** High	Mayomi et al. (2018)

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Table 3 Methodology adopted for geomorphic indices in the Asan watershed

No.	Parameter	Formula	Explanation	References
1	Drainage Basin Asymmetry (A_f)	$A_f = 100(A_r/A_t)$ A_r=Area of the right (facing downstream) of the mainstream A_t=Area of the watershed	$A_f = 50$: Stable environmental setting $A_f < 50$: Tilting Suggested	Molin et al. (2004)
2	Hypsometric integral (H_i)	$H_i = (E_{mean}-E_{min})/(E_{max}-E_{min})$ E_{mean}=Mean elevation value E_{max}= Maximum elevation value E_{min}= Minimum elevation value (outlet)	$H_i \leq 0.3$; Indicates old stage, it means watershed is fully stabilized, $0.3 \leq H_i \leq 0.6$; Indicates watershed is susceptible to erosion $H_i \geq 0.6$; In equilibrium or young stage indicates watershed is highly susceptible to erosion	Strahler (1952)
3	Basin shape index (B_s)	$B_s = L_b/W_b$ L_b= Length of a watershed measured from the headwaters to the mouth, W_b= Width of the watershed at its widest point	$B_s = 1.7$–3.22: Elongated basin $B_s = 1.21$–1.76: Semi-elongated basin $B_s = 1.11$–1.20: Circular basin	Mahmood and Gloaguen (2012)
4	Valley Floor Width to height ratio (V_f)	$V_f = 2 V_{fw}/[(E_{ld}-E_{sc}) + (E_{rd}-E_{sc})]$ E_{rd}=Elevation of the river-right valley divide (ridgeline) E_{ld}=Elevation of the river-left valley divide (ridgeline) E_{sc}= Elevation of the valley floor V_{fw}=Width of the valley floor	$V_f \leq 0.5$: V-shaped valley $0.5 \leq V_f < 1.0$: Flat floored valley $V_f \geq 1$: U-shaped valley	Hamdouni et al. (2008)
5	Stream Length Gradient Index (S_L)	$S_L = (\Delta H/\Delta L) L$ ΔH= Variation in altitude ΔL= Length of a reach L= Horizontal length from the watershed divide to a midpoint of the reach	$S_L > 400$: Soft rocks/high value of 'S_L' $S_L = 400$–200: Moderate rocks/moderate value of 'S_L' $S_L < 200$: Hard rock/ less value of 'S_L'	Anand and Pradhan (2019)

Source composed by author

are averaged to determine the Relative active tectonic index (R_i).

Morphometric analysis

The morphometry of watershed is the 'measurement of surficial features formed due to endogenetic as well as exogenetic processes' (Ahmad et al. 2013). The geometrical description of the watershed can be classified under the three broad categories-Linear (one dimension), Areal (two dimensions)

and Relief aspects (three dimensions). Parameters with mathematical calculation are shown in Table 2.

Linear aspect of drainage pattern & channel network

The hierarchical arrangement of streams called Stream ordering (S_u) is the primary step of the study (Strahler 1952). The stream network of the Asan watershed extends to sixth-order (higher-order) (Fig. 3) and shows the dendritic type of drainage pattern, which is an indication of

Table 4 Weightage class distribution of LAR and GI of Asan watershed showing weights given to each class according to the classification criteria

No.	LAR & GI	Tectonic classes	References
Linear, Areal and Relief (LAR)			
1	Mean bifurcation ratio (R_{bm})	Class 1: < 3	Iron (1985)
		Class 2: 3–5	
		Class 3: > 5	
2	Drainage density (D_d)	Class 1: ≥ 2.10	Anand and Pradhan (2019)
		Class 2: 2.09–2.00	
		Class 3: < 2.00	
3	Stream frequency (F_s)	Class 1: > 0.80	Shukla et al. (2013)
		Class 2: 0.80–0.85	
		Class 3: < 0.85	
4	Drainage texture (D_t)	Class 1: > 10	Anand and Pradhan (2019)
		Class 2: 10–5	
		Class 3: < 5	
5	Length of overland flow (L_g)	Class 1: < 0.2	Chandrashekar et al. (2015)
		Class 2: 0.2–0.3	
		Class 3: > 0.3	
6	Elongation ratio (R_e)	Class 1: < 0.50	Cuong and Zuchiewicz (2001)
		Class 2: 0.50–0.75	
		Class 3: > 0.75	
7	Ruggedness number	Class 1: ≥ 3.25	Anand and Pradhan (2019)
		Class 2: 3.24–2.66	
		Class 3: < 2.66	
8	Relief ratio/watershed slope (R_h)	Class 1: > 0.1	Shukla et al. (2013)
		Class 2: 0.05–0.1	
		Class 3: < 0.05	
Geomorphic Indices			
9	Drainage basin asymmetry (A_f)	Class 1: > 5.91	Mahmood and Gloaguen (2012)
		Class 2: $2.95 - \leq 5.91$	
		Class 3: ≤ 2.95	
10	Hypsometric integral (H_i)	Class 1: 0.51–0.78	Mahmood and Gloaguen (2012)
		Class 2: 0.37–0.50	
		Class 3: < 0.37	
11	Basin shape index (B_s)	Class 1: 1.7–3.22	Mahmood and Gloaguen (2012)
		Class 2: 1.21–1.76	
		Class 3: 1.11–1.20	
12	Valley floor width to height ratio (V_f)	Class 1: 0.02–0.44	Mahmood and Gloaguen (2012)
		Class 2: 0.45–1.0	
		Class 3: 1.01–3.25	
13	Stream length gradient ratio (S_L)	Class 1: $S_L \geq 500$	Hamdouni et al. (2008)
		Class 2: $S_L \geq 300 \geq 500$	
		Class 3: $S_L < 300$	

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texture's homogeneity. Also, this pattern is the characteristic of the presence of natural rivers and the minimum influence of geological factors controlling the channels. This pattern evolves where the river channel pursues the slope of the terrain (Lambert 1998) and lithology must be impermeable and non-porous. All the streams extracted and updated from Cartosat-1 Digital Elevation Model (spatial resolution-10 m) and numbered according to the stream ordering scheme proposed by Strahler (1952).

