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Morphometric analysis of the Kadalundi River basin, North Kerala, India, using GIS and Remote Sensing Techniques

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ABSTRACT

Morphometric analysis was carried out to evaluate the quantitative characteristics of the Kadalundi River Basin (KRB), a west-flowing river system in North Kerala. Linear, areal, and relief aspects were computed using ArcGIS 10.8, including parameters such as stream order (Nu), stream length (Lu), bifurcation ratio (Rb), stream length ratio (Rl), drainage density (Dd), stream frequency (Fs), form factor (Ff), elongation ratio (Re), circularity ratio (Rc), shape index (Sw), basin relief (R), ruggedness number (Rn), relief ratio (Rr), dissection index (DI), and Melton ruggedness number (MRn). KRB, a sixth-order river with 22 fourth-order sub-basins (SB1–SB22) draining 1257.37 km², displays a dendritic drainage pattern. Key morphometric values include perimeter (227 km), Rb (22.10), basin length (65 km), Lu (1157.01 km), Fs (1.44), T (1.31), Lg (0.55), C (1.10), Ff (0.30), Rc (0.31), Re (0.62), and Sw (3.33). The mean drainage density is 0.91 km/km², indicating very coarse drainage texture and a mature geomorphic stage. Relief parameters show R = 1320 m, Rr = 0.02, Rn = 1.20, DI = 0.99, and Rg = 0.20. The mean Rl is 9.43, with variations (0.97–8.09) reflecting slope and topographic control. Rho values range from 0.13 to 0.92, with higher values (≥0.50) in sub-basins such as SB4 (ρ = 0.92), suggesting enhanced hydrologic storage and erosion attenuation. The basin exhibits an S-shaped hypsometric curve, consistent with a mature landscape. These morphometric insights reveal basin hydrological behaviour, sub-basin variability, and structural influences, providing a foundation for watershed management.

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Supplemental data for this article can be accessed online at our website

1. Introduction

Morphometric analysis is widely applied to understand the geomorphological evolution of river basins and involves the quantitative assessment of the earth's surface, shapes, and dimensions of landforms, providing critical insights into the basin's hydrological and geological characteristics (Sangma and Guru 2020). The significance of drainage pattern analysis in characterizing geomorphic features and evaluating the influence of structural and lithological controls on the evolution of fluvial landforms have been well established since the foundational studies of Horton (1945), Thornbury (1954), and Strahler (1964) .

Morphometric parameters provide a relatively straightforward method for comparing basin characteristics and elucidating basin processes, thereby improving the understanding of basins' geological and geomorphic evolution (Mesa 2006). This ultimately helps to forecast the hydrological behaviour of watersheds (Esper 2008), which is mainly related to the physiographic parameters, including the linear, areal, and relief parameters of river basins (Chorley 1969, Gregory and Walling 1973). GIS facilitates integrating and analysing these spatial data, enabling detailed mapping.

The visualization of terrain features (Strahler, 1964). Nookaratnam et al., 2005 and Rais and Javed (2014) have successfully used morphometric parameters for prioritizing the watersheds in locating artificial recharge sites. A wide range of information can be effectively integrated for characterizing the surfaces using digital data, particularly in mapping, and information system development. Remote sensing technologies, often provide high-resolution data essential for deriving morphometric parameters such as slope, aspect, and elevation (Goyal et al., 2018).

The Shuttle Radar Topographic Mission, (SRTM) DEM and the CARTOSAT DEM are widely used for extracting morphometric parameters due to the higher spatial resolution. In India, the morphometric analysis of several river basins has been carried out using remote sensing and GIS applications (Arulbalaji and Padmalal, 2020) and has been applied for various purposes such as groundwater resource development, prioritization of micro-watersheds, and watershed characterization (Sreedevi et al., 2009; Ratnam et al., 2005; Vittala et al., 2004). Morphometric analyses have been carried out in many of the river basins of Kerala, including the Kuttiyadi Chalakkudy, Pamba, Meenachil, Achankovil, and Kallada Rivers (James and Padmini, 1983; Maya, 1997; Rajendran, 1982; Aju et al., 2019; Vijith and Satheesh 2006; Manu and Anirudhan, 2008).

The present study focused on the morphometric characteristics of the drainage system of the Kadalundi River Basin (KRB), North Kerala. The paper comprehensively evaluates the linear, areal, and relief characteristics which help in understanding the drainage pattern and network, providing insights into the spatial distribution and organization of the watershed and offering a detailed understanding of the topographic and elevation variations within the watershed.

2. Study Area

The Kadalundi River originates to the east of Karuvarakkundu in the Kozhikode district of Kerala, extending between latitudes 10°51′42″N and 11°10′42″N, and longitudes 75°48′21″E and 76°24′30″E, as demarcated on Survey of India (SOI) toposheets numbered 49M/16, 49N/13, 58A/8, 58A/4, 58B/1, and 58B/5, all at a scale of 1:50,000 (Figure 1). The river is formed by the confluence of two main tributaries: the Olipuzha and the Veliyar. The Olipuzha has its source at Cherakkombhanmala, while the Veliyar originates from the forested region of Eratakombanmala. The Kadalundi River flows for approximately 130 km, draining a catchment area of 1,268 km², before meeting the Arabian Sea roughly 5 km south of the Chaliyar River. The estuarine zone falls within the administrative boundaries of the Kadalundi and Vallikunnu panchayath.

The basin encompasses rugged terrain with elevation ranging from 20 m to 1,340 m above mean sea level, and is physiographically divided into three zones: highland, midland, and lowland, each characterized by distinct geomorphic and land use features. The drainage pattern is predominantly governed by variations in topography, slope gradient, lithological composition, and structural discontinuities, contributing to marked geographical diversity within the basin. The estimated annual surface water potential of the basin stands at approximately 1,829 million cubic metres (Mm^3). Human influence in the basin is relatively limited, with urban development being minimal. Agriculture remains the dominant land use, sustained mainly through rainfall and groundwater sources, as formal irrigation infrastructure is largely absent. A wide range of crops-including paddy, coconut, tapioca, areca nut, pepper, rubber, and cashew-are cultivated, supported by the basin's varied agroclimatic conditions. The climate is tropical, exhibiting clear wet and dry seasons. The southwest monsoon (June to September) contributes around 60% of the region's average annual rainfall of 3,610 mm, followed by 30% from the northeast monsoon, and the remaining 10% from pre-monsoon summer showers. While the basin supports a few small-scale industries, including coir manufacturing units, industrial development is limited, allowing much of the natural landscape and hydrological regime to remain intact. Geologically, the Kadalundi basin is characterized by a heterogeneous lithological framework rooted in the Precambrian era, predominantly composed of charnockites and hornblende gneisses (Figure 2).

These crystalline basement rocks are unconformably overlain by lateritic formations developed during the Pleistocene, formed through intense tropical weathering processes. The laterite occurs as both residual and transported deposits, displaying significant spatial variability in thickness across different geomorphic settings. The basin also hosts extensive Quaternary deposits, including coastal sands, riverine alluvium, and valley fill sediments, typically comprising fine- to medium-grained sands. Subsurface lithology has been delineated using a combination of borehole records, tube well data, and direct observations from open wells. In the coastal plains, a prominent layer of alluvium, ranging from 5 to 15 meters in thickness-composed mainly of well-sorted sands, caps the subsurface sequence. This is typically underlain by laterites, compacted weathered rock, and intercalated lithomargic clay.

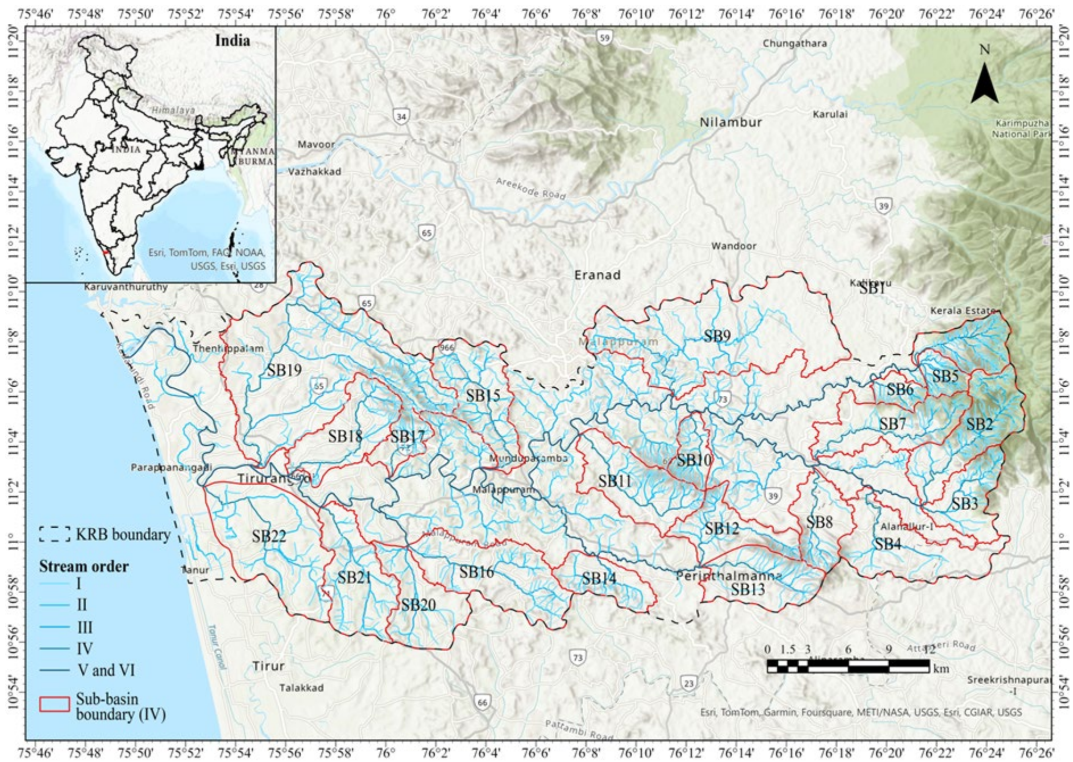

Figure 1. The geographic location of the Kadalundi River basin (KRB) with drainage and its IVth order sub-basins

