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Article

Morphometric characterization of the Rani-khola watershed, Sikkim, India, using remote sensing and GIS techniques

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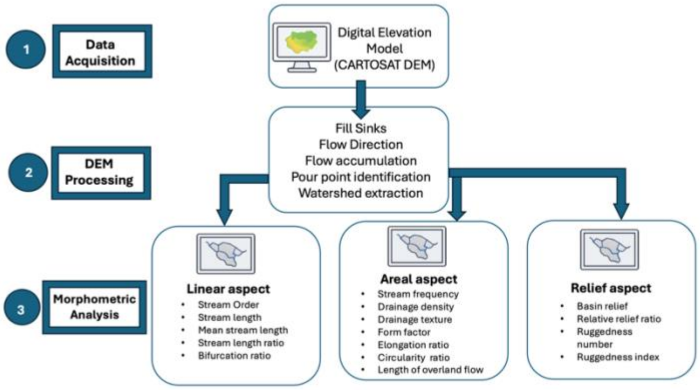

Highlights

- *The Rani-khola watershed was characterized by a dendritic drainage pattern and a coarse drainage texture.*
- *The drainage density and stream frequency were attributed to highly permeable subsoil and dense vegetation conditions.*
- *Morphometric analysis indicated that the watershed would experience reduced peak flows of longer duration.*
- *Rani-khola watershed could be considered as an area with good spring-water prospects.*

Abstract

Morphometric analysis is a quantitative method that involves comparison and statistical determination of the physical and hydrological characteristics of a watershed. Remote sensing (RS) and geographic information system (GIS) have been adopted because they provide detailed spatial data used in watershed characterization. Several morphometric parameters have been determined using a remotely sensed digital elevation model (DEM). The study area, the Rani-khola watershed in Sikkim, India, has a regional elevation ranging from 300 to 4,100 m and is bounded by high mountains of the Himalayas and low valleys. Rani-khola stream is a 4th order stream which is also a tributary of river Teesta having a total length of 153.88 km. The mean bifurcation ratio was 1.7, which implies that the basin can be categorized as normal, i.e., containing an elongated and dendritic type drainage pattern. The drainage density and stream frequency of the stream were 0.60 km/km^2 and 0.57 streams/km^2, respectively, which indicates that the basin exhibits highly permeable subsoil and dense vegetation conditions. The drainage texture of the watershed was calculated as 1.82 km^{-1}, which indicates a very coarse drainage texture. Further studies integrating ground control points would be necessary to develop an appropriate natural resource management plan.

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1 Introduction

Morphometric analysis refers to the quantitative assessment of landform features (Uniyal and Gupta, 2013; Yunus et al., 2014; Sukristiyani et al., 2018). This analysis is widely used as a basis for watershed characterization and achieving valuable insights into the hydrogeological behavior of the watershed (Memon et al., 2024; Shekar and Mathew, 2024). Topographical maps were used for the quantitative analysis and characterization of the drainage basin. Although the topographic maps were very helpful for carrying out these studies, they were laborious and time-consuming. Remotely sensed digital elevation models (DEM) and geographic information systems (GIS) have become powerful tools to extract morphometric characteristics of a drainage basin (Vijith and Satheesh, 2006; Shekar and Mathew, 2024). As most portion of the rainfall is lost as runoff, the drainage basin analysis for hilly terrain plays an important role in designing and selecting sites for water storage structures such as check dams and reservoirs. The analysis further aids in planning of drainage channels for erosion prone regions, and irrigation water management (Waikar and Nilawar, 2014). Improvised management of natural resources with the developed GIS databases has been made possible in the current social situation (Todorovic and Steduto, 2003).

Bogale (2021) carried out morphometric analysis in the Gilgel Abay watershed, Ethiopia. They used remote sensing (RS) and GIS techniques to calculate various morphometric parameters. The Shuttle Radar Topography Mission (SRTM) DEM was used to carry out the study. They observed that the upper part of the Gilgel Abay watershed was susceptible to flood and soil erosion, while infiltration and sediment deposition were at the downstream (Bogale, 2021). Bogale (2021) further observed significant hydrological variation within the basin with a greater potential for flooding and soil erosion. Vitalla et al. (2004) carried out morphometric analysis in 9 sub-watersheds of Tumkur district, South India, using IRS-1C and 1D of both LISS-III and PAN satellite sensors data. They showed that, of all the 9 sub-watersheds, stream frequencies were positively correlated with the drainage density. Of the 9 sub-watersheds, eight sub-watersheds were observed to have an elongated pattern.

Ansari et al. (2012) conducted GIS-based morphometric analysis in parts of Fatehabad district, North India, using SRTM DEM in three sub-basins. Drainage maps were created using Survey of India toposheet and geocoded false color composite (FCC) of bands 2, 3, and 4 of IRS-1D, and LISS-III satellite sensors. They concluded that the sub-basins were elongated, and stream frequencies exhibited positive correlation with the drainage density values for basins I and III. Waikar and Nilawar (2014) delineated the morphometric characteristics of the Penganga River, Maharashtra, using the RS and GIS approach, in which they suggested that the basin was nearly elongated and was classified as a sub-dendritic to dendritic pattern. The river is a fourth ordered stream and has low run off and high infiltration rates, suggesting a good groundwater prospect.