The Asan River watershed is subdivided into 12 sub-watershed (SW) for the study (Fig. 4). The parametric evaluation is done at the sub-watershed level than compared afterwards. The sub-watersheds are recognized because of variations in the drainage pattern. Also, the

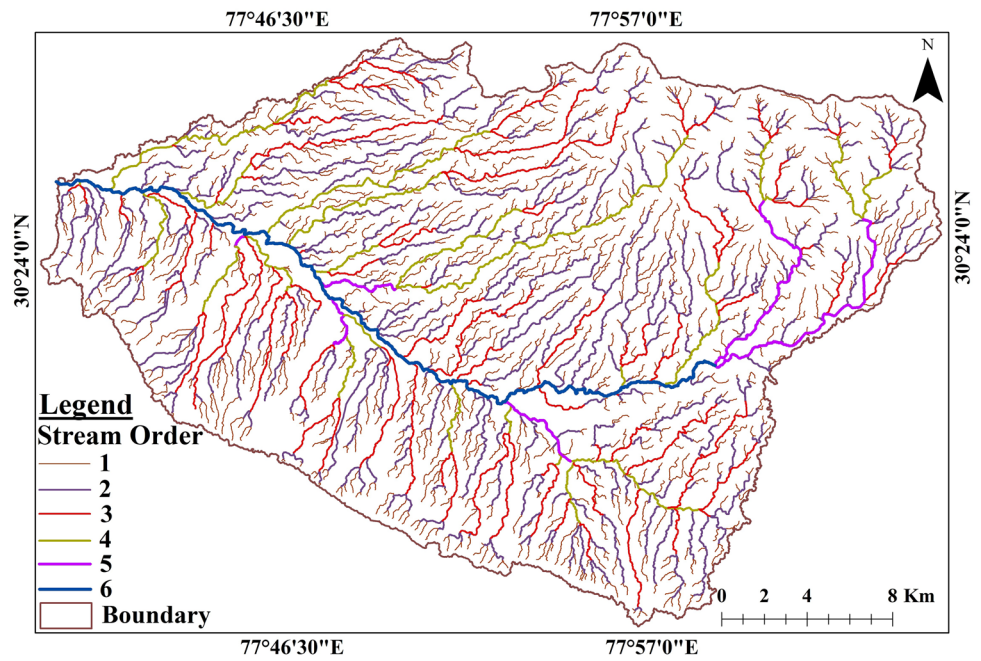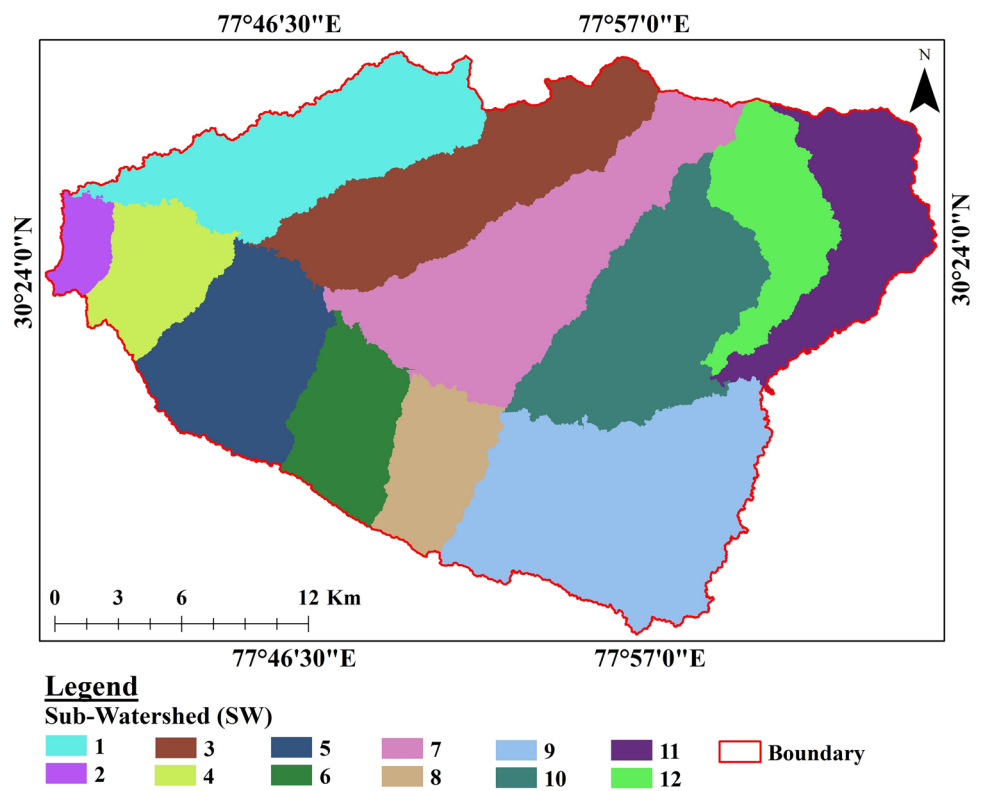**Fig. 3** Drainage network of the study area

Fig. 4 The demarcated sub-watershed of the study area

designation of sub-watershed (SW1-12) are mentioned in Fig. 4.

The total number of streams (N_u) belongs to their respective order is 1194 out of which 835, 264, 68, 20, 6 and 1 belongs to first to sixth order stream respectively (Table 5).

It is noticed that the first-order stream has a maximum number of streams while the stream frequency decreases with an increase in the stream order, with sixth-order streams having the minimum. The sub-watershed (SW9) shows a maximum number of a stream (198) whereas the sub-watershed (SW2)

Table 5 Order-wise characteristics of Streams

		Sub-watershed (SW)												Total
		SW1	SW2	SW3	SW4	SW5	SW6	SW7	SW8	SW9	SW10	SW11	SW12	
Number of stream (N_u)														
Stream order (S_u)	1	94	17	105	39	46	32	119	38	135	76	69	65	835
	2	32	4	27	16	15	11	35	14	47	27	17	19	264
	3	6	2	6	5	6	4	7	3	12	8	5	4	68
	4	2	1	3	1	2	2	1	1	3	2	1	1	20
	5	–	–	–	–	1	1	1	–	1	–	1	1	6
	6	–	–	–	–	–	–	–	–	–	1	–	–	1
	Total	134	26	141	61	70	50	163	56	198	114	93	90	1194
Length of stream (L_u) km^2														
Stream order (S_u)	1	75	8	97	38	57	29	118	52	123	80	51	37	765
	2	62	16	48	33	30	28	71	22	90	66	30	24	520
	3	27	2	36	12	38	19	26	13	59	32	9	10	283
	4	20	0.2	28	5	9	6	29	4	15	9	9	4	138.2
	5	–	–	–	–	1	3	4	–	5	–	26	26	65
	6	–	–	–	–	–	–	–	–	–	43	–	–	43
	Total	184	26	209	88	135	85	248	91	292	230	125	101	1814.2

Source composed by author

shows the minimum (26). The sum of streams for each order gives its stream length (L_u) which is 1814.2 km out of which 765, 520, 283, 138.2, 65 and 43 belongs to the first to sixth order stream respectively (Table 5). It has been seen that 'L_u' is dominant for the first-order stream and decreases with successive orders. The sub-watershed (SW9) shows the maximum length of stream (292 km) whereas the sub-water shed (SW2) shows the minimum (26 km).

