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Morphometric analysis in the sub basins of the Kali River using Geographic Information System, Karnataka, India

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ABSTRACT

Morphometric analysis serves as a crucial tool for quantitatively characterizing drainage basins and exploring the intricate relationships between hydraulic parameters and geomorphological characteristics. This study presents a comprehensive morphometric analysis of the Kali Subbasin in Karnataka, covering an area of 1175.45 km^2. Utilizing remote sensing data and GIS tools, we quantified various morphometric parameters, including stream order, stream length, bifurcation ratio, drainage density, stream frequency, form factor, and circularity ratio, to understand the basin's geomorphological and hydrological characteristics. The study area is classified as a seventh-order basin displaying a dendritic drainage pattern with a drainage density of 2.853 km/km^2. Notably, the bifurcation ratio ranges from 4.396 to 3, indicating low to moderate structural control within the basin. The subbasin's elongated shape, with an elongation ratio of 0.604 and a circularity ratio of 0.298, indicates moderate peak flow and high susceptibility to erosion. Relief parameters showed significant elevation variations, contributing to intense erosion and heightened flood risks in lower-lying areas. The study identifies the basin's transition to a mature geomorphic stage, evidenced by an escalating stream length ratio from lower to higher orders. These findings underscore the importance of tailored watershed management strategies, including floodplain zoning, retention basins, afforestation, and terracing, to mitigate flooding and soil erosion. The study's insights are crucial for developing effective, localized water resource management plans and enhancing the resilience of the Kali Subbasin to future hydrological challenges.

1. Introduction

The switching of operation on geomorphology from a classical descriptive basis to quantification with the impetus given by Horton [13] has contributed a lot to the characterisation of the geomorphic feature. The term "morphometry" broadly refers to the measurement of the shape or geometry of any natural form, encompassing entities such as plants, animals, or relief features [41]. However, in the field of geomorphology, "morphometry" is more specifically defined as the measurement and mathematical analysis of the Earth's surface configuration, including the examination of the shape and dimensions of its landforms [5].

The morphometric analysis involves the quantitative measurement and analysis of the shape, size, and spatial distribution of geological features, such as mountains, river networks, fault systems, and volcanic landforms [28]. This approach harnesses the power of mathematics, statistics, and geospatial technology to extract valuable information from geological data, enabling researchers to derive meaningful insights that may not be readily apparent through traditional qualitative observations [1,5]. The morphometric analysis is effectively conducted by measuring various parameters, including the linear dimensions, areal characteristics, relief features, the gradient of the channel network, and the slope of the contributing ground within the basin [18,24,25]. A well-accepted tenet of morphometry is that the morphology of a drainage basin serves as a reflection of the complex interplay of geological and geomorphological processes that have occurred over time. This insight is supported by numerous morphometric studies [3,6,9,13,20,23,26,27,34,40,41].

The review of existing literature indicates that in the past, drainage morphometric parameters were primarily derived from topographical maps or field surveys. The integration of remote sensing and GIS plays a pivotal role in enabling more comprehensive and sophisticated morphometric analyses in several fields [39]. GIS is a highly potent analytical tool due to its capacity to swiftly create, manipulate, store,

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and process spatial data. It excels in delivering high-quality results and seamlessly integrating thematic layers to offer a comprehensive geo-spatial perspective [33,44]. However, with the emergence of a high-resolution digital elevation model (DEM), the extraction of drainage parameters from DEM has gained popularity over the last three decades. This is primarily due to the swift, accurate, up-to-date, and cost-effective approach it offers for conducting watershed analysis [17, 22].

The morphometric technique serves as a vital and potent method for a wide range of applications, including watershed management, groundwater monitoring, delineation of groundwater potential zones, pedological assessment, and environmental and ecological evaluations [8]. Morphometric parameters have found utility in forecasting flood peak levels, evaluating sediment yields, and estimating erosion rates in various other studies [2,10]. The study focuses on delineating the morphometric parameters of the Kali Subbasin of Karnataka which can be used as an important aid in the proper watershed management of the basin. The basin witnessed floods in 2019, 2020, and 2021 which resulted in substantial destruction to infrastructure, property, and loss of life. The consistent flooding in this region calls for the need for proper watershed management which has to be done effectively, hence the morphometric analysis of the basin is an essential step.