López-Ramos et al. (2022) observed that the middle and lower Sinú River basin is highly flood-prone, and they successfully applied a rainwater harvesting potential index to identify zones optimal for water resource management. Their study illustrated how morphometric and GIS-derived data can guide sustainable water planning and broader basin-scale decision-making. Mani et al. (2022) studied the Suswa River basin using a 30 m SRTM DEM and observed a sub-dendritic to dendritic drainage pattern. They estimated a drainage density of 2.84 km/km^2, and an elongation ratio of 0.49—indicating a distinctly elongated basin with moderate relief. The morphometric analysis of the Halda River basin using GIS technique revealed critical spatial variations in drainage density, slope, and infiltration capacity, indicating zones with higher susceptibility to erosion and surface runoff (Chowdhury, 2024). All these findings highlighted the importance of integrating GIS-derived morphometric parameters into watershed planning to support sustainable flood control and soil conservation strategies.

The present study addressed the drainage characteristics of the Rani-khola watershed in Sikkim, India. We used a combination of RS and GIS techniques to study the morphometry of the watershed. The climate of Rani-khola is under serious stress due to the constructions of roads, bridges, the expansion of urban areas, and hydroelectric power development (Dey et al., 2025). In recent years, these human-driven developmental activities, combined with climate change and other natural processes, have increasingly disrupted the ecological balance surrounding Rani-khola watershed regions (Shekar and Mathew, 2022). Therefore, understanding the hydrology of the Rani-khola watershed drainage basin could be useful in planning and designing appropriate environmental conservation measures to protect the soil and water resources.

2 Study area

The Rani-khola (also called Rongni Chu) watershed has an area of approximately 253 km^2 (**Fig. 1**). It lies between latitude of 27°23'50.17" and 27°13'7.5" N and longitude of 88°29'34.71" and 88°43'19.57" E. The basin has a perimeter of 79.53 km and a length of 30.64 km. The elevation of the basin varies from 300 m at the valley to 4,100 m at the peak. As the region lies in the sub-Himalayan plains, it is characterized by extremely high mountains (>4,000 m), very high mountains (3,000–4,000 m), high mountains (2,000–3,000 m), medium high mountains (1,000–2,000 m), low mountains (<1,000 m), landslide zones and narrow valleys.

The watershed is a sub-system of river Teesta and joins river Teesta near Singtam, Sikkim, while it originates from a high peak as Rora Chu. Its tributaries downstream are Yali Chu, Rishi-khola, Leh Chu, Tsang Rang Chu (Kali-khola), Rani-khola, Aho-khola, Andheri-khola, Chuba-khola, Pagla-khola, Martham-khola, Sang-khola; Rongni Chu, and finally contributes to the river Teesta. The sharp decrease in elevation from 4,100 m to 300 m resulted in diverse climatic conditions within the watershed, which is predominantly

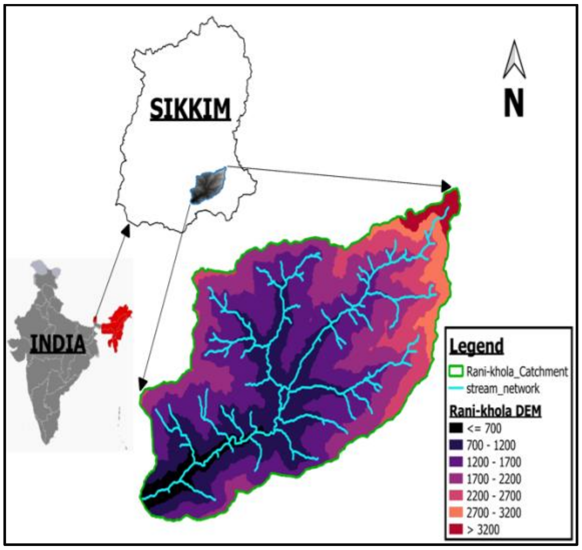

Figure 1. *Map showing the location of study area.*

characterized by subtropical to alpine climates with four distinct seasons. The region contains four soil textural classes, namely, coarse loamy, fine loamy, fine silty and loamy skeletal. Pre-kharif, kharif and rabi are the three agricultural seasons experienced in the region. The major crops grown in the region are rice, wheat, finger millet, maize, pulses, soyabean, rapeseed, and mustard.