Schumm (1956) defines Bifurcation ratio (R_b) as 'the ratio between the total number of streams (N_u) of particular order and number of streams of the next higher-order (N_u+1)'. The calculated 'R_b' for the sub-watersheds varies from 1 to 7 (Table 6). The 'R_b' is classified on the basis of lower to higher values (Table 2). The higher value of 'R_b' indicates a younger stage while the lower 'R_b' represent a mature stage of stream development (Manu and Anirudhan 2008; Shukla et al. 2013; Anand and Pradhan 2019). Also, the higher 'R_b' indicates comparatively higher tectonism and prominent soil erosion compared to other lower-orders (Strahler 1964). Based on the classification mentioned in Table 2, the Mean Bifurcation Ratio (R_{bm}), the SW2, 5 and 6 are having almost the flat region compares to other subwatershed. These sub-watersheds are under the influence of minimal structural control/structural distortions and the least dominance of slopes.

Table 6 Order-wise characteristics of streams

		Sub-watershed (SW)											
		SW1	SW2	SW3	SW4	SW5	SW6	SW7	SW8	SW9	SW10	SW11	SW12
Bifurcation ratio (R_b)	Stream order (S_u)												
	1	–	–	–	–	–	–	–	–	–	–	–	–
	2	2.9	4.3	3.8	2.4	3.1	2.9	3.4	2.7	2.8	2.8	4	3.4
	3	5.3	2	4.5	3.2	2.5	2.7	5	4.6	3.9	3.3	3.4	4.7
	4	3	2	2	5	3	2	7	3	4	4	5	4
	5	–	–	–	–	2	2	1	–	3	–	1	1
	6	–	–	–	–	–	–	–	–	–	1	–	–
	Total	11.2	8.3	10.3	10.6	10.6	9.6	16.4	10 .3	13.7	12.1	13.4	13.1
	Mean bifurcation ratio (R_{bm})												
		3.7	2.7	3.4	3.5	2.6	2.4	4.1	3.4	3.4	3.1	3.4	3.3

Source composed by author

Areal aspect of the watershed

The areal aspects of the watershed share a significant connection with the study of two-dimensional feature which includes the shape and size of the watershed. The erosional condition of the watershed is interpreted through the parameters of the areal aspect. These parameters are dependent upon the structure, relief, slope, lithology etc. of the terrain. The SW9 having the maximum areal coverage (A) (114.4 Km^2) and SW2 having the minimal (10.9 km^2). The perimeter (P) of the SW7 is the maximum (93.8 km) and the minimum for the SW2 (23.9 km). Also, the basin length (L_b) of the SW7 is the maximum (21.2 km) while SW2 having the minimum (5 km) (Table 7).

The texture and proximity of channels within a watershed are predicted by drainage density (D_d). These are influenced by rainfall intensity, vegetation, soil properties and geological setup of the terrain (Horton 1945). The calculated value of 'D_d' is mentioned in Table 8 and based on the classification indicates that the area comes within the range of medium drainage density with rock surfaces drained by the watershed having moderately permeable strata with medium run-off and infiltration (Shukla et al. 2013) (Table 2).

Drainage texture (D_t) is 'a degree of the relative spacing of drainage lines in a fluvial-dissected terrain' (Smith 1939).

The calculated value of 'D_t' is mentioned in Table 8. Using the methodology shown in Table 2, 'D_t' of all the sub-watersheds come under the category of coarser drainage texture (Smith 1939). This indicates the area is having less drainage density and the channel developed on the erosion-resistant rock formations and permeable material.

Stream frequency (F_s) is 'the total number of stream segments of all orders per unit area' (Horton 1932). Using the methodology, the calculated 'F_s' of the watershed is mentioned in Table 2. It indicates that the watershed is having moderate ground slope and rock permeability, so as their run-off and infiltration. The SW2 is having moderately high 'F_s' while other sub-watershed shows moderate one. The factors on which the occurrence of different stream segments depends are rock structure, vegetation cover, amount of rainfall and permeability of soil (Vittala et al. 2004) (Table 8).

The length of overland flow (L_g) is 'the length of water over the ground before it gets concentrated into certain stream channels approximately equals to half of the reciprocal of drainage density' (Horton 1945). It affects the hydrologic and physiographic development of the watershed. The runoff by overland flow carries material of the river such as sand, silt and organic matter and deposited them in piedmont zones. It depends upon the characteristic of the degree of the hillslope. Using the methodology, 'L_g' are classified on the

Table 7 Description of a physical characteristic of watershed

Sub-watershed (SW)												Total
SW1	SW2	SW3	SW4	SW5	SW6	SW7	SW8	SW9	SW10	SW11	SW12	
Area (km^2)												
74.2	10.9	79.5	32	59.5	36.6	98.4	31.9	114.4	80.4	53.8	40.7	712.34
Perimeter (km)												
87.7	23.9	83.4	42.8	54.9	43.4	93.8	39.3	88.3	77.2	76.2	58.9	769.8
Basin length (km)												
19	5	18.5	7.4	10.8	9.8	21.2	8.3	13	14	20	14	161

Source composed by author

Table 8 Tabular characteristics of Areal parameters

Sub-watershed (SW)											
SW1	SW2	SW3	SW4	SW5	SW6	SW7	SW8	SW9	SW10	SW11	SW12
Drainage density (km^{-1})											
2.5	2.4	2.6	2.8	2.3	2.3	2.5	2.9	2.6	2.9	2.3	2.5
Drainage texture (km^{-1})											
1.5	1.1	1.7	1.4	1.3	1.2	1.7	1.4	2.3	1.5	1.2	1.5
Stream frequency (km^{-2})											
1.8	2.4	1.8	1.9	1.2	1.4	1.7	1.8	1.7	1.4	1.7	2.2
Length of overland flow (km)											
0.20	0.21	0.19	0.18	0.22	0.22	0.20	0.18	0.20	0.17	0.22	0.20
Elongation ratio (R_e)											
0.3	0.4	0.3	0.4	0.5	0.4	0.3	0.4	0.5	0.4	0.3	0.3

Source composed by author

basis of length of the flow path (Table 2). The lower value of 'L_g' denotes higher relief / steeper slope / more runoff and vice-a-versa. The calculated value of 'L_g' for all sub-watershed (Table 8) shows well develop streams network with moderate slopes from different intermediate surface runoff of the study area and also showing rainwater travels a relatively shorter distance before getting concentrated to channels (Chandrashekar et al. 2015).

The horizontal projection of watershed shape can be represented using the Elongation Ratio (R_e) (Cannon 1976). The lower value of 'R_e' correspond to the elongated watershed (Schumm 1956). Also, it is more susceptible to the erosional environment for the watershed (Sreedevi et al. 2009). Using the methodology, 'R_e' of all the sub-watershed has been indicating an elongated shape with low to medium relief and moderate infiltration (Table 2).