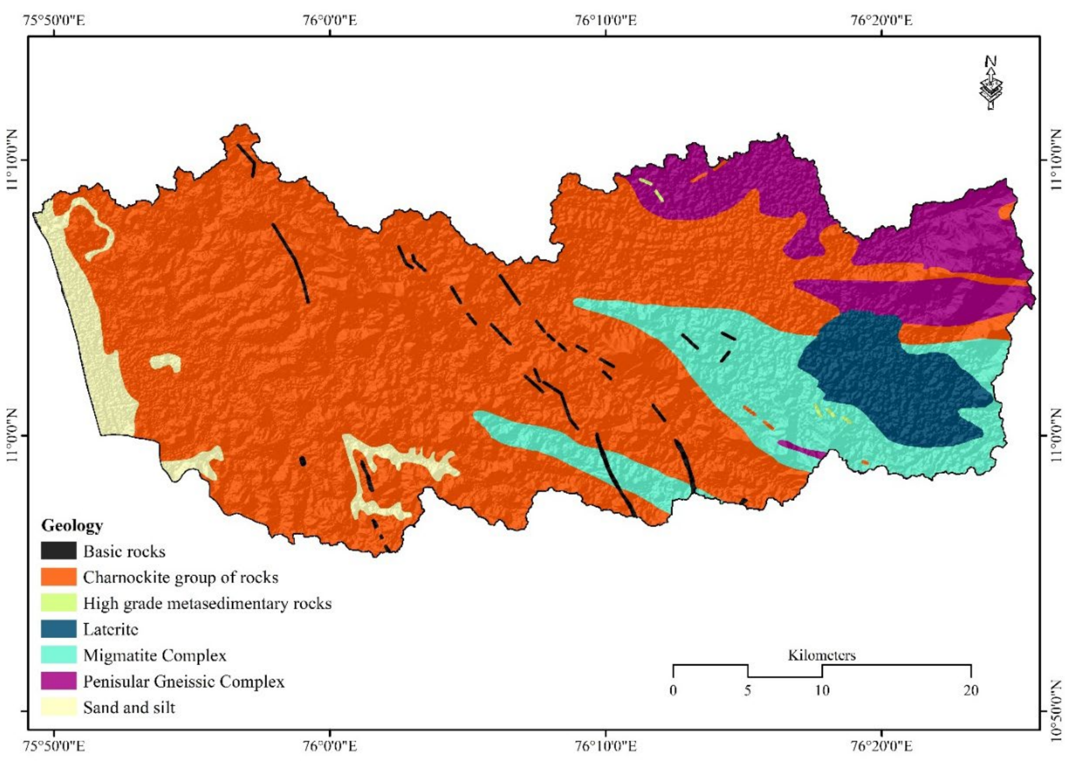

Figure 2. Geological map of the study area

In the midland region, laterite thickness ranges from 5 to 20 meters, overlying a thin lateritic soil horizon (0.5 to 2.0 meters), followed by lithomargic clay and weathered bedrock, each typically 0.5 to 2 meters thick. These layers grade into fractured and occasionally massive crystalline bedrock. The highland sector presents a relatively thin brown soil layer (1 to 3 meters), beneath which laterites and weathered rocks rest directly on jointed or fractured bedrock. Here, lateritic profiles range between 2 and 10 meters thick and are often devoid of significant clay interlayers. Bedrock depth in these highland zones is highly variable, extending from 5 up to 27 meters below ground level (Narasimhaprasad et al., 2007).

3. Materials and Methods

As part of the study, Survey of India (SOI) topographic maps at a 1:50,000 scale were utilized to delineate the Kadalundi River Basin (KRB), including its fourth-order sub-basins. Using a Geographic Information System (GIS) platform, elevation contours and the stream network were digitized through on-screen interpretation to develop a structured geodatabase. Based on the integrated analysis of drainage patterns and topographic contours, the KRB was systematically subdivided into 22 fourth-order sub-basins (Figure 1). Drainage channels within the basin were categorized according to their hierarchical order.

For morphometric analysis, the stream network of each sub-basin was evaluated using Horton's (1945) empirical framework, while stream ordering followed Strahler's (1964) hierarchical classification. The comprehensive methodological workflow adopted in this study is presented in Figure 3. The morphometric parameters were classified into three primary categories: linear, areal, and relief aspects. Fundamental basin attributes including area, perimeter, basin length, and total stream length were extracted from the geospatial database. These primary metrics served as inputs for computing a range of derived morphometric indices using standard mathematical formulations (Table 1). Furthermore, hypsometric analysis, comprising the hypsometric integral (HI) and hypsometric curve, was employed to evaluate the distribution of elevation within the drainage basin and to infer the extent of erosional modification relative to its original landform volume. These metrics offer insight into the geomorphic maturity of the basin and are closely linked to its tectonic and geomorphological evolution. The hypsometric curve illustrates the normalized elevation profile of the basin area and serves as a diagnostic tool for classifying stages of landscape evolution. Concave profiles are indicative of old, heavily eroded terrains; S-shaped (sigmoidal) curves suggest mature topographic conditions; while convex profiles reflect relatively young, less-eroded basins (Strahler, 1952).

The hypsometric integral (HI) quantifies the proportion of a basin's volume that remains uneroded and is calculated as the ratio of the area under the hypsometric curve to the total area of the plot. It effectively captures the degree of terrain dissection and denudation (Zhu et al., 2013). According to established thresholds, basins can be geomorphologically classified as young (HI > 0.6), mature ($0.35 \leq HI \leq 0.60$), or old (HI < 0.35) (Strahler, 1952). The HI values range between 0 and 1 and are computed using the following equation:

$$HI = \frac{(Elev.mean - Elev.min)}{(Elev.max - Elev.min)} \quad (1)$$

Where $Elev_{mean}$, $Elev_{min}$, and $Elev_{max}$ are the mean, minimum, and maximum elevation, values respectively. A high Hi value suggests a relatively young landscape developed by recent tectonic activity. On the other hand, a low Hi value is associated with older landforms with significant erosion and has been less influenced by recent tectonic processes.

4. Results and Discussion

The Kadalundi River Basin (KRB) is classified as a sixth-order fluvial system, exhibiting a well-defined dendritic drainage pattern, indicative of homogeneous lithological conditions and minimal structural control. While the overall drainage density across the basin is relatively low, the central, eastern, and northeastern hilly terrains exhibit locally dense drainage networks, reflecting higher runoff potential and steeper gradients in these regions. As the river progresses toward its lower course, it transitions into a broad alluvial plain. The basin's geological framework and soil characteristics contribute to limited groundwater infiltration, particularly in the upper and central zones. However, select midland regions and the entire lowland sector offer favorable conditions for groundwater development, owing to relatively higher porosity and permeability. For morphometric analysis, the basin was subdivided into 22 fourth-order sub-basins, and the stream network along with the sub-basin boundaries is presented in Figure 1. Detailed evaluation of linear, areal, and relief morphometric parameters has been conducted, with the results and interpretations presented under the subsequent subheadings.