3 Methodology

The morphometric studies offer systematic and precise insights into the characteristics of drainage basin (Uniyal and Gupta, 2013; Yunus et al., 2014; Sukristiyani et al., 2018; Ajaykumar and Reghunath, 2025). In this study, various hydrological parameters were quantified using established formulas, which are presented in **Table 1**. The delineation of the watershed was carried out using Cartosat DEM, downloaded from https://bhuvan.nrsc.gov.in/, having 30 m spatial resolution and Survey of India toposheets at a scale of 1:50,000. Georeferenced toposheets were superimposed on DEM-derived drainage networks map to validate and, where necessary, manually correct watershed boundaries and stream courses. This allowed correction of ambiguities in flat terrain and detection of minor streams not captured by the DEM, ensuring that the extracted hydrological features accurately represent the site conditions. For delineating the basin boundary and drainage network, the 'Hydrology tool' inside the Spatial Analyst module of ArcGIS Pro software was used. Basin parameters such as perimeter, area and morphometric parameters (linear, aerial and relief aspects) such as stream order, stream number, bifurcation ratio, drainage density, form factor, and basin relief of the watershed were obtained through geospatial analysis.

4 Results

4.1 Stream order

The stream order (U) has been determined using the method described by Strahler (1964); first ordered channel segments are the smallest, and unbranched fingertip streams (**Table 1**). Interception of two first order channels produce a channel segment of second order and so on. However, the confluence of two streams of different orders results in the channel segments of either channel, maintaining the order of the higher order channel only. The number of streams declines as stream order increases, indicating the branching nature of the drainage network. There are 73 first order, 32 second order, 24 third order, and 16 fourth order streams in the studied watershed (**Fig. 2 and Table 2**). The negative relationship between the stream order and stream number is a characteristic of mature, well-organized drainage systems (Nayyeri et al., 2025). The Rani-khola is a fourth order stream.

4.2 Stream length

According to Horton (1945), the cumulative length of the same ordered channel defined the stream length (Lu). As the stream order increases, the length of individual segments decreases (**Table 1**). This may be due to the difference in the number of streams of lower order than the higher order. The first order streams accounted for 69.36 km, followed by 37.12 km of second order, 28.32 km of third order, and 19.08 km of fourth order streams (**Table 2**). The cumulative length of the stream in the study area was found to be 153.88 km. Although the number of streams decreases, the total length showed that higher order streams were able to maintain significant lengths due to their cumulative flow paths. However, Nath et al. (2022) reported a total stream length of 36.535 km, which is significantly lower than our

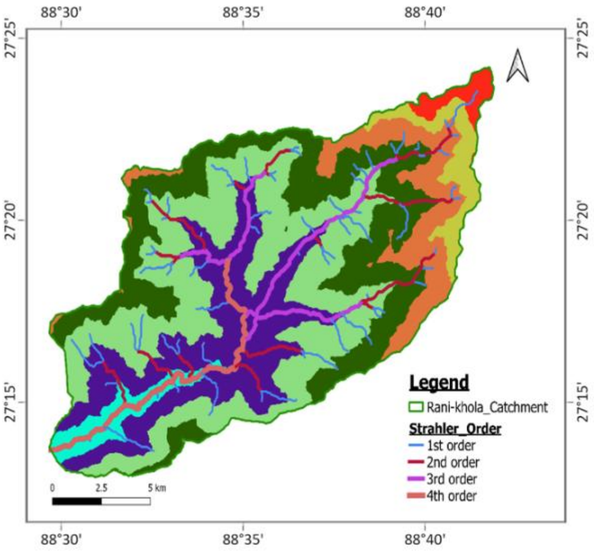

Figure 2. *Stream network and stream ordering of the study area.*

estimate. This difference could be attributed to the methods and study area delineation in these studies.

4.3 Mean stream length

The mean stream length (L_{sm}) is one of the important characteristics of a drainage network and its surface features. It is calculated by dividing the total length of streams of a given order (u) by the number of streams of the same order (**Table 1**). The mean stream length of the Rani-khola watershed was found increasing with the increasing channel order, which indicates longer channel development as the smaller streams converge (Robinson and Scheingross, 2024).

Table 1. *Methodology adopted in the calculation of morphometric parameter of the basin.*

Sl. No.	Parameters	Formula	Reference
Linear aspect			
1.	Stream order (U)	Hierarchical rank.	Strahler, 1964
2.	Stream length (L_u)	Length of the stream (km).	Horton, 1945
3.	Mean stream length (L_{sm})	$L_{sm} = L_u / N_u$ Where, L_u = Total stream length, and N_u = Total number of stream segments of order ‘u’.	Strahler, 1964
4.	Stream length ratio (R_L)	$R_L = L_u / L_{u-1}$ Where, L_u = Total stream length of the order ‘u’, and L_{u-1} = Total stream length of its next lower order.	Horton, 1945
5.	Bifurcation ratio (R_b)	$R_b = N_u / N_{u+1}$ Where, N_u = Total number of stream segments of order ‘u’. and N_{u+1} = Total number of stream segments of the next higher order.	Schumm, 1956
Aerial aspect			
6.	Drainage density (D)	$D = L_u / A$ Where, L_u = Total stream length (km), and A = Area of the basin (km^2).	Horton, 1932
7.	Stream frequency (F_s)	$F_s = N_u / A$ Where, N_u = Total number of streams, and A = Area of the basin (km^2).	Horton, 1932
8.	Drainage texture (R_t)	$R_t = N_u / P$ Where, N_u = Total number of streams, and P = Perimeter (km).	Horton, 1945
9.	Form factor (R_f)	$R_f = A / L_b^2$ Where, A = Area of the basin (km^2), and L_b^2 = Square of the basin length.	Horton, 1932
10.	Circularity ratio (R_c)	$R_c = 4 \pi A / P^2$ Where, A = Area of the basin (km^2), and P^2 = Square of the perimeter.	Miller, 1953
11.	Elongation ratio (R_e)	$R_e = 2 * (A / \pi)^{0.5} / L_b$ Where, A = Area of the basin (km^2), and L_b = Basin length.	Schumm, 1956
12.	Length of overland flow (L_g)	$L_g = 1 / D * 2$ Where, L_g = Length of overland flow, and D = Drainage density.	Horton, 1945