Relief aspects of the watershed

The relief aspects of the watershed share a significant connection with the study of a three-dimensional feature of the landform. The study of denudational characteristics of the watershed which include terrain relief, permeability, sub-surface flow and landform development are discussed in this section. Basin Relief (H) of the sub-watershed are mentioned in Table 9. The minimum value (z) observed in the plains

and the maximum value (Z) observed in the mountainous areas (GIS analysis/DEM). It indicates runoff and transportation of sediments from the upper to the lower reaches of the watershed. Among all the sub-watershed, the SW3 shows the maximum relief (1796 m) in the northern part while SW2 shows the minimum (380 m) in the eastern part. High relief belongs to rugged terrain comprised of Lesser Himalayan regions while the low relief belongs to the watershed's outlet.

Relief ratio (R_h) is indicative of the relief characteristic of the watershed. It is the ratio between basin relief (H) and the basin length (L_b) (Schumm 1956). The stream's gradient flow and erosional processes are responsible for sediment loss operating especially on the slope of the watershed. It is the indicator to measure the overall steepness of the watershed. The calculated Relief ratio (R_h) of all the sub-watersheds indicates the presence of moderate to gentle slopes and less resistant rocks. The presence of basement rocks exposed in the form of small ridges with the lower degree of a slope lead to moderate runoff and erosion.

Strahler (1968) defines Ruggedness number (R_n) is 'the product of basin relief and drainage density'. It usually combines slope steepness with its length and depends upon other environmental parameters such as slope, precipitation, weathering, soil texture, natural vegetation etc. 'R_n' indicates structural complexity of the terrain, intensity of

Table 9 Tabular classification represent characteristic of sub-watershed relief

Sub-watershed (SW)											
SW1	SW2	SW3	SW4	SW5	SW6	SW7	SW8	SW9	SW10	SW11	SW12
Maximum elevation value (m)											
883	883	2188	885	838	862	2112	861	843	1524	2146	2106
Minimum elevation value (m)											
352	345	392	353	381	415	410	439	463	460	544	553
Basin Relief (m)											
531	538	1796	532	457	447	1702	422	380	1064	1602	1553
Relief ratio											
0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Ruggedness number											
1.3	1.3	4.7	1.5	1.0	1.0	4.3	1.2	1.0	3.0	3.7	3.9

Sub-watershed (SW)												
	SW1	SW2	SW3	SW4	SW5	SW6	SW7	SW8	SW9	SW10	SW11	SW12
Point	V_f											
a	0.11	0.77	0.12	0.74	1.08	0.44	0.25	0.59	0.33	0.09	0.05	0.43
b	0.41	0.18	0.22	0.63	0.28	1.58	0.83	0.14	0.26	0.02	0.05	0.13
c	1.11	0.07	2.22	0.29	1.00	0.75	0.06	0.22	0.05	0.09	1.90	0.08
d	2.28	0.92	0.57	0.15	0.54	0.33	0.53	0.02	0.10	0.70	0.07	0.20
	Mean											
	0.98	0.48	0.78	0.45	0.72	0.78	0.42	0.24	0.19	0.23	0.52	0.21

Source composed by author

erosion within the watershed. Also, it categorizes watershed as rugged and non-rugged (Patton and Baker 1976). The calculated value of different sub-watershed of the Asan is mentioned in Table 9. Based on the methodology adopted after Mayomi et al. (2018), the SW3, 7, 10, 11 and 12 are having rugged topography with moderately high conditions of soil erosion and flood potential than others (Table 2).

Morphotectonic parameter/geomorphic indices

Various parameters are commonly used as an investigating tool in tectonic geomorphology to describe the relationship between tectonics and basin morphologies (Bull and McFadden 1977; Burbank and Anderson 2001). Several morphotectonic parameters with mathematical equations are shown in Table 3.

Drainage Basin asymmetry (A_f):

The Drainage Basin Asymmetry or Asymmetrical Factor (A_f) is defined as 'the ratio of the right side of the stream facing downstream to the total area of the watershed' (Cox 1994). This parameter determines the direction of differential tectonic activity and the lateral tectonic tilting of the watershed with respect to the highest order stream (Cox 1994; Cuong and Zuchiewicz 2001; Mohan et al. 2007; Singh and Srivastava 2011). The deviation from A_f=50 (which indicates that the stable flow path of streams) suggests tilting (Table 3). In the present study, it is found that the mainstream of all sub-watershed flow towards the 6th ordered stream (highest order) in the central portion of the watershed and tilted towards a similar direction of major faults in the area. Also, the tributaries present on the right side of the mainstream are occupying a large area compared to the tributaries present on the left side with a lesser area (Fig. 5). Based on the methodology given in Table 3, the observed value of 'A_f' has been calculated for all sub-watersheds. For comprehending the better result, the 'A_f' absolute value is calculated using the difference between an observed value and neutral value (50) is adopted after (Perez-Pena et al. 2010). Based on the classification, the A_f-50 is evaluated and categorized into different classes viz: Class 1: A_f<4 (Symmetrical basin); Class 2: 4 < A_f <8 (Gently asymmetrical basin); Class 3: 8 < A_f <12 (Moderately asymmetrical basin); Class 4: 12 < A_f <16 (Asymmetrical basin); Class 5: A_f>16 (Strongly asymmetric basin). The observed absolute value of 'A_f' is categorized SW1,

2, 9 and 12 into Class 1 category; SW4 and 10 into Class 2; and finally SW3, 5, 6, 7, 8 and 11 into Class 3 category.

Hypsometric integral (H_i) & hypsometric curve

Hypsometric integral (H_i) explains the distribution of elevation in the watershed (Strahler 1952). 'H_i' is a general index for erosional development and an important geomorphic index of the watershed (Keller and Pinter 2002; Pike and Wilson 1971). The index is defined as the area below the hypsometric curve and thus expresses the volume that has not been eroded (Mahmood and Gloaguen 2012). The shape of the hypsometric curve and hypsometric integral value provide details related to erosional, tectonic, climatic and lithological factors controlling it (Willgoose and Hancock 1998). High values of 'H_i' indicates that most of the topography in the watershed behave like a smooth upland surface cut by deeply incised streams, rugged relief and indicates a youthful stage of the watershed whereas, intermediate to a low value of the 'H_i' is associated with an evenly dissected stream network. Using Strahler's equation mentioned in Table 3, the 'H_i' is calculated as 0.4–0.5 for all sub-watershed and it suggests that the watershed is susceptible to dominated by fluvial erosion (erosion susceptibility is a key indicator of tectonism and dissected stream network in a region). The 'H_i' values are grouped into three classes according to the classification adopted after Dehbozorgi et al. 2010, concerning the shape of the hypsometric curve: Class 1: $H_i \geq 0.5$ (convex curves); Class 2: $0.4 \leq H_i < 0.5$ (concave-convex/S-shaped curves); Class 3: $H_i < 0.4$ (concave curves) (Fig. 6). The classes from 1 to 3 is associated with young (weakly eroded), mature (moderately eroded) and old (highly eroded).