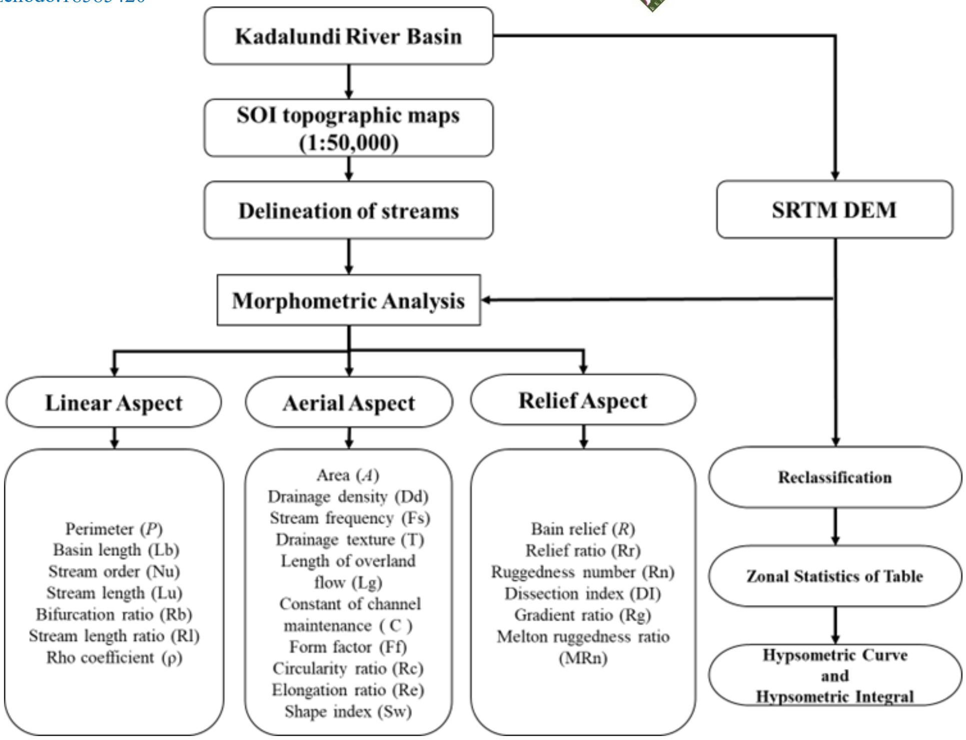

Figure 3. The methodology adopted for the morphometric analysis

Table 1. Morphometric parameters for morphometric analysis

Sl. No.	Parameters	Definition	Units	References
		Linear aspects		
1	Perimeter (P)	Length of the watershed boundary	Km	
2	Basin length (Lb)	Maximum length of the watershed measured parallel to the main drainage line	km	
3	Stream order (Nu)	Hierarchical ordering	Dimensionless	Strahler (1957)
4	Stream length (Lu)	Length of the major stream	km	Horton (1945)
5	Bifurcation ratio (Rb)	Rb=Nu/N(u+1), where Nu is number of streams of any given order and N(u+1) is number in the next higher order	Dimensionless	Horton (1945)
6	Stream length ratio (Rl)	Rl=Lu/L(u−1), where Lu is stream length order u and L(u−1) is stream segment length of the next lower order	Dimensionless	Horton (1945)
7	Rho coefficient (ρ)	ρ=Rl/Rb	Dimensionless	Horton (1945)

(Continues.)

		Areal aspects		
8	Area (A)	Area of watershed	km^2	
9	Drainage density (Dd)	Dd=ΣLt/A, where ΣLt is the total length of all the ordered streams	km km^{-2}	Horton (1945)
10	Stream frequency (Fs)	Fs= ΣNt/A, where Nt is the total number of stream segments of all orders	km—2	Horton (1945)
11	Drainage texture (T)	T =Dd x Fs	km km^{-4}	Smith (1950)
12	Length of overland flow (Lg)	Lg=1/2Dd	km	Horton (1945)
13	Constant of channel maintenance (C)	C =1/Dd	km	Schumm(1956)
14	Form factor (Ff)	$Ff=A/Lb^2$	Dimensionless	Horton (1945)
15	Circularity ratio (Rc)	$Rc=4\pi A/P^2$	Dimensionless	Miller (1953)
16	Elongation ratio (Re)	Re = (1.128√A)/Lb	Dimensionless	Schumm(1956)
17	Shape index (Sw)	Sw=1/Ff	Dimensionless	Horton (1932)
		Relief aspects		
18	Bain relief (R)	R = H−h, where H is maximum elevation and h is minimum elevation within the basin	km	Schumm (1956)
19	Relief ratio (Rr)	Rr=R/Lb	Dimensionless	Schumm (1956)
20	Ruggedness number (Rn)	Rn=R x Dd	Dimensionless	Strahler (1958)
21	Dissection index (DI)	DI=R/Ra, where Ra is absolute relief	Dimensionless	Singh and Dubey (1994)
22	Gradient ratio (Rg)	Rg=Es−Em/Lb, where Es is the elevation at the source, Em is the elevation at the mouth	Dimensionless	Sreedevi et al.(2004)
23	Melton ruggedness ratio (MRn)	$MRn=H-h/A^{0.5}$	Dimensionless	Melton (1965)

4.1 Linear aspects

Perimeter (P)

The total perimeter of the Kadalundi River Basin (KRB) measures 227 km, with the perimeters of its 22 fourth-order sub-basins detailed in Table 2. Among these, sub-basins SW9 and SW19 exhibit the largest perimeters, each approximately 68 km, corresponding to relatively extensive basin areas of 93 km² and 119 km², respectively. In contrast, sub-basin SW5 has the smallest perimeter, measuring 12 km. The perimeter is a key morphometric parameter influencing the hydrological behavior of river basins, particularly in terms of water collection, concentration, and flow dynamics (Chorley and Kennedy, 1971; Zhang and Montgomery, 1994). Sub-basins with larger perimeters generally exhibit a moderated response to rainfall events, often attenuating flash flood peaks. Conversely, smaller or more compact sub-basins tend to generate rapid runoff, which can lead to intensified and more immediate flooding (Gregory and Walling, 1973; Fan et al., 2020).

Basin length (Lb)

The basin length (Lb) of KRB is 65 km, and Table 2 lists the Lbs of the 22 sub-basins. Subbasins SB2, SB7, SB8, SB9, SB11, SB13, SB15, SB16, SB18, SB19, SB20, SB21, and SB22 are relatively longer (Lb > 8 km), than SW7 and SW8 (Lb ≤ 3 km). Additionally, these sub-basins are comparatively elongated, covering larger basin areas (r = 0.96). This supports the hypothesis that headward erosion contributes to the formation of longer channels. Longer subbasins respond slowly to rainfall events, causing lower peak discharges and moderate flood events, as water takes longer to travel to the outlet (Fan et al., 2020). On the other hand, shorter subbasins cause faster runoff, leading to higher peak discharges and intense flooding, particularly during flash floods (Wang et al., 2022).

Stream order (Nu)

Categorizing streams based on the number and types of their tributary junctions is a proven method for indicating the size, discharge, and drainage area of streams (Strahler, 1957). KRB is a sixth-order river and has 1,372 first-order streams, 348 second-order streams, 77 third-order streams, 22 fourth-order streams, and 7 fifth-order streams. Lower-order streams (1st to 3rd order) typically experience faster runoff and are more prone to flash floods due to their smaller drainage areas (Moussa and Bocquillon 2009). On the other hand, higher-order streams (4th and above) receive contributions from multiple lower-order streams, resulting in larger, slower-developing floods with higher volumes but longer durations (Ali and Rehman, 2020).

Stream length (Lu)

The mean and total stream lengths for each stream order are presented in Table 2. Generally, the average length of channel segments in a given order exceeds that of the immediately lower order but remains shorter than that of the next higher order. This trend suggests that watershed evolution is primarily controlled by erosional processes acting upon geologic materials with relatively uniform weathering characteristics (Nag and Chakraborty, 2003). Nevertheless, deviations from this pattern are observed in sub-basins SB4, SB5, SB6, SB7, SB8, SB9, SB11, SB12, SB13, SB16, SB19, SB20, SB21, and SB22. Notably, the mean stream lengths in SB3 and SB11 exhibit abrupt increases, likely reflecting the influence of underlying structural controls. Streams exceeding 300 km in length are known to delay peak discharge, resulting in slower and more moderated flood events, although they may extend flood duration (Wang and Zhang, 2022). Conversely, shorter streams tend to generate rapid runoff, causing more intense and localized flood peaks, especially during high-intensity rainfall events (Goyal and Pandey, 2020). The relationship between stream order and stream length in a drainage basin is described by two fundamental empirical laws formulated by Horton (1945). The first, the Law of Stream Numbers, states that the number of streams decreases geometrically with increasing stream order, quantified by the bifurcation ratio. The second, the Law of Stream Lengths, state that the average length of streams increases geometrically with stream order, indicating that higher-order streams are generally longer than lower-order counterparts. Figure 4 illustrates a strong correlation between stream order and the number of streams across the study area, with coefficients of determination (R^2) ranging from 0.955 for SB4 to 0.999 for SB5, underscoring the consistency of these morphometric relationships.

Bifurcation ratio (Rb)

The bifurcation ratio (Rb), an indicator of the degree of branching within a drainage network, plays a critical role in influencing the peak runoff response of a basin (Mesa, 2006; Chorley, 1969). Typically, Rb values range between 3.0 and 5.0 in basins developed over homogeneous lithologies with minimal structural disruptions, whereas values exceeding 10.0 often reflect significant tectonic or structural controls (Mekel, 1970; Chow et al., 1988). Additionally, watershed morphology substantially affects Rb, with variations in stream network geometry mirrored in changes to bifurcation ratios (Verstappen, 1983; Ghosh and Chhibber, 1984). In the Kadalundi River Basin (KRB), the overall Rb value is notably high at 22.10, with individual sub-basin values ranging from 3.25 to 15.78 (Table 2), aligning with figures typically observed in mountainous or highly dissected terrains.