Table continued to next page.

Relief aspect			
13.	Basin relief (H)	Vertical distance between the lowest and the highest points of the basin.	Schumm, 1956
14.	Relief ratio (R_h)	$R_h = H / L_b$ Where, H = Total relief (relative relief) of the basin in km, and L_b = Basin length.	Schumm, 1956
15.	Relative relief ratio (R_{hm})	$R_{hm} = H * 100 / P$ Where, H = Relative relief of the basin in km, and P = Perimeter of the basin in km.	Melton, 1958
16.	Ruggedness number (R_n)	$R_n = H * D$ Where, H = Basin relief, and D = Drainage density.	Schumm, 1956

It varied from 0.95, 1.16, 1.18 and 1.19 km from the first ordered channel to the fourth ordered channel, respectively (**Table 2**). The gradual increase in mean stream length suggests that the stream segments grow longer with increasing order and drainage maturity.

4.4 Stream length ratio

The stream length ratio (R_L) is strongly related to surface flow and discharge. It is calculated as the ratio of the mean stream length of one order channel segments to the consecutive mean stream length of lower order channel segments (Horton, 1945). The R_L between the second and third order stream is the maximum (**Table 2**). The variation in R_L is mainly due to the variation in the slope of the terrain, lithology, and erosional development between different order streams. However, the increasing trend of R_L also signifies the maturity of geomorphic stages, and it is understood that the R_L between the first and the second order channels is low because of a sudden change in the elevation (Mahala, 2020).

4.5 Bifurcation ratio

Bifurcation ratio (R_b) is calculated as the ratio of the number of stream channel segments of one order to the consecutive number of stream channel segments of higher order. Bifurcation ratio is considered an index of relief and dissections (Horton, 1945). Climate, topography, soil infiltration capacity, vegetation, and geology are among several factors that affect the bifurcation ratio. Small variation in R_b indicates that the channels do not exercise a dominant influence by geological structures (Eze and Efiong, 2010). The mean bifurcation ratio (R_{bm}) of 1.70 signifies that the watershed can be considered under the normal basin category with a stable geomorphological setup (**Table 2**).

4.6 Drainage density

Drainage density (D) represents the ratio between the total length of all stream channel segments within a basin and its surface area. This metric indicates the closeness of spacing of the channels. It is an important indicator of the terrain shaped by fluvial processes (Horton, 1932). At the catchment scale, drainage density provides an estimate of the average length of the stream channel. Low values commonly occur where subsurface materials are highly permeable, vegetation cover is substantial, and relief is gentle; in contrast, impermeable lithologies, sparse vegetation, and rugged topography generally yield higher densities (Pisupati and Ratnakar, 2025). The drainage density calculated for the study basin is 0.60 km/km^2, which suggests the presence of dense vegetation cover and highly permeable soil materials (**Table 3**).

Table 2. *Results of the linear aspects of morphometric analysis in the study area.*

Stream order	Stream number (N_u)	Stream Length (km)	Mean stream length (km)	Stream length ratio (R_L)	Bifurcation ratio (R_b)	Mean Bifurcation ratio (R_{bm})
1st order	73	69.36	0.95	-	2.28	1.70
2nd order	32	37.12	1.16	0.54	1.33	
3rd order	24	28.32	1.18	0.76	1.5	
4th order	16	19.08	1.19	0.67	-	

Table 3. *Results of the aerial aspects of morphometric analysis in the study area.*

Drainage density (km/km^2)	Stream frequency (km^{-2})	Drainage texture (km^{-1})	Form Factor (R_f)	Circulatory ratio (R_c)	Elongation ratio (R_e)	Length of overland flow (km)	Constant channel maintenance (C)
0.60	0.57	1.8	0.27	0.51	0.59	0.83	1.67

4.7 Stream frequency

Stream frequency (F_s) denotes the number of stream segments of all orders contained within a basin per unit area (Horton, 1932). This parameter is particularly important because it contributes to the computation of the infiltration number (I_f), defined as the product of drainage density (D) and stream frequency (F_s). In the study area, the stream frequency is 0.57 km/km^{-2}, resulting in an infiltration number of 0.342 (**Table 3**). Lower infiltration numbers typically indicate that the basin has a higher capacity of water infiltration and consequently lower surface runoff (Prabhakaran and Jawahar Raj, 2018).