Basin shape index (B_s)

Bull (1977) proposed one of the significant parameters, Basin Shape Index (B_s) for identifying relative young drainage basin in tectonically active areas. 'B_s' influences the fluxes and delivery of runoff and sediment from headwater reaches. In the tectonically active area, the relatively younger watershed is elongated in shape correspondence to topographic slope or young active fault. The reduction of tectonism and topographic evolution of any region leads to the conversion of the elongated shape of the watershed into the circular one (Bull 1977). This conversion in the shapes of the watershed is because the width of the watershed is narrower near the mountain front in the actively tectonic area. The classification proposed by Mahmood and Gloaguen (2008) is used in the present study which suggests that SW1, 3, 6, 7, 9, 11 and 12 are elongated in shape whereas the rest are semi-elongated (Table 3).

Valley floor width to height ratio (V_f)

The parameter helps in assessing the area on the basis of tectonism. It enables the comparison of erosional patterns between watersheds. The index was initially used to differentiate the U-shaped valley from V-shaped valleys (Bull 1977). Higher 'V_f' index values are associated with relatively moderate to less active mountain fronts that represent low uplift rates and wide/flat valley floor with base-level erosion whereas low values correspond to actively uplifting V-shaped valley (Bull 1977, 1978; Bull 2007; Burbank and Anderson 2001). The calculated 'V_f' is the average of four 'V_f' points for each sub-watershed taken at an equal interval for the mainstream for the study (Fig. 7).

The calculation is adopted using the methodology given by Hamdouni et al. (2008) suggests that all sub-watershed categorised as the flat-floored valley where streams laterally eroded and the incision has taken place in response to inactive relative tectonics into the adjacent hill slopes (Keller et al. 1996; Keller and Pinter 2002) (Table 3). The flat-floored valley is the result of aggradation (depositional) process where thick alluvial cover much of which is too deep for the stream to scour while the remaining shows the lower values of 'V_f'. The four randomly selected 'V_f' points which are equidistant to each other are designated as 'a', 'b', 'c', 'd' demarcated on the major stream of the sub-watershed. These points are taken from the outlet to the upper reaches are arranged in increasing order of their nomenclature (Table 9).

Stream length gradient ratio (S_L-index)

This index was introduced by Hack (1973). It has a prominent influence over channel slope; this allows the determination of finding the tectonism in the area. Even shaped river gradient reflects the lithological variation in the river beds. S_L-Index helps to study relative tectonic activity. Whenever rivers or streams flow above the uplifted region, the value of S_L-Index increases (Keller and Pinter 2002). The major thrust/faults present in the watershed like Main Boundary Thrust (MBT) Santaugarh thrust (ST) and Bhauwala thrust (BT) and Majahaun Fault (MjF) are passing across the streams whereas the Nun River Fault (NRF), Tons Fault (TF) and Asan Fault (AF) are running along with streams. For the present study, S_L-Index was generated using Cartosat-1 DEM and for every 200 m difference of elevation, the distance from the source was calculated in a GIS environment (Fig. 8). The graphical representation of a longitudinal profile and S_L-index for the mainstream of all sub-watersheds in the watershed is shown in Fig. 9. High peaks of S_L-index across longitudinal profile are corresponding to topographic breaks and/or knick points. These are often recorded in the middle and upper reaches of all the prominent streams.

Based on the categorization of highest to lowest values of S_L-index, the adopted classification categorizes the values according to Hamdouni et al. (2008) (2). SW 3, 10 and 11 belong to Class 1 while, SW 1, 7 and 8 belongs to Class 2 and the rest of the sub-watershed i.e. SW 2, 4, 5, 6, 9 and 12 belongs to class 3 (Fig. 8). The S_L-Index is high where the channels flow over active uplifts and cross the soft rocks e.g., alluvial. Conversely, lesser S_L-Index indicates low tectonic activity and also rivers flow over less-resistant harder underlying rocks (Anand and Pradhan 2019) e.g. Doon gravels. The SW 2, 4, 5 and shows the presence of the unknown geological structure at the elevation of 800–1000 m and the distance of 4000 to 8000 m. In the present research, we considered it as an unknown structure designated as 'UN' in the graph and further studies are required to explore the structure.

Cumulative analysis and validation of LAR & GI

Different indices are analysed for Asan watershed exhibits wide variations in their values which may be due to change in features characteristic of river channels, the behaviour of associated strata and topography. In this study, the Relative Active Tectonic Index (R_i) is used to determine the tectonic setting of the watershed. The spatial distribution of relative tectonic activity of the study area is evaluated through 'R_i' by taking the arithmetic mean of the class number assigned to the linear, areal, relief (LAR) and geomorphic indices (GI). Each parameter used in the study is classified into three classes based on previous literature as Class 1, 2 and 3 (Table 4). Class 1 represent higher tectonic activity whereas Class 3 represents the least. The established 'R_i' classes through DEM evaluation categorize the watershed into four classes based on the degree of tectonic activities: Class 1: < 1.97 (very high activity); Class 2: 1.97–2.05 (high activity); Class 3: 2.05–2.21 (moderate activity); Class 4: > 2.21(low) activity (Hamdouni et al. 2008).The spatial distribution of calculated 'R_i' is represented in Table 10. The interpretation of 'R_i' has been validated with field studies. The values reveal the variation of the degree of activeness from place to place. The intersection along a longitudinal profile of rivers may indicate some upliftment in topography due to recent tectonic activity. The calculated 'R_i' for SW10 and 12 falls into Class 1 category; SW2, 7 and 8 into Class 2; and SW1, 3, 4, 5, 6 and 11 lies into Class 3 category. In the total area of 712.34 km^2 of the watershed, around 17% of the area (121.1 km^2) belongs to the Class 1 category; 19.82% of the area (141.2 km^2) belongs to the Class 2 category and the major part 63.2% of the area (449 km^2) belongs to Class 3 category.