2. Study area

The study is centred on the Kali Subbasin, situated within the Uttara Kannada district of northern Karnataka and the South Goa district in Goa, India (Fig. 1). This subbasin spans from approximately 15° 4′ 4.10'' N to 14° 45' 41.52'' N in latitude and 74° 5′ 14.66'' E to 74° 41' 54.65'' E in longitude, covering a total area of 1175.45 km^2. The land within the river basin varies from sea level in the coastal lowland region to 901 m above mean sea level (MSL) at the escarpment zone. The study area accommodates two hydroelectric dams and reservoirs. The landscape is characterised by distinct low-lying hills interspersed with the elevated formation of the Western Ghats. The streams collectively create a well-defined drainage network, comprising streams of orders ranging from 1st to 7th, with an overall dendritic drainage pattern. The study area, part of the Archean age Dharwar Supergroup, mainly exhibits diverse lithological units including granite gneiss, schist, granitoid, and meta basalts (Fig. 2). Common intrusions include basic and acid dykes, alongside enclaves of amphibolite and talc chlorite schist [14,19]. Lineaments, directed in NW-SE, NNE-SSW, and NEE-SWW orientations, regulate the paths of the main river and its tributaries [43]. The climate narrative is marked by a substantial influx of rainfall during the south-west monsoon from mid-June until late September. This meteorological phenomenon yields an average annual rainfall of 3841 mm. This orographic precipitation pattern accentuates the region's vulnerability to flooding in low-lying areas, highlighting the intricate interplay between topography and hydrology.

3. Data-sets used

The study area in Uttara Kannada district of Karnataka is illustrated on topographic maps numbered: 48I/4, 48I/8, 48I/12, 48 J/1, 48 J/5, and 48 J/9, each having a scale of 1:50,000 downloaded from the Survey of India's Onlinemaps portal. The geological map was derived from

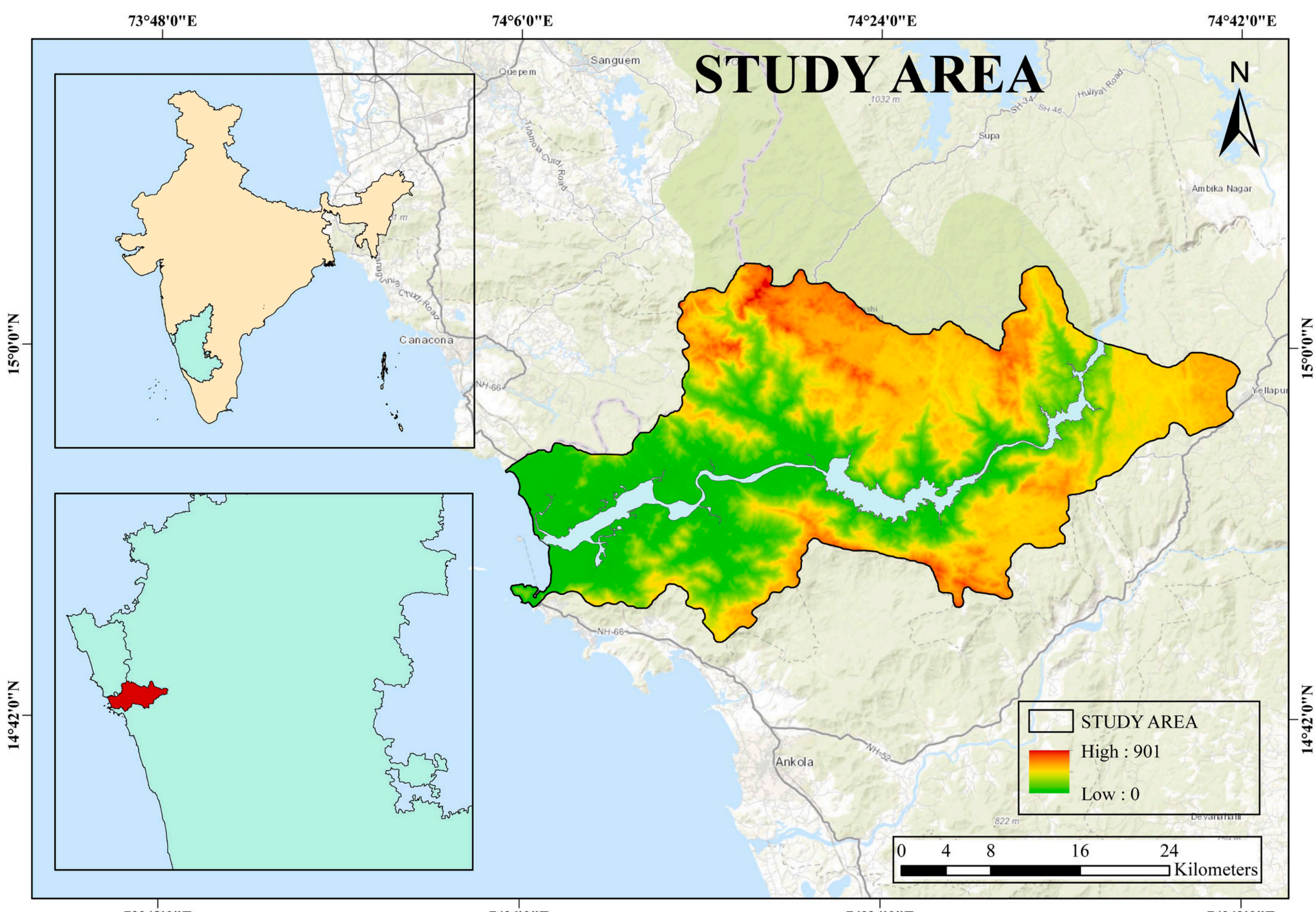

Fig. 1. Location map of the study area.