4.8 Drainage texture

Drainage texture (D_t) is quantified as the sum of stream segments across all orders divided by the perimeter of the watershed. This index reflects the relative spacing and intricacy of drainage lines and is influenced by factors such as substrate permeability and surface roughness (Horton, 1945; Bhadra and Pattanayak, 2025). It is an important concept of geomorphology, since over impermeable areas, drainage lines are numerous than in permeable areas. According to widely used classification methods, the reported drainage texture can be broadly categorized as very coarse (<2), coarse (2–4), moderate (4–6), fine (6–8), and very fine (>8 (Dragičević et al., 2019). The studied watershed exhibits a very coarse drainage texture (**Table 3**).

4.9 Form factor

The form factor (R_f) expresses the relationship between the area of the basin and the square of the length of the basin. The form factor indicates the flow intensity within a basin of a given size (Horton, 1932). The calculated R_f value of 0.27 for the study basin reflects an elongated catchment. Such low form factor values are characteristic of basins that generate lower and more prolonged peak discharges, thereby reducing flood susceptibility. In contrast, basins with higher form factors exhibit larger peak flows of shorter duration and increased flooding risk (Sukristiyanti et al., 2018). The value of R_f should always be less than 0.7854, which corresponds to a perfectly circular basin.

4.10 Circulatory ratio

The circulatory ratio (R_c), as defined by Miller (1953), is the ratio of the basin's area to the area of a circle with a perimeter equal to that of the basin (**Table 1**). This morphometric index is influenced by a range of factors, including stream network characteristics, geology, land use patterns, climatic conditions, relief, and slope (Sukristiyanti et al., 2018). The circulatory ratio of 0.51 suggests an elongated form, which is generally associated with slower runoff conditions and the presence of permeable subsurface materials (**Table 3**).

4.11 Elongation ratio

The elongation Ratio (Re) describes basin shape by comparing the diameter of a circle having the same area as the drainage basin to the basin's maximum length (Schumm, 1956). The Re values near unity indicate low-relief terrain, while values nearing 0.6 indicate that the basin had developed on steeper slopes and higher relief settings (Strahler, 1964). The obtained elongation ratio of 0.59 supports that the watershed is elongated. The Re values further indicate that the studied basin exhibits high relief and steep gradients (**Table 3**).

4.12 Length of overland flow

Overland flow (L_g) is defined as the distance that water travels across the land surface before entering a defined channel (Horton, 1945). It is the ratio of half the reciprocal of drainage density (**Table 1**). This parameter influences the hydrologic response of a basin because the longer flow paths generally slow runoff and allow more time for infiltration. The computed Lg values of 0.83 km suggest that surface water must traverse a relatively long distance prior to channelization, which may enhance infiltration and promote groundwater recharge (Sakthivel et al., 2019).

4.13 Relief ratio

The total or relative relief (H) represents the elevation difference between the highest and lowest points within a watershed. The relief ratio (R_h), defined as the maximum vertical relief divided by the horizontal distance of the basin's longest axis parallel to the principal drainage line, provides a useful indication of overall terrain steepness (Schumm, 1956). Relief ratio is closely linked to channel gradient and is

Table 4. *Result of the relief aspects of morphometric analysis in the study area.*

Basin relief (km)	Relief ratio (R_h)	Relative relief ratio (R_{hm})	Ruggedness number (Rn)
0.99	0.03	1.24	1.65

often associated with hydrological behavior, including runoff coefficient and erosional intensity. The calculated Rh value of 0.03 indicates that the basin possesses relatively steep slopes (**Table 4**).

4.14 Relative relief ratio

Relative relief ratio (R_{hm}) was suggested by Melton (1958) and is defined as the percentage ratio of relative relief (H) to the perimeter of the watershed. The lower value of R_{hm} indicates fewer resistant rocks (Ansari, 2012). The studied watershed had a R_{hm} value of 1.24 (**Table 4**).

4.15 Ruggedness number

Ruggedness number (R_n) is calculated by multiplying drainage density (D) and relative relief (H). When the values of D and H are high, and the slopes are both steep and long, the ruggedness number is extremely high (Strahler, 1957). The results of R_n (1.65) indicate that the studied terrain is highly susceptible to soil erosion and structurally complex (**Table 4**).

5 Discussions

5.1 Drainage network characteristics and basin evolution

Rani-khola watershed exhibited a well-organized drainage network following Horton's laws of drainage composition. The negative relationship between stream order and stream number, 73 first order streams have decreased to 16 fourth order streams, demonstrated the mature and well-developed drainage networks in mountainous terrain (Nayyeri et al., 2025). This pattern indicated that the watershed had reached a relatively stable geomorphological state despite its location in the tectonically active Himalayan region. Sonker et al. (2023) also observed comparable outcomes in the Upper Teesta River basin located in the nearby mountainous region.