Table 10 Calculation of relative index of active tectonics (R_i) using LAR and GI

SW	LAR parameters								Geomorphic Indices					R_i
	R_{bm}	D_d	F_s	L_g	D_t	R_e	R_h	R_n	A_f	H_i	B_s	V_f	S_L	
	Classes													
SW1	2	1	1	3	3	3	2	3	1	2	3	2	2	3
SW2	1	1	1	3	3	3	2	3	1	2	1	2	3	2
SW3	2	1	1	3	3	3	2	1	3	2	3	2	1	3
SW4	2	1	1	3	3	1	2	3	2	2	2	2	3	3
SW5	1	1	1	3	3	3	2	3	3	2	2	2	3	3
SW6	1	1	1	3	3	3	2	3	3	2	1	2	3	3
SW7	2	1	1	3	3	3	2	1	3	2	1	2	2	2
SW8	2	1	1	3	3	3	2	3	3	2	2	1	2	2
SW9	2	1	1	3	3	3	2	3	1	2	3	1	3	3
SW10	2	1	1	3	3	3	2	1	2	2	1	1	1	1
SW11	2	1	1	3	3	3	2	1	3	2	3	2	1	3
SW12	2	1	1	3	3	1	2	1	1	2	3	1	3	1

Final ($Avg_{LAR} + Avg_{GI}$)/n, *LAR* $R_b + R_{bm} + D_d + F_s + L_g + D_t + R_e + R_h + R_n$; *GI* $A_f + H_i + B_s + V_f + S_L$, *LAR* Linear, areal and relief; *GI* geomorphic indices, *n* number of parameters, *SW* Sub-watershed

Source composed by author

Fig. 5 Asymmetry in the study area
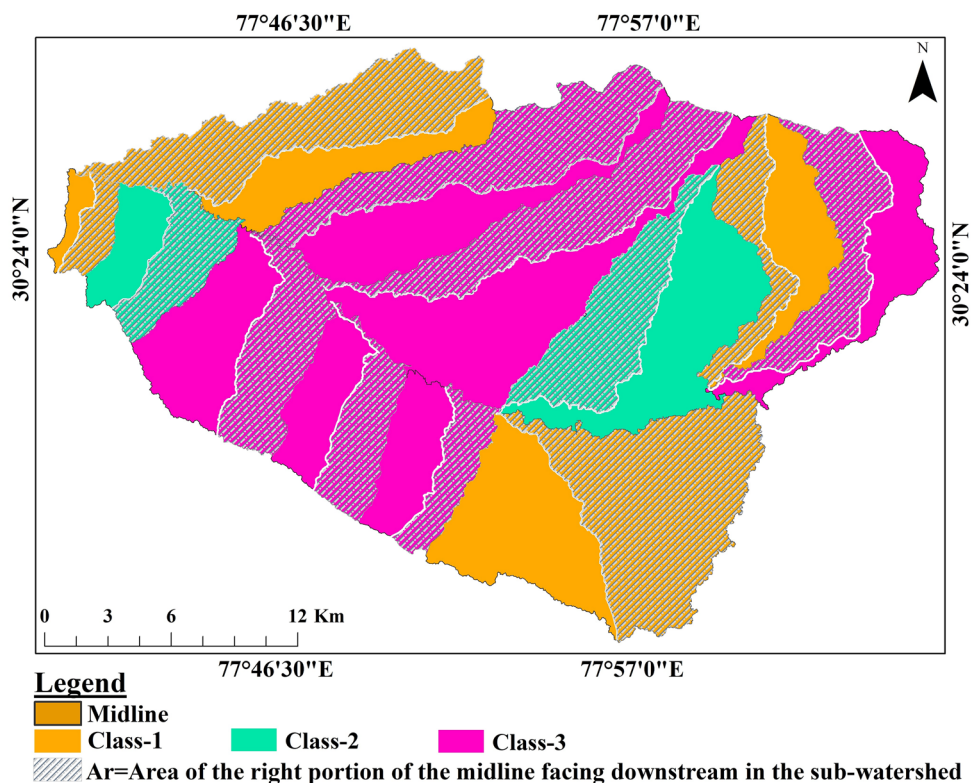
Conclusion

The morphological characteristics of the DEM derived stream network and structural behaviour of the watershed are evaluated in the present work using the GIS approach are interpreted through different parameters associated with morphometry and geomorphic indices. On the basis of adopted classification, the calculated parametric values can be categorised into three classes: Class 1 to Class 3, which is a representative of the higher to the lower influence of tectonism in an area (Table 4). Here, sixteen morphometric parameters and five geomorphic indices are evaluated and act as a significant tool for identifying
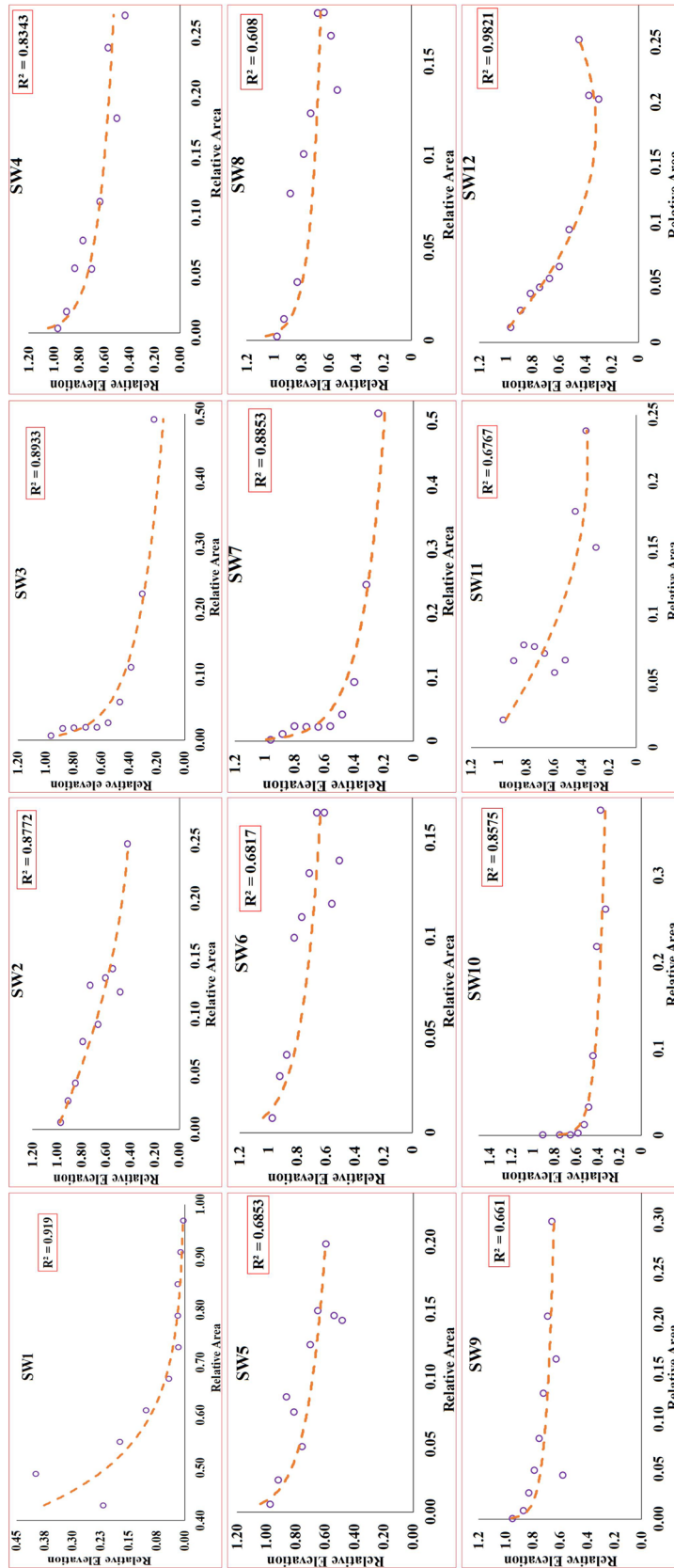
Fig. 6 Graphs showing the Hypsometric Curve of the Sub-watershed (SW 1–12)