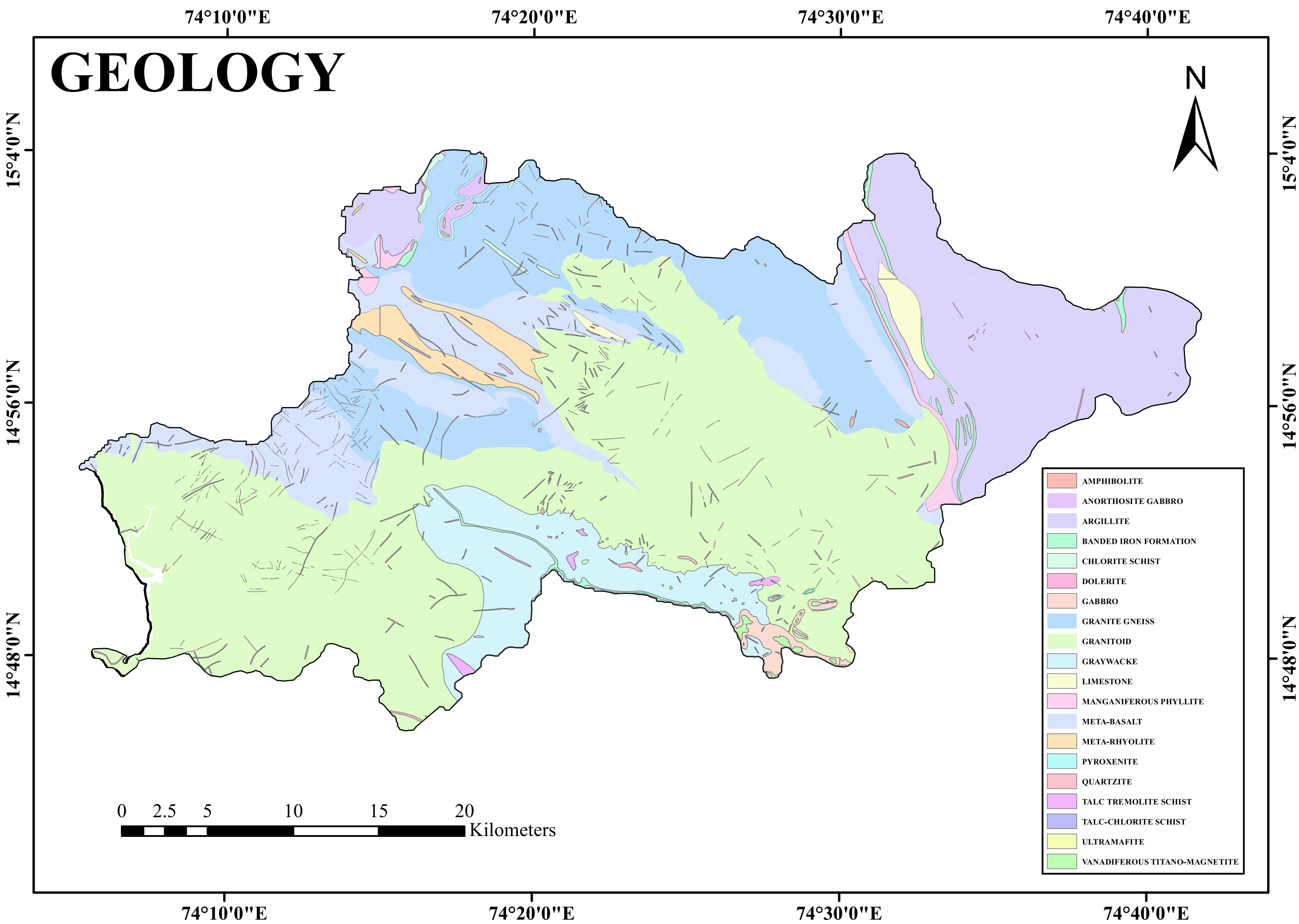

Fig. 2. Geological map of the study area.

the Geological Survey of India's Bhukosh website. To supplement the analysis, the SRTM (Shuttle Radar Topography Mission) Digital Elevation Model (DEM) with a spatial resolution of 30 m was obtained from the United States Geological Survey (USGS) website (https://earthexplorer.usgs.gov/). The study area's boundary was determined through a combination of topographic sheets and DEM data. Subsequently, the pre-processed DEM and drainage network were employed for the extraction and measurement of morphometric characteristics. All data were processed and analysed using ESRI ArcGIS 10.8 software.

4. Methodology

The streams that were delineated served as the basis for deriving various morphometric parameters (Fig. 3), including Stream order (u), Stream number (Nu), Stream length (Lu), Mean stream length (Lsm), Stream length ratio (RL), Bifurcation ratio (Rb), Drainage density (Dd), Length of overland flow (Lo), Stream frequency (Sf), Drainage texture (T), Circularity ratio (Rc), Elongation ratio (Re), Form