The mean bifurcation ratio (R_{bm}) of 1.70 is notably lower than the typical range of 3.0–5.0 reported for drainage basins with minimal geological control (Chowdhury, 2024). This unusually low value suggests either strong geological influence on drainage development or unique physiographic conditions specific to the Rani-khola catchment. The low bifurcation ratio may reflect the influence of tectonics and geological structure, such as fractures or fault systems, which can create preferential pathways for stream development (Eze and Efiong, 2010).

5.2 Hydrological implications and runoff characteristics

The morphometric parameters collectively indicated that the Rani-khola watershed was characterized by moderate to high infiltration capacity. The low drainage density (0.60 km/km^2) combined with low stream frequency (0.57 km^{-2}) suggested the presence of highly permeable subsoil conditions and dense vegetation cover, which are characteristic of well-vegetated watersheds. These conditions favor groundwater recharge over surface runoff, indicating good potential for sustainable water resource management (Prabhakaran and Jawahar Raj, 2018).

The infiltration number (0.342) further supported this interpretation, as lower values indicated higher infiltration capacity and reduced surface runoff. This characteristic is particularly significant for flood management, as it suggests that under normal precipitation conditions, the watershed can effectively absorb rainfall, reducing downstream flood risks. However, during extreme precipitation events typical of the monsoon climate, the steep terrain (relief ratio = 0.03) could still generate rapid runoff despite the high infiltration capacity.

5.3 Basin geometry and flow dynamics

The elongated nature of the Rani-khola watershed, as suggested by the low form factor (0.27), circulatory ratio (0.51), and elongation ratio (0.59), had significant implications for flood behavior and water management. Elongated basins typically exhibited lower peak flows for extended duration compared to circular basins, which is advantageous for flood mitigation (Sukristiyanti et al., 2018). The elongated shape suggested that the rainfall-runoff response will be characterized by moderate lag time and sustained flow, making the system more predictable for water resource planning.

The length of overland flow (0.83 km) indicated relatively long flow paths before water reaches defined stream channels. This extended flow-path provides additional opportunities for infiltration and sediment deposition, contributing to natural water retention and groundwater recharge. Such characteristics were particularly valuable in mountain watersheds where water conservation is crucial for downstream communities and ecosystems.

5.4 Erosional processes and terrain complexity

The ruggedness number (1.65) indicated moderate to high terrain complexity with significant potential for soil erosion. While this value suggested structural complexity, it is not extreme compared to other watersheds in the Himalayan region, indicating that the appropriate environmental conservation measures could effectively manage erosion risks (Strahler, 1957). The combination of steep relief (relief ratio = 0.03) and moderate drainage density create conditions where erosional processes are active but not overwhelming. The relative relief ratio (1.24) suggested moderate rock resistance, indicating that the watershed contained materials of varying erodibility. This variability in rock strength likely contributed to the complex topography observed in the study area and influenced the spatial distribution of erosional processes across the watershed.

5.5 Comparative analysis with similar watersheds

When compared to other Himalayan watersheds, the Rani-khola exhibited distinctive characteristics. The drainage density (0.60 km/km²) is lower than the Halda River Basin (1.22 km/km²) observed by Chowdhury (2024), suggesting better vegetation cover and more permeable geology in the Rani-khola watershed. Similarly, the stream frequency is lower than many reported Himalayan basins, strengthening the interpretation of good infiltration capacity and stable terrain conditions.

The very coarse drainage texture observed in the Rani-khola watershed aligned with the results from other well-vegetated mountainous basins. As such, sparse drainage networks are favored suitably for increased infiltration and higher groundwater recharge conditions (Dragičević et al., 2019). This characteristic distinguishes the watershed from more arid or degraded mountainous basins that typically exhibit finer drainage textures.

The morphometric characteristics of the Rani-khola watershed indicate significant implications for environmental management, including strong potential for groundwater recharge and drought resilience due to its low drainage density, high infiltration capacity, and elongated basin shape. While the overall flood risk is reduced, the steep terrain and high concentration of first order streams in headwater areas make it susceptible to flash floods during intense rainfall. Erosion control efforts should focus on these headwater zones, considering local geological and slope factors. Additionally, conserving existing forest covers and restoring degraded areas are crucial to maintaining favorable infiltration conditions, reducing surface runoff, and sustaining the watershed's hydrological stability.

6 Limitations and future research directions

The morphometric analysis of the Rani-khola watershed offers useful insights but has limitations, as it relies mainly on topographic data and mathematical calculations that may not fully reflect the dynamic interactions of climate, vegetation, and recent human activities (Shekar and Mathew, 2022; Dey et al., 2025). Future research should address these gaps by incorporating spatio-temporal analysis, validating the results through field observations, integrating hydrological modeling to confirm runoff and infiltration predictions, assessing the impacts of anthropogenic activities on watershed morphometry, and evaluating climate change vulnerability based on projected precipitation patterns.