Fig. 7 Locations of the cross-section for the calculation of 'V_f' in the area (*Vfw* Width of the valley floor, E_{ld} Elevation of the left ridgeline, E_{rd} Elevation of a right ridgeline, E_{sc} Elevation of the valley floor)
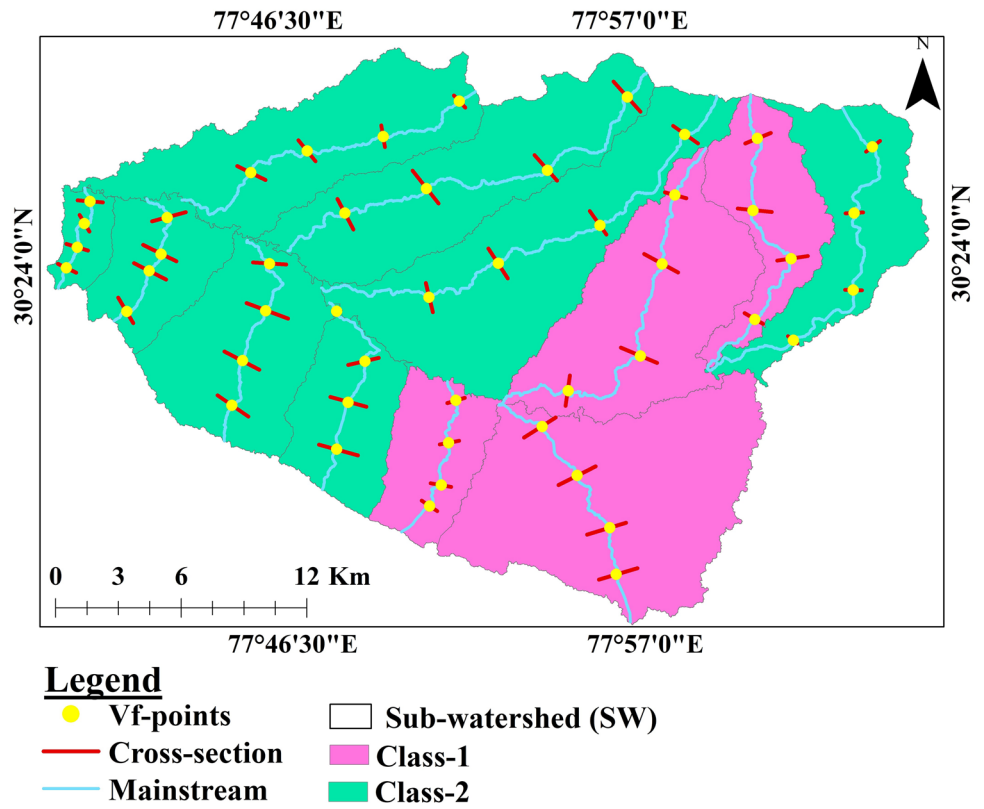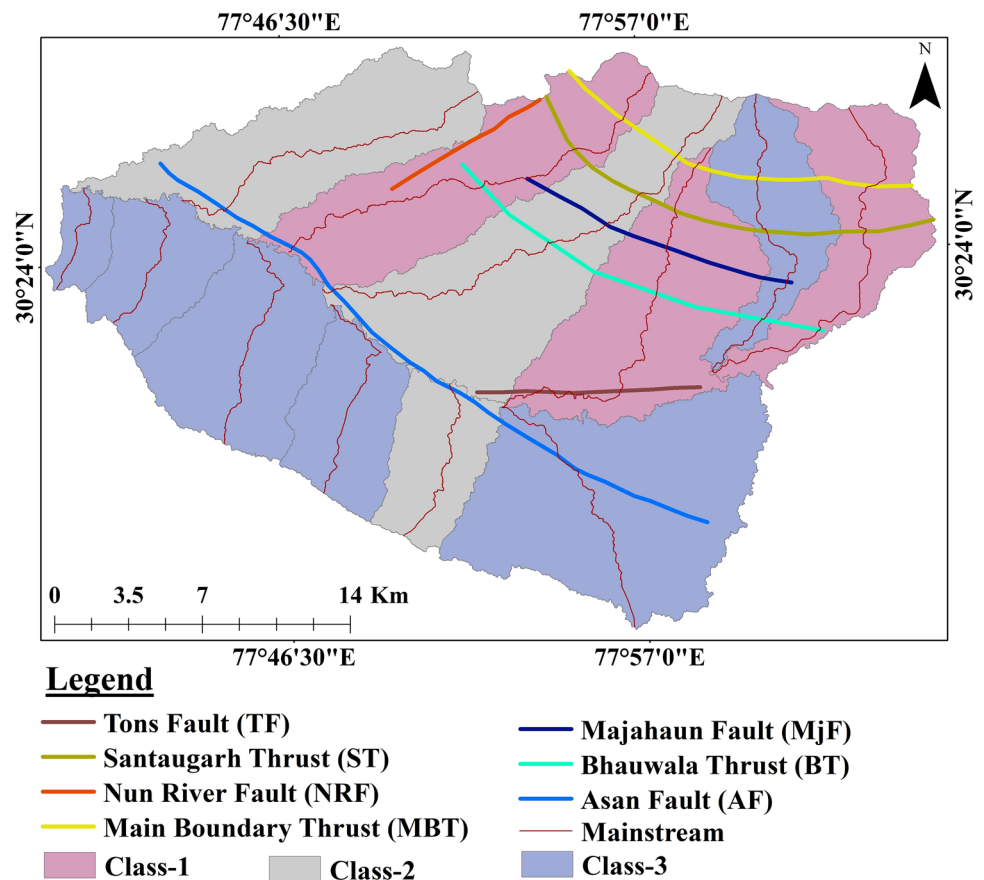