The relatively narrow variation in mean bifurcation ratios among grouped sub-basins (e.g., SB4 and SB5; SB3, SB6, SB8, SB13, SB14, SB17, SB18, and SB20; SB1, SB7, SB11, SB12, SB15, SB21, and SB22; and SB2, SB9, and SB19) likely reflects underlying geometric similarities of their respective watersheds. Elevated Rb values in SB19, SB9, SB2, and SB1 correspond with hilly landscapes characterized by steeper slopes and structural influences, promoting increased overland flow and discharge. Conversely, lower Rb values in SB4 and SB5 suggest development on relatively uniform rock units with limited structural complexity. Giusti and Schneider (1965) postulated a general decline in Rb values with increasing stream order within a basin; however, this trend is not consistently observed across several KRB sub-basins (SB1, SB2, SB3, SB4, SB5, SB6, SB9, SB10, SB11, SB12, SB14, SB15, SB16, SB20, and SB22), indicating that both lithology and topographic relief exert significant control on stream network branching. Statistical analysis reveals a moderate positive correlation ($r = 0.63$) between basin area and Rb, supporting the notion that basins with varying sizes but equivalent stream order tends to exhibit lower bifurcation ratios in smaller basins, indicative of structural influences driven by tectonic uplift and deformation. In contrast, Rb exhibits modest negative correlations with drainage density (Dd; $r = -0.47$), stream frequency (Fs; $r = -0.42$), and basin elongation ratio (Lb; $r = -0.42$), suggesting complex interactions among morphometric parameters.

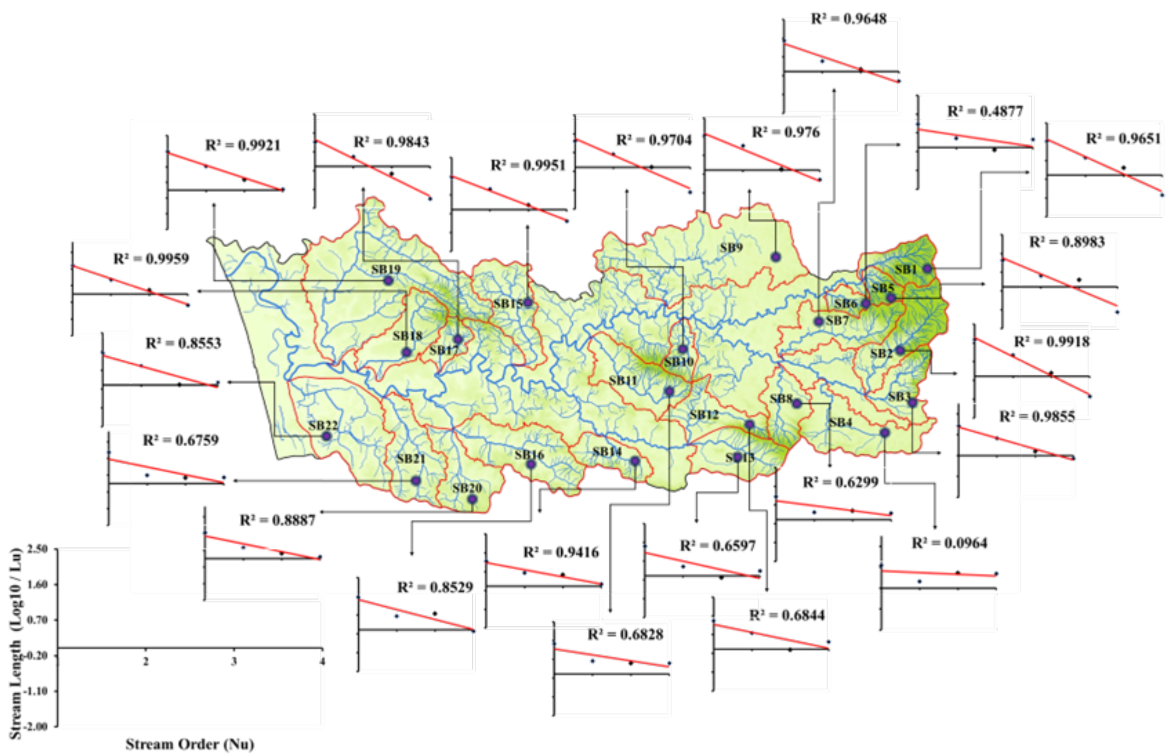

Figure 4. The correlation of stream order with stream length plotted for the fourth-order sub-basins of KRB

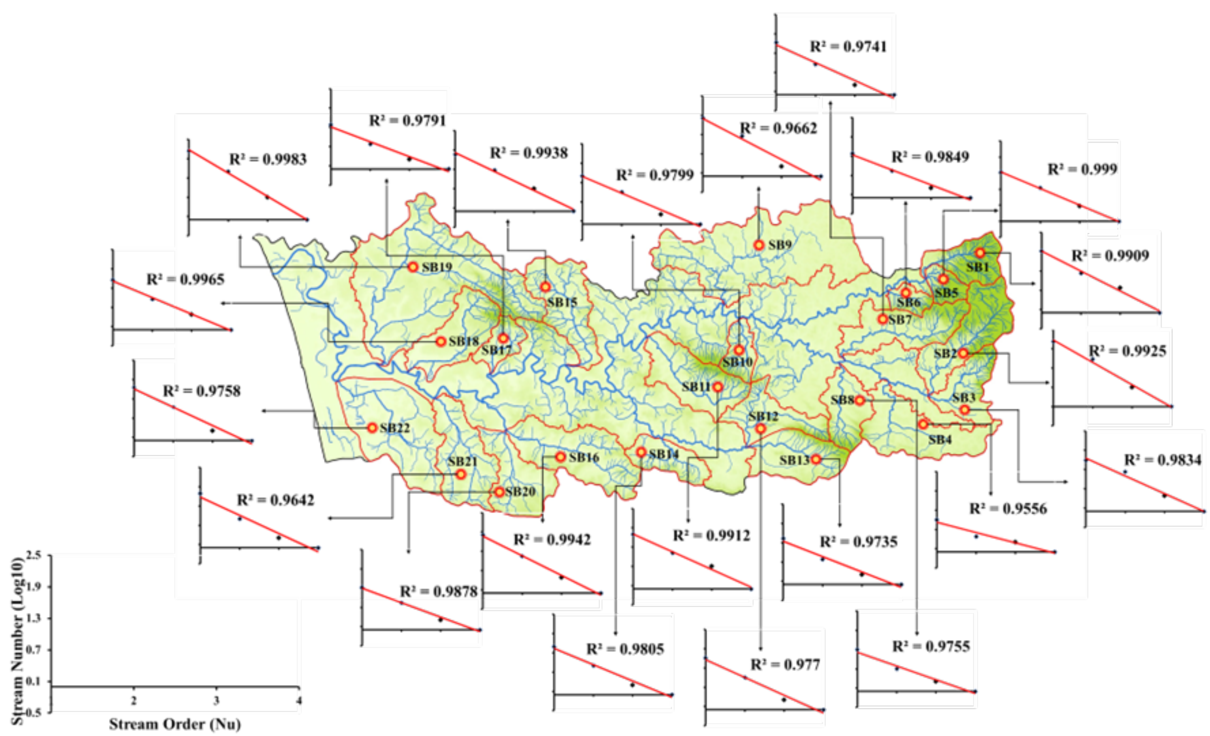

Figure 5. The correlation of stream order with number of streams plotted for the fourth-order sub-basins of KRB

Furthermore, a positive correlation (r = 0.73) underscores the significant role of geoenvironmental variables in governing stream organization within the basin. From a hydrological perspective, elevated bifurcation ratios generally exceeding 4.0 are associated with accelerated runoff and heightened flood potential due to rapid stream convergence, while lower values imply more gradual, stable discharge regimes with reduced flood risk (Sekhar et al., 2023). High Rb values are also commonly linked to steep slopes and increased erosion susceptibility, whereas lower ratios correspond to flatter terrains with greater infiltration capacity and reduced erosive activity (Sekhar et al., 2023).

Stream length ratio (Rl)

The mean Rl of KRB is 9.43, varying from 0.97 to 8.09 across the 22 sub-basins (Table 2). Fluctuations in Rl over successive stream orders result from variations in topography and slope, significantly influencing the watershed's erosional stage and discharge (Sreedevi et al., 2004). While there is no consistent pattern in Rl between consecutive stream orders, some anomalous values suggest that the drainage system is in disequilibrium. This may be linked to the upward extension of tributaries or the downstream extension of higher-order segments. A high negative correlation between mean Rl and area (A) (r = -0.0023) indicates lower erosional activity, less rapid bifurcation, and the development of higher-order streams. The wide variability in Rl values of KRB suggests the dominance of local geology over channel segment lengths. An increase in Rl from lower to higher orders, as seen in KRB, may indicate the attainment of geomorphic maturity. A higher stream length ratio above 2.0 typically promotes slower runoff and delayed peak discharge, resulting in reduced risk of immediate flash floods, while a low stream length ratio leads to faster runoff and an increased risk of flooding, especially during intense rainfall events (Sekhar et al., 2022).