7 Conclusion

Remote sensing and GIS techniques have been effective in the delineation of watershed boundary and in extracting the morphometric characteristics of the basin. A detailed morphometric study of the Rani-khola watershed represented that the basin has a dendritic drainage pattern and exhibited coarse drainage texture. The basin is elongated in shape, and the mean bifurcation ratio indicated that there is no major control of the geological structures in the drainage pattern. However, the variation in the bifurcation ratio was the result of difference in topography and geometry of the terrains, as the region is a steep mountainous region. The observed drainage density and stream frequency values are attributed to highly permeable subsoil and dense vegetation conditions. The value of the relief ratio and the visual interpretation of the DEM indicate that the terrain exhibited a steep slope. Also, the values of the relative relief ratio and ruggedness number indicate that the terrain is highly susceptible to soil erosion due to surface runoff. Soil erosion management measures should be considered to prevent further degradation of critically eroded areas. Rani-khola watershed can be considered for spring water potential, as the area possesses permeable subsurface conditions favorable for surface water infiltration.

8 Data availability statement

The data that supports this research will be shared upon reasonable request to the corresponding authors.

9 Ethical statements

Not applicable.

10 Conflict of interest

No actual or potential competing financial interests.

11 Author contributions

D. Rizal: Conceptualization, methodology, data collection, data analysis, software, visualization, and writing original draft. G.T. Patle: Conceptualization, draft editing, and supervision. Parimita Saikia: Methodology, draft editing, and supervision.

12 Copyright statement

References

Ajayakumar, A., Reghunath, R., 2025. Delineation of groundwater recharge zones in lateritic terrains using geospatial techniques. Discover Geoscience, 3(1). https://doi.org/10.1007/s44288-025-00110-z

Ansari Z.R., Rao L.A.K., Yusuf, A., 2012. GIS based morphometric analysis of Yamuna drainage network in parts of Fatehabad area of Agra district, Uttar Pradesh. Journal Geological Society of India, 79, 505–514. https://doi.org/10.1007/s12594-012-0075-2

Bhadra, A.K., Pattanayak, S.K., 2025. Drainage Basin Morphometry of Gandhamardan Hills in Western Odisha Using Geographic Information System. In Advances in Geographical and Environmental Sciences (pp. 217–265). Springer Nature Singapore. https://doi.org/10.1007/978-981-96-1733-3_12

Bogale, A., 2021. Morphometric analysis of a drainage basin using geographical information system in Gilgel Abay watershed, Lake Tana Basin, upper Blue Nile Basin, Ethiopia. Applied Water Science, 11, 122. https://doi.org/10.1007/s13201-021-01447-9

Chowdhury, M.S., 2024. Morphometric analysis of Halda River basin, Bangladesh, using GIS and remote sensing techniques. Heliyon, 10, e29085. https://doi.org/10.1016/j.heliyon.2024.e29085

Dey, S., Yadav, V., Pan, S., Chattaraj, S., Bera, S., 2025. Spatio-temporal assessment of land use, climate dynamics, and biophysical parameters in the Ranikhola watershed, Sikkim Himalaya, India. Journal of Water and Climate Change. https://doi.org/10.2166/wcc.2025.646

Dragičević, N., Karleuša, B., Ožanić, N., 2019. Different approaches to estimation of drainage density and their effect on the erosion potential method. Water, 11, 593. https://doi.org/10.3390/w11030593

Eze, E.B., Efiong, J., 2010. Morphometric parameters of the Calabar River basin: implication for hydrologic processes. Journal of Geography and Geology, 2, 18.

Horton, R.E., 1932. Drainage basin characteristics. Transactions of the American Geophysical Union, 13, 350–361. https://doi.org/10.1029/TR013i001p00350

Horton, R.E., 1945. Erosional development of streams and their drainage basins; Hydrophysical approach to quantitative morphology. *Geological Society of America Bulletin,* 56, 275–370. https://doi.org/10.1130/0016-7606(1945)56[275:EDOSAT]2.0.CO;2

López-Ramos, A., Medrano-Barboza, J.P., Martínez-Acosta, L., Acuña, G.J., Remolina López, J.F., López-Lambraño, A.A., 2022. Assessment of morphometric parameters as the basis for hydrological inferences in water resource management: A case study from the Sinú River basin in Colombia. ISPRS International Journal of Geo-Information*,* 11, 459. https://doi.org/10.3390/ijgi11090459

Mahala, A., 2020. The significance of morphometric analysis to understand the hydrological and morphological characteristics in two different morpho-climatic settings. Applied Water Science, 10, 33. https://doi.org/10.1007/s13201-019-1118-2

Mani, A., Kumari, M., Badola, R., 2022. Morphometric analysis of Suswa river basin using geospatial techniques. Engineering Proceedings, 27, 65. https://doi.org/10.3390/ecsa-9-13225

Melton, M.A., 1958. Correlation structure of morphometric properties of drainage systems and their controlling agents. The Journal of Geology, 66, 442–460. https://doi.org/10.1086/626527

Memon, A.V., Patel, Y.S., Parangi, T., 2024. Exploring watershed dynamics: a comprehensive review on morphometric analysis and geospatial techniques. ISH Journal of Hydraulic Engineering, 30, 744–757. https://doi.org/10.1080/09715010.2024.2383184

Miller, V.C., 1953. A quantitative geomorphic study of drainage basin characteristics in the clinch mountain area, Virginia and Tennessee, Proj. NR 389-402, Tech Rep 3, Columbia University, Department of Geology, ONR, New York.