Fig. 8 Location of stream taken for the analysis of SL-index in the watershed along with Major Faults and Thrust
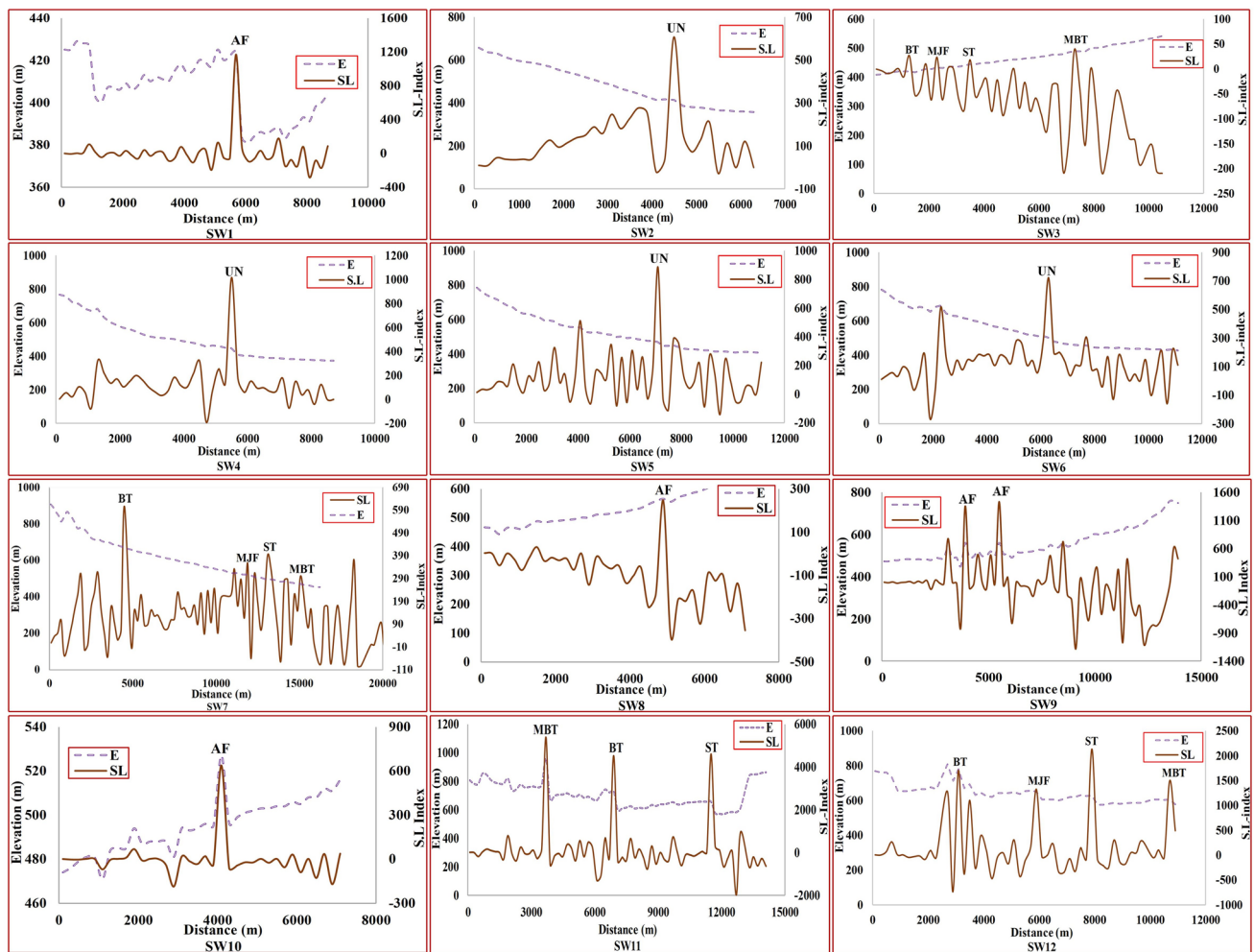
Fig. 9 Graphical representation of S_L-Index for selective streams belongs to different sub-watershed

relative tectonic activity in the watershed. The Relative Active Tectonic Index (average of the computed parameters) is classified into four classes which categorizes the watershed into a lower to a higher degree of relative tectonic activity. The calculated values of parameters and their corresponding methodology reveal that the higher value of the Bifurcation ratio (R_b) and Mean bifurcation ratio (R_{bm}) is associated with the dominance of structurally controlled sub-watershed. The medium texture, run-off and infiltration which corresponds to the presence of moderately permeable strata in the watershed is indicated by areal parameters such as Drainage density (D_d), Drainage texture (D_t) and Length of overland flow (L_g). It concluded with the presence of moderate tectonic activity in the watershed. The elongated shape of the watershed corresponds to moderate activeness evaluated using the Elongation ratio (R_e) while the Length of overland flow (L_g) admits the presence of moderate slope and relief which affects the hydrologic and physiographic characteristics

of the watershed. The run-off carries material of the river from the upper reaches and deposited them in piedmont zones. The presence of structural features likes, fractures and faults in an area is globally accepted as a controlling factor for the initiation and development of streams. The drainage network in the watershed depicts that several streams flow across the major faults and thrust present in the watershed, this indicates the stream formation is older than the start of tectonic activities whereas the mainstream of the watershed (Asan River) follow the direction of Asan fault which indicates that the stream formation into the watershed is younger than the start of tectonic activities in the area. This, also depicts that in the lower reaches of the watershed the stream formation is comparatively younger from the initial phase of tectonic activities than the higher reaches of the watershed. Asymmetry factor (A_f) gives significant information about the presence of tectonic tilt in different sub-watershed shows structural discontinuity as it passes through major thrust/faults. 'S_L

-Index' is calculated for mainstreams of 12 sub-watersheds at an interval of 200 m and it reveals the influence of several faults and thrust at the drainage region of the watershed. The intersection of the longitudinal profile along the streams may indicate some upliftment in the topography due to significant tectonic disturbances. The evaluation of Hypsometric integral (H_i) reveals that S-shaped hypsometric curves are associated with a mature stage of stream development correspond to the presence of moderately eroded strata. Valley floor to height ratio (V_f) classified the watershed as flat-floored with a moderately active setting. The observations as well as the parametric evaluation of the Relative Active Tectonic Index (R_i) suggests the influence of tectonics in an area. The conclusion confirms the usefulness of such parametric analyses for assessing regional tectonics. In general, this sort of parametric evaluation is attributed to the surface and subsurface crustal deformations. It also reveals, the lithology and prevailing climate played a significant role in the evolutionary history of any region. Also, the watershed at times must have experienced distinctive upliftment in the varying erosional rate.

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