Rho coefficient (ρ)

The Rho coefficient, which allows for evaluating the storage capacity of the drainage network and, consequently, determines the final degree of drainage development in a given watershed, is an essential parameter relating drainage density to the physiographic evolution of a watershed (Horton 1945). The changes in this parameter are influenced by various natural and anthropogenic parameters. Rho values in the KRB and sub-basins span from 0.13 to 0.92 (Table 2). SB 4 reports the largest value (ρ = 0.92) while, SB6, SB8, SB9, SB10, SB11, SB12, and SW13 also show second higher values (ρ ≥ 0.50), indicating increased hydrologic storage with reduced erosion during flood events. A high Rho coefficient often above 0.5 suggests a well-developed drainage network with longer streams relative to their bifurcation, which can lead to slower runoff and lower flood risks, while a low Rho coefficient may indicate faster water concentration and a higher likelihood of flooding due to inefficient drainage systems (Taib et al., 2023).

4.2 Areal aspects

Area (A)

The KRB drains an area of 1268 km^2, and Table 3 lists the areas of each fourth-order sub-basin. Among the 22 sub-basins, SB5 is the smallest of all (A = 4 km^2), whereas SB19 is the largest (A = 119 km^2). SB19, SB4, SB7, SB13, SB17, and SB12 sub-basins have areas less than 20 km^2 while, SB2, SB3, SB4, SB7, SB8, SB9, SB11, SB12, SB13, SB15, SB16, SB18, SB19, SB20, SB21, and SB22 have areas in excess of 20 km^2. The mean area of fourth order watershed stands at 35.55 km^2.

Drainage density (Dd)

Drainage density (Dd) is a crucial hydrological parameter that connects the morphological characteristics of a watershed to the processes occurring along its stream network. It is particularly sensitive to the degree of erosional development within a basin (Strahler, 1952; Gregory and Walling, 1973). According to Verstappen (1983), while multiple factors influence Dd, key contributors include rock resistance to erosion, soil infiltration capacity, and climatic conditions, all of which play a prominent role in determining the degree of fluvial dissection within a drainage basin. In the case of the Kadalundi River Basin (KRB), the overall Dd is 0.91, as shown in Table 3. This value suggests that the basin experiences significant rainfall and is characterized by steep, impermeable, and highly dissected topography (Horton, 1932; Langbein, 1947). Among the sub-basins, SB5 exhibits the highest Dd at 6.07, while SB22 has the lowest value at 0.56, reflecting substantial variability in drainage patterns across the basin. Overall, the KRB and its 22 fourth-order sub-basins can be classified as having moderate to well-developed drainage networks, with variations primarily driven by geological factors, including lithology, rock resistance to erosion, and the infiltration capacity of the terrain.

Table 2. The subbasin wise linear aspects of Kadalundi River basin

#		SB1	SB2	SB3	SB4	SB5	SB6	SB7	SB8	SB9	SB 10	SB 11	SB 12	SB 13	SB 14	SB 15	SB 16	SB 17	SB 18	SB 19	SB 20	SB 21	SB 22	KRB
P		22	36	27	41	12	14	38	23	68	18	31	30	28	22	34	37	19	30	68	34	34	40	227
Lb		7	11	7	6	4	4	12	8	13	6	10	6	8	6	11	13	5	9	15	8	11	13	65
Number of Streams	**N1**	84	107	39	10	34	24	43	20	65	32	50	41	27	31	59	65	24	36	140	21	49	45	1372
	N2	17	30	17	3	11	7	9	5	18	10	13	10	6	8	19	14	6	9	32	7	8	11	348
	N3	6	4	3	2	3	2	2	2	2	2	5	2	2	2	5	3	2	3	5	2	2	2	77
	N4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	22
	N5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	7
	N6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1
	Nt	108	142	60	16	49	34	55	28	86	45	69	54	36	42	84	83	33	49	178	31	60	59	1827
Mean stream length	**L1**	0.53	0.54	0.66	1.22	0.55	0.55	0.70	0.65	0.75	0.56	0.56	0.57	0.98	0.52	0.61	0.55	0.63	0.63	0.66	0.85	0.64	0.75	0.63
	L2	0.40	0.34	0.41	0.69	0.31	0.39	0.35	0.45	0.80	0.43	0.32	0.60	0.46	0.55	0.51	0.32	0.48	0.53	0.54	0.47	0.32	0.77	0.49
	L3	0.37	0.35	0.53	2.62	0.71	0.38	0.63	1.34	0.56	0.50	0.65	0.46	0.40	1.76	0.32	1.96	0.22	0.50	0.69	0.87	0.93	0.51	0.69
	L4	0.11	0.11	0.73	5.00	0.06	2.46	0.34	2.06	0.35	0.06	3.34	2.27	1.71	1.28	0.28	0.84	0.03	0.30	1.13	1.22	1.94	1.35	1.18
	L5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	4.85
	L6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	6.92
	Lt	1.40	1.34	2.33	9.54	1.63	3.79	2.02	4.48	2.46	1.54	4.87	3.90	3.56	4.11	1.72	3.67	1.36	1.96	3.02	3.40	3.82	3.37	14.76
Total stream length	**LT1**	44.46	57.54	25.88	12.23	18.66	13.18	30.02	12.91	48.61	17.78	27.97	23.19	26.49	16.02	35.75	35.58	15.03	22.67	93.06	17.77	31.30	33.68	867.50
	LT2	6.75	10.33	6.92	2.06	3.45	2.76	3.16	2.24	14.46	4.26	4.19	6.03	2.78	4.42	9.71	4.49	2.90	4.77	17.31	3.28	2.54	8.44	169.68
	LT3	2.21	1.40	1.58	5.25	2.12	0.77	1.25	2.67	1.12	1.00	3.23	0.92	0.80	3.52	1.62	5.87	0.45	1.51	3.45	1.74	1.86	1.02	52.94
	LT4	0.11	0.11	0.73	5.00	0.06	2.46	0.34	2.06	0.35	0.06	3.34	2.27	1.71	1.28	0.28	0.84	0.03	0.30	1.13	1.22	1.94	1.35	26.04
	LT5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	33.94
	LT6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	6.92
	LT	53.53	69.36	35.12	24.55	24.29	19.17	34.78	19.88	64.54	23.10	38.73	32.41	31.78	25.24	47.36	46.78	18.41	29.24	114.95	24.01	37.64	44.49	1157.01
	Rb1-2	4.94	3.57	2.29	3.33	3.09	3.43	4.78	4.00	3.61	3.20	3.85	4.10	4.50	3.88	3.11	4.64	4.00	4.00	4.38	3.00	6.13	4.09	3.94
	Rb2-3	2.83	7.50	5.67	1.50	3.67	3.50	4.50	2.50	9.00	5.00	2.60	5.00	3.00	4.00	3.80	4.67	3.00	3.00	6.40	3.50	4.00	5.50	4.52
	Rb3-4	6.00	4.00	3.00	2.00	3.00	2.00	2.00	2.00	2.00	2.00	5.00	2.00	2.00	2.00	5.00	3.00	2.00	3.00	5.00	2.00	2.00	2.00	3.50
	Rb4-5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3.14
	Rb5-6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	7.00
	Rb	13.77	15.07	10.96	6.83	3.25	8.93	11.28	8.50	14.61	10.20	11.45	11.10	9.50	9.88	11.91	12.31	9.00	10.00	15.78	8.50	12.13	11.59	22.10
	R1 2-1	0.75	0.64	0.61	0.56	0.57	0.72	0.50	0.69	1.07	0.77	0.58	1.07	0.47	1.07	0.84	0.59	0.77	0.84	0.81	0.55	0.50	1.02	0.77
	R1 3-2	0.93	1.01	1.30	3.82	2.26	0.98	1.79	2.99	0.70	1.17	2.00	0.77	0.87	3.19	0.63	6.09	0.46	0.95	1.28	1.85	2.92	0.67	1.41
	R1 4-3	0.30	0.31	1.38	1.91	0.09	6.40	0.55	1.54	0.62	0.13	5.17	4.91	4.25	0.73	0.86	0.43	0.12	0.59	1.63	1.40	2.09	2.63	1.72

Rl 5-4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	4.10
Rl 6-5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.43
Rl	1.98	1.96	3.29	6.29	2.92	8.09	2.84	5.22	2.39	2.06	7.75	6.74	5.59	4.98	2.34	7.11	1.36	2.38	3.72	3.80	5.50	4.32	9.43
Rho	0.14	0.13	0.30	0.92	0.90	0.91	0.25	0.61	0.16	0.20	0.68	0.61	0.59	0.50	0.20	0.58	0.15	0.24	0.24	0.45	0.45	0.37	0.43

Note: #, Parameters; P, perimeter; Lb, basin length; Rb, bifurcation ratio; Rl, stream length ratio; and Rho, Rho coefficient.