Nath, N.K., Agrawal, A., Gautam, V.K., Kumar, A., Das, P., 2022. Morphometric evaluation of Ranikhola watershed in Sikkim, India using geospatial technique. Environment Conservation Journal, 23(3), 273–284. https://doi.org/10.36953/ecj.10672257

Nayyeri, H., Moradi, R., Sanikhani, H., 2025. Fractal and morphometric characterization of drainage and fault systems in the tectonically active Mereg Basin, Western Iran. International Journal of River Basin Management, 1–18. https://doi.org/10.1080/15715124.2025.2517831

Pisupati, S.L., Ratnakar, P.J, 2025. Morphometric analysis and prioritization of sub-watersheds in the Gosthani River Basin of southern India using PCA-WSM and geospatial techniques. Journal of Water and Climate Change, 16(6), 2006–2031. https://doi.org/10.2166/wcc.2025.727

Prabhakaran, A., Jawahar Raj, N., 2018 Drainage morphometric analysis for assessing form and processes of the watersheds of Pachamalai hills and its adjoinings, Central Tamil Nadu, India. Applied Water Science, 8, 31. https://doi.org/10.1007/s13201-018-0646-5

Robinson, M.J., Scheingross, J.S., 2024. The length and spacing of river tributaries. Proceedings of the National Academy of Sciences USA, 121, e2313899121. https://doi.org/10.1073/pnas.2313899121

Sakthivel, R., Jawahar Raj, N., Sivasankar, V., Akhila, P., Omine, K., 2019. Geo-spatial technique-based approach on drainage morphometric analysis at Kalrayan Hills, Tamil Nadu, India. Applied Water

Science, 9, 24. https://doi.org/10.1007/s13201-019-0899-7

Schumm, S.A., 1956. Evolution of drainage systems and slopes in Badlands at Perth Amboy, New Jersey. *Geological Society of America Bulletin,* 67, 597–646. https://doi.org/10.1130/0016-7606(1956)67[597:EODSAS]2.0.CO;2

Shekar, R.P., Mathew, A., 2024. Morphometric analysis of watersheds: A comprehensive review of data sources, quality, and geospatial techniques. Watershed Ecology and the Environment, 6, 13–25. https://doi.org/10.1016/j.wsee.2023.12.001

Shekar, P.R., Mathew, A., 2022. Evaluation of Morphometric and Hypsometric Analysis of the Bagh River Basin using Remote Sensing and Geographic Information System Techniques. Energy Nexus, 7, 100104. https://doi.org/10.1016/j.nexus.2022.100104

Sonker, I., Tripathi, J.N., Swarnim, Singh, A.K., 2023. Morphomertic and neotectonic study of Upper Teesta River basin, Sikkim Himalaya using geospatial techniques. Journal of Applied Geophysics, 212, 104978. https://doi.org/10.1016/j.jappgeo.2023.104978

Strahler, A.N., 1957. Quantitative analysis of watershed geomorphology. Transactions of the American Geophysical Union, 38, 913–920. https://doi.org/10.1029/TR038i006p00913

Strahler, A.N., 1964. Quantitative geomorphology of drainage basins and channel networks. In: Chow, V., Ed., Handbook of Applied Hydrology. McGraw Hill Book Company, New York, 439–476.

Sukristiyanti, S., Maria, R., Lestiana, H., 2018. Watershed-based morphometric analysis: a review. IOP Conference Series: Earth and Environmental Science, 118, 012028. https://doi.org/10.1088/1755-1315/118/1/012028

Todorovic, M., Stedito, P., 2003. A GIS for irrigation management. Physics and Chemistry of the Earth, 28, 163–174. https://doi.org/10.1016/S1474-7065(03)00023-8

Uniyal, S., Gupta, P., 2013. Prioritization based on morphometric analysis of Bhilangana watershed using spatial technology. International Journal of Remote Sensing & Geoscience, 3, 49–57.

Vijith, H., Satheesh, R., 2006. GIS Based morphometric analysis of two major upland sub-watersheds of Meenachil River in Kerala. Journal of the Indian Society of Remote Sensing, 34, 181–185. https://doi.org/10.1007/BF02991823

Vitalla, S.S., Govindaiah, S., Gowda, H.H., 2004. Morphometric analysis of sub-Watersheds in the Pavagada area of Tumkur district, South India using remote Sensing and GIS techniques. Journal of the Indian Society of Remote Sensing, 32, 351–362. https://doi.org/10.1007/BF03030860

Waiker, M.L., Nilawar, A.P., 2014. Morphometric analysis of a drainage basin using geographical information system: A case study. International Journal of Multidisciplinary and Current Research, 2, 179–184.

Yunus, A.P., Oguchi, T., Hayakawa, Y.S., 2014. Morphometric analysis of drainage basins in the western Arabian Peninsula using multivariate statistics. International Journal of Geosciences, 5, 527–539. https://doi.org/10.4236/ijg.2014.55049

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