Table 3. Areal parameters of MW and sub-basins of Kadalundi River basin

#	SB 1	SB 2	SB 3	SB 4	SB 5	SB 6	SB 7	SB 8	SB 9	SB 10	SB 11	SB 12	SB 13	SB 14	SB 15	SB 16	SB 17	SB 18	SB 19	SB 20	SB 21	SB 22	KRB
A	19	37	22	38	4	7	34	22	93	13	36	22	30	17	34	46	12	31	119	30	37	79	1268
Dd	2.82	1.87	1.60	0.65	6.07	2.74	1.02	0.90	0.69	1.78	1.08	1.47	1.06	1.48	1.39	1.02	1.53	0.94	0.97	0.80	1.02	0.56	0.91
Fs	5.68	3.84	2.73	0.42	12.25	4.86	1.62	1.27	0.92	3.46	1.92	2.45	1.20	2.47	2.47	1.80	2.75	1.58	1.50	1.03	1.62	0.75	1.44
T	16.02	7.19	4.35	0.27	74.39	13.30	1.65	1.15	0.64	6.15	2.06	3.62	1.27	3.67	3.44	1.84	4.22	1.49	1.44	0.83	1.65	0.42	1.31
Lg	0.18	0.27	0.31	0.77	0.08	0.18	0.49	0.55	0.72	0.28	0.46	0.34	0.47	0.34	0.36	0.49	0.33	0.53	0.52	0.62	0.49	0.89	0.55
C	0.35	0.53	0.63	1.55	0.16	0.37	0.98	1.11	1.44	0.56	0.93	0.68	0.94	0.67	0.72	0.98	0.65	1.06	1.04	1.25	0.98	1.78	1.10
Ff	0.39	0.31	0.45	1.06	0.25	0.44	0.24	0.34	0.55	0.36	0.36	0.61	0.47	0.47	0.28	0.27	0.48	0.38	0.53	0.47	0.31	0.47	0.30
Rc	0.49	0.36	0.38	0.28	0.35	0.45	0.30	0.52	0.25	0.50	0.47	0.31	0.48	0.44	0.37	0.42	0.42	0.43	0.32	0.33	0.40	0.62	0.31
Re	0.70	0.62	0.76	1.16	0.56	0.75	0.55	0.66	0.84	0.68	0.68	0.88	0.77	0.78	0.60	0.59	0.78	0.70	0.82	0.77	0.62	0.77	0.62
Sw	2.58	3.27	2.23	0.95	4.00	2.29	4.24	2.91	1.82	2.77	2.78	1.64	2.13	2.12	3.56	3.67	2.08	2.61	1.89	2.13	3.27	2.14	3.33

Note: #, Parameters; A, area; Dd, drainage density; Fs, stream frequency; T, drainage texture; Lg, length of overland flow; C, constant of channel maintenance; Ff, form factor; Rc, circularity ratio; Re, elongation ratio; and Sw, shape index.

Table 4. Relief parameters of MW and sub-basins of Kadalundi River basins

#	SB 1	SB 2	SB 3	SB 4	SB 5	SB 6	SB 7	SB 8	SB 9	SB 10	SB 11	SB 12	SB 13	SB 14	SB 15	SB 16	SB 17	SB 18	SB 19	SB 20	SB 21	SB 22	KRB
R	1182	1302	864	358	1074	493	1137	498	165	572	590	502	505	168	343	170	463	470	439	171	129	106	1320
Rr	0.17	0.12	0.12	0.06	0.27	0.12	0.09	0.06	0.01	0.10	0.06	0.08	0.06	0.03	0.03	0.01	0.09	0.05	0.03	0.02	0.01	0.01	0.02
Rn	3.33	2.44	1.38	0.23	6.52	1.35	1.16	0.45	0.11	1.02	0.63	0.74	0.53	0.25	0.48	0.17	0.71	0.44	0.42	0.14	0.13	0.06	1.20
DI	0.94	0.97	0.94	0.94	0.94	0.91	0.98	0.96	0.92	1.06	0.98	0.84	0.97	0.93	1.01	1.06	1.01	1.02	1.00	1.07	1.08	1.06	0.99
Es (m)	1200	1158	640	232	1058	488	968	476	60	432	482	486	428	160	240	138	350	460	340	152	88	80	1340
Em (m)	96	60	60	44	98	70	40	40	40	40	20	42	42	20	20	20	20	20	20	20	20	20	20
Rg	1.58	1.00	0.83	0.31	2.40	1.05	0.77	0.55	0.02	0.65	0.46	0.74	0.48	0.23	0.20	0.09	0.66	0.49	0.21	0.17	0.06	0.05	0.20
MRn	0.27	0.21	0.18	0.06	0.54	0.19	0.19	0.11	0.02	0.16	0.10	0.11	0.09	0.04	0.06	0.03	0.13	0.08	0.04	0.03	0.02	0.01	0.04

Note: #, Parameters; R, basin relief; Rr, relief ratio; Rn, ruggedness number; DI, dissection index; Es, elevation at source; Em, elevation at mouth; Rg, gradient ratio; and MRn, Melton ruggedness number.

A high drainage density indicates a dense network of streams, resulting in faster runoff and a higher likelihood of flash flooding, while a low drainage density suggests slower water movement and reduced flood risks. High Dd values are typically associated with steep slopes and low permeability surfaces, which enhance surface runoff and predispose the region to rapid accumulation of water, thereby increasing the potential for flooding.

Stream frequency (Fs)

The Fs for KRB is 1.4 km^{-2}, while Fs of the sub-basins are presented in Table 3. In addition, Fs possess a strong positive correlation with Dd value. Fs across the sub-basins vary significantly, ranging from 0.42 in SB4 to 12.25 in SB5. Sub-basins with higher Fs values, such as SB5 (12.25) and SB9 (0.92), exhibit greater stream densities, indicating more frequent and potentially smaller streams per unit area. In contrast, sub-basins with lower Fs values, such as SB4 (0.42) and SB22 (0.75), have fewer streams, which may suggest less frequent stream development or more extensive areas of less densely branched networks. This variability in stream frequency highlights differences in drainage density and landscape characteristics across the sub-basins, reflecting varying degrees of surface runoff, erosion, and potential geological influences on stream distribution. A high drainage frequency indicates more channels per area, leading to quicker surface runoff and an increased risk of flash floods, while a low drainage frequency allows for slower water movement and reduced flood risks (Rahman et al, 2023; Cea and Costabile, 2022).

Drainage texture (T)

Drainage texture refers to the relative spacing of channels within a fluvially dissected terrain, providing insight into the hydrological characteristics and stage of development of a watershed (Smith, 1950). Several factors influence drainage texture, including lithology, vegetation, climate, soil type, relief, and the overall developmental stage of the watershed. The drainage texture (T) values for the Kadalundi River Basin (KRB) and its 22 sub-basins are presented in Table 3. According to Smith's (1950) classification, drainage texture can be categorized into five distinct classes based on drainage density (Dd) values: very coarse (<2), coarse (2-4), moderate (4-6), fine (6-8), and very fine (>8). In the present study, the KRB and sub-basins such as SB4, SB7, SB8, SB9, SB13, SB16, SB18, SB19, SB20, SB21, and SB22 are classified as exhibiting very coarse texture, reflecting their high drainage densities. Sub-basins SB11, SB12, SB14, and SB15 are categorized as coarse texture, while SB3 and SB17 show moderate texture. SB2 and SB10 exhibit fine texture, and sub-basins SB1, SB5, and SB6 are classified as very fine texture. A higher drainage texture value indicates a denser network of streams, which accelerates surface runoff and increases the likelihood of flash flooding.

This is primarily due to the reduced infiltration time in regions with closely spaced drainage channels.

Length of overland flow (Lg)

The length of overland flow (Lg), which affects the physiographic and hydrologic evolution of drainage basins, is determined by the amount of water flowing over land before concentrating in specific stream channels (Horton, 1945). KRB has an Lg value of 0.55, while sub-basins range from 0.08 to 0.89 (Table 3). Both KRB and most sub-basins are in a mature geomorphic stage, characterized by relatively higher Lg values. In contrast, SB5, with a lower Lg value, is in a late youth or early mature stage of development. A short overland flow distance leads to quicker water concentration in streams, increasing the risk of flash floods, while a longer distance allows more infiltration, reducing flood risks (Le et al., 2022).

Constant of channel maintenance (C)

The C values for the fourth-order sub-basins range from 0.16 to 1.78, with KRB showing a value of 1.10 (Table 3). Sub-basins with lower C values are predominantly found in less dissected regions with moderate structural impacts (Vijith and Satheesh, 2006). In contrast, sub-basins such as SB4, SB7, SB8, SB9, SB11, SB13, SB16, and SB22, which have higher C values, indicate significantly higher infiltration rates compared to the others. A low constant of channel maintenance indicates a denser drainage network, leading to faster runoff and greater flood risk (Soni 2017).

Form factor (Ff)

According to Horton (1945) and Gregory and Walling (1973), the flow frequency (Ff) parameter forecasts the flow intensity of a watershed and is directly related to peak discharge. The Ff for KRB is 0.30, while the values for the 22 sub-basins range from 0.24 to 1.06 (Table 3). Sub-basins such as SB4, SB9, SB12, and SB19, with Ff values greater than 0.50, indicate higher flow peaks but of shorter duration. In contrast, sub-basins like SB1, SB2, SB5, SB7, SB15, SB16, and SB21, with Ff values of 0.30 or lower, suggest a more elongated watershed shape and flatter peak flows of longer duration. The remaining sub-basins have Ff values between 0.30 and 0.50. A low form factor (elongated basins) results in slower, sustained runoff, while a high form factor (circular basins) causes faster concentration of runoff, increasing flood potential (Bogale, 2021).

Circularity ratio (Rc)

The circularity ratio (Rc) is defined as the ratio of the basin area (A) to the area of a circle that has the same perimeter as the basin. An Rc value of 1.0 is achieved when the watershed's outline is perfectly circular (Miller, 1953). The Kadalundi River Basin (KRB) has an Rc value of 0.31, with

Rc values for the 22 sub-basins ranging from 0.25 to 0.62 (Table 3). Lower Rc values indicate an elongated shape, while higher Rc values are indicative of basins with shapes approaching circularity. Sub-basins SB1 to SB21 exhibit low Rc values, reflecting their more elongated forms, whereas SB22, with a high Rc value of 0.62, indicates a relatively more circular shape. A high Rc value suggests that the basin is more mature, with water more quickly concentrated within the basin, heightening the potential for flooding, particularly during periods of peak discharge. In contrast, sub-basins with lower Rc values indicate a younger, less evolved watershed stage. The evolutionary stage of a watershed, as reflected by Rc, influences hydrological dynamics: basins with higher Rc values (e.g., SB22) are more prone to rapid water concentration and elevated flood risks, while basins with lower Rc values are associated with less immediate runoff and more dispersed water flow (Islam, 2020).

Elongation ratio (Re)

The relief ratio (Re) of KRB is 0.62, while it ranges from 0.55 to 1.16 in the 22 sub-basins (Table 3). According to Verstappen (1983), watersheds with higher Re values, such as SB4, SB9, SB12, and SB19, have shorter flow paths, leading to a greater discharge over a shorter period of time. Based on the classification by Strahler (1964), SB4, SB9, SB12, and SB19 have outlines that are more oval-shaped (0.90 > Re > 0.80), while SB1, SB3, SB6, SB13, SB14, SB17, SB18, SB20, and SB22 have less elongated outlines (0.80 > Re > 0.70). The remaining sub-basins are characterized by elongated outlines (Re < 0.70). The elongated shape of a watershed, coupled with high relief and steep slopes, typically results in a smoother hydrograph, as the time lag for water to travel from the upper reaches of the catchment to the outlet is extended. A low elongation ratio (indicating an elongated basin) generally leads to slower water concentration, thereby reducing the flood risk. In contrast, a high elongation ratio (indicating a basin with a shape approaching circularity) accelerates the concentration of runoff, increasing the potential for flooding during peak flow events (Soni, 2017).

Shape index (Sw)

The stream frequency ratio (Sw) for the Kadalundi River Basin (KRB) is 3.33, with values for the individual sub-basins ranging from 0.95 to 4.24 (Table 3). This metric reflects the number of streams per unit area, indicating variability in the stream density across the basin. Additionally, the length-to-width ratio of the drainage network in KRB is 1:2.95, suggesting that drainage channels are more developed along the width of the basin, rather than extending predominantly in the east-west direction. This configuration highlights the influence of topography and the basin's geomorphological development on the stream network's orientation and density. A high shape index indicates a basin that is more elongated, reducing the speed of runoff and the flood risk, while a low shape index leads to faster water concentration (Das et al., 2022).

4.3 Relief aspects

Basin relief (R)

According to Hadley and Schumm (1961), the parameter R influences stream gradient, flood patterns, and the amount of sediment that can be transported. It can be significantly affected by isolated peaks within the watershed. Understanding the basin's denudational features requires consideration of its relief (Sreedevi et al., 2004). The KRB has an RRR value of 1320 m, while the RRR values for the 22 sub-basins are provided in Table 4. The larger RRR values observed are attributed to the paleo- and neo-tectonic activities of the Western Ghats.

Relief ratio (Rr)

It is widely accepted that Rr, a dimensionless height-to-length ratio representing basin length and relief, is a useful indicator of the watershed's gradient aspects (Schumm, 1956). The Rr value for KRB is 0.05, while the Rr values for all sub-basins are provided in Table 4. The basement rocks of sub-basins SB4, SB7, SB8, SB9, SB10, SB11, SB12, SB13, SB14, SB15, SB16, SB17, SB18, SB19, SB20, SB21, and SB22 are exposed as ridges and mounts and are showing relatively low Rr values (Rr<0.10R_r < 0.10Rr<0.10). In contrast, SB5 shows higher Rr values (Rr>0.20R_r > 0.20Rr >0.20), suggesting the presence of areas with steeper slopes and higher relief underlain by resistant rocks (Vittala et al., 2004). A high relief ratio suggests steeper slopes and faster runoff, elevating the risk of floods (Chaithong, 2022).

Ruggedness number (Rn)

The ruggedness number (Rn) is obtained by multiplying drainage density by basin relief (Strahler, 1958). The Rn for KRB is 1.20, while the Rn values for the 22 sub-basins are provided in Table 4. These values range from 0.06 (SB22) to 6.52 (SB5). The high ruggedness values for KRB and its sub-basins indicate that these areas are more susceptible to soil erosion and exhibit intrinsic structural complexity related to their relief and drainage density (Vijith and Satheesh, 2006). A high ruggedness number indicates rugged, uneven terrain, which leads to rapid runoff and a higher flood potential (Artha et al., 2024).

Dissection index (DI)

According to Singh and Dubey (1994), DI is a parameter that indicates the extent of vertical erosion or dissection and describes the phases of landscape or terrain evolution in a given physiographic region or watershed. On average, DI values range from '0', indicating a completely flat surface with no vertical dissection or erosion to '1'. DI value of KRB and the sub-basins (Table 4), imply that the basin it's a young or rejuvenated stage of geomorphic development and minimum denudation stage. Subbasins SB10, SB15, SB16, SB17, SB18, SB19, SB20, SB21, and SB22 sub-basins are relatively younger or rejuvenated (DI > 1), while SB1, SB2, SB3, SB4, SB5, SB6, SB7, SB8, SB9, SB11, SB12, SB13, and SB14 are moderately young or rejuvenated (DI > 0.90). A high dissection index reflects steep, highly dissected terrain, increasing the potential for quick runoff and flash floods (Tola and Shetty, 2022).

Gradient ratio (Rg)

Gradient ratio is a channel slope indicator that allows the runoff volume to be evaluated (Sreedevi et al. 2004). KRB has an Rg of 0.20 and that of all sub-basins (Table 4) varies from 0.02 (SB9) to 2.40 (SB5). The greater Rg values represent rugged topography with mountainous terrains. Approximately 75% of the main stream flows through the plateau which is also confirmed by the relatively low values of Rg. A high gradient ratio indicates steep slopes, which result in faster water movement, increasing flood risk.

Melton ruggedness number (MRn)

Relief ruggedness within the watershed is spatially represented by the MRn, a slope index (Melton 1965). MRn of the river basin is 0.04, while that of the subbasins ranges from 0.01 to 0.54 (Table 4). Based on Wilford classification, SB1, SB2, and SB5 are debris flood watersheds where the bed load component dominates sediment under transport, while the remainder of sub-basins and KRB are water flood watersheds (Wilford et al. 2004). The occurrence of debris flows and the movement of sediment by rivers are contingent upon the availability of debris. However, a less rugged landscape suggests the presence of locations that can effectively capture debris from upstream regions and tributaries where debris flow predominates, thereby facilitating bed load transport, as reported by Marchi and Fontana (2005). A high Melton ruggedness number suggests steep, rugged terrain, leading to fast runoff and a higher likelihood of flash floods (Shivhare et al., 2024).

Hypsometric integrals (Hi) and hypsometric curves

The hypsometric curve is a graphical representation that depicts the relationship between the elevation and area of a basin. It provides insight into the developmental stages of a watershed by illustrating how much of the basin's area lies within various elevation ranges.

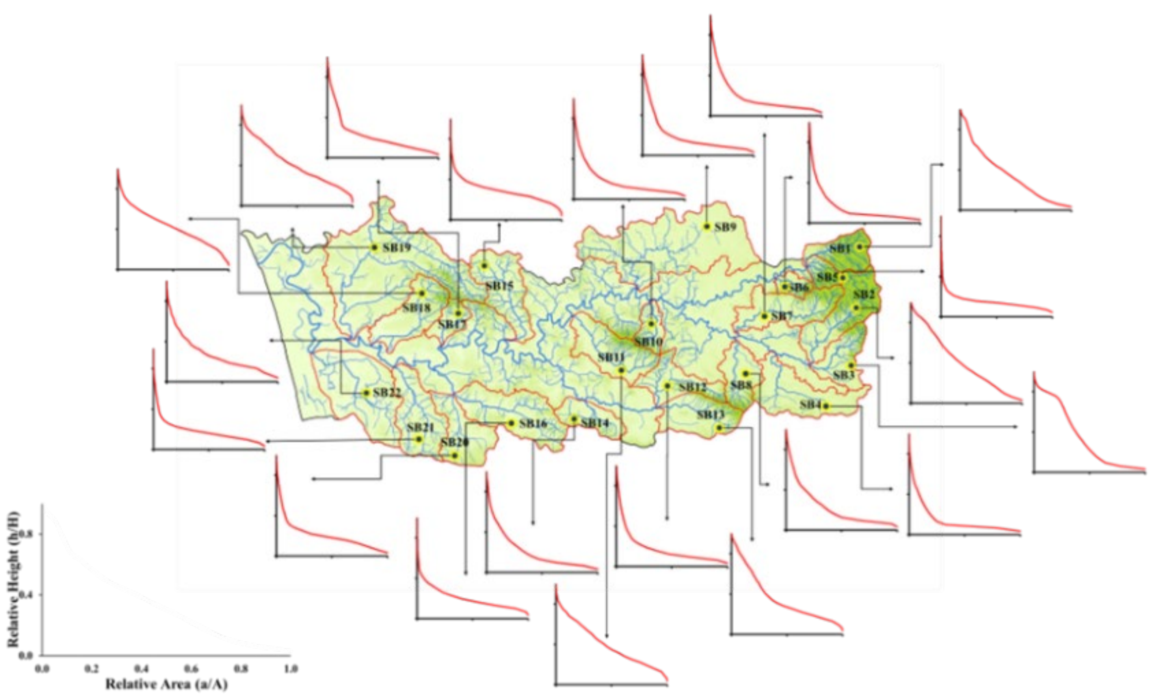

Figure 6. Hypsometric curves of the fourth order sub-basins in KRB

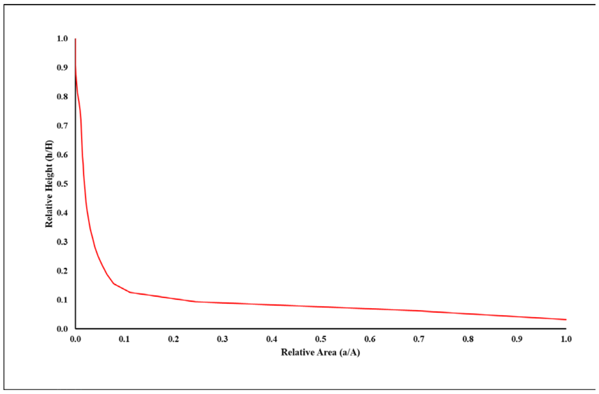

Figure 7. Hypsometric curve

The hypsometric integral (HI) quantifies this relationship and is used to calculate the total volume of the non-eroded portion of the basin. It is a dimensionless measure that reflects the relative distribution of elevation within a basin, offering insights into its geomorphological evolution. The HI values of subbasins and the stage of development are detailed in Table 5. Higher HI suggests significant recent incisions into younger geomorphic surfaces, which may have resulted from depositional processes or active tectonics in the basin (El Hamdouni et al. 2008). Conversely, lower HI values often indicate more mature landscapes that have experienced considerable erosion. In the present study, the HI values for the KRB and its 22 sub-basins range from 0.47 to 0.504, indicating medium to high hypsometric integral values. This range suggests that the landscapes in these areas are relatively mature, with ongoing balanced erosion processes. The hypsometric curves for these basins generally exhibit an 'S' shape indicating the mature stage of river basins, with balanced erosion processes. The topography has been shaped by both erosional and tectonic forces. The medium HI values suggest that these basins are experiencing a moderate degree of erosion, with geomorphic surfaces having undergone both recent and historical tectonic activities. The 'S' type hypsometric curve typically signifies that the basin's landscape is in equilibrium, having reached a stage where erosion and sediment transport are relatively balanced. This implies that while there is evidence of ongoing geomorphic processes, the landscape is not in an early stage of active tectonic uplift or significant depositional changes. Figures 6 and 7 illustrate the hypsometric curves for the basins, reinforcing the observation of mature and balanced erosion stages. The consistency of HI values across the sub-basins and the KRB further supports the conclusion that these areas have reached a state of geomorphic maturity, where the impact of recent active tectonics is moderate. The HI values and hypsometric curve shapes indicate that the basins studied are in a mature stage of development, characterized by balanced erosion processes and moderate impact from recent tectonic activities. This reflects a landscape that has undergone significant geomorphic evolution and is currently experiencing a state of relative equilibrium.

Table.5. Sub-basin wise HI values and stage of evolution in the Kadalundi River basin

Basins	HI Value	Stage of basin
SB1	0.491	Mature Stage
SB2	0.49	Mature Stage
SB3	0.48	Mature Stage
SB4	0.481	Mature Stage
SB5	0.504	Mature Stage
SB6	0.487	Mature Stage
SB7	0.492	Mature Stage
SB8	0.47	Mature Stage
SB9	0.48	Mature Stage
SB10	0.472	Mature Stage
SB11	0.486	Mature Stage
SB12	0.476	Mature Stage
SB13	0.491	Mature Stage
SB14	0.476	Mature Stage
SB15	0.471	Mature Stage
SB16	0.497	Mature Stage
SB17	0.484	Mature Stage
SB18	0.492	Mature Stage
SB19	0.483	Mature Stage
SB20	0.485	Mature Stage
SB21	0.47	Mature Stage
SW22	0.481	Mature Stage
KRB	0.47	Mature Stage

4.4 Hydrological implications

The stream network development in the Kadalundi River Basin (KRB) exhibits asymmetry, with thirteen tributaries originating from the right bank, compared to only nine tributaries on the left bank. This asymmetry creates a hydrological disparity within the watershed, suggesting that watershed geometry and drainage properties have a significant influence on the hydrologic regime, both within individual sub-basins and across the entire basin.

While much of the focus in river basin development and management strategies has been on morphometric analysis of the river and its basin, there remains a gap in understanding the relationships among various morphometric parameters and their direct impact on hydrological variables. A detailed morphometric analysis is essential for understanding the hydrological behavior of drainage basins. Insight into how river basins respond to both natural processes and anthropogenic influences is critical for developing effective management strategies. The effects of morphometric parameters on factors such as stream flow, sediment transport, and debris flows are vital for formulating basin-specific management approaches.

5. Conclusions

The evaluation of the drainage characteristics of the Kadalundi River Basin (KRB) and its fourth-order sub-basins underscores the critical role of morphometric analysis in understanding terrain features and basin evolution. The key findings of the study are as follows:

Drainage Network: The KRB exhibits a well-developed drainage system, with a preponderance of first- and second-order streams. The network follows Horton's laws, revealing a relatively low overall drainage density. However, the central, eastern, and northeastern regions of the basin display a dense concentration of drainage channels, indicative of mountainous terrains. Toward the river's mouth, the river traverses a plain area, resulting in a shift in drainage characteristics.

Structural Influence: High bifurcation ratios and drainage density (Dd) suggest considerable structural disturbances, such as lineaments, fractures, and antiforms and synforms in the rocky basement. These features significantly influence surface runoff, leading to steeper slopes and increased dissection in the basin, a process compounded by the region's humid climate. Conversely, sub-basins with lower stream frequency and more elongated shapes exhibit slower runoff, which mitigates the risk of flash floods and promotes greater water infiltration.

Relief and Morphology: The relief parameters reveal that the KRB encompasses complex mountainous and plateau landscapes, which are pivotal in shaping stream segments. The drainage pattern is predominantly influenced by the basin's relief and structural features.

Hypsometric Integral (HI): The HI values, ranging from 0.47 to 0.504, reveal that much of the basin is characterized by an S-type hypsometric curve. This, along with the moderate HI values, indicates a mature landscape with balanced erosion and moderate impacts from recent tectonic activity.

Flood Dynamics and Erosion: The elongated shape of the KRB suggests lower flood peaks but longer flood durations, which could offer advantages in flood management.

The high bifurcation ratios, along with high drainage density and low elongation ratios, suggest geological control from recent tectonic processes, shaping the drainage network. The basin is subject to sheet, rill, and gully erosion, with significant sediment transport, further compounded by extensive plantations of coconut, areca nut, secondary pepper, and banana.

Integrated Hydrological Insights: The complex hydrological system and morphometric characteristics provide valuable insights into both terrain and hydrological behavior. The integration of morphometric analysis with conventional watershed assessment methods provides a more comprehensive understanding for effective watershed management. In conclusion, this study highlights the critical importance of combining morphometric and hydrological analyses to fully comprehend the dynamics of watershed behavior. These findings emphasize the need for a holistic approach in watershed management strategies, particularly for addressing issues related to erosion, sediment transport, and flood management.

CRediT authorship contribution statement.

Mohammed Maharoof P: Conceptualization, Methodology, Software, Investigation, Data Curation, Writing – Original Draft, Visualization; **Raicy M C:** Formal Analysis, Validation, Writing – Review & Editing; **C D Aju:** Conceptualization, Supervision, Project Administration, Writing – Review & Editing**; A. L Achu:** Resources, Supervision, Writing – Review & Editing**.**

Declaration of competing interest

The authors declare that they have no known financial or personal conflicts of interest that could have influenced the work reported in this paper.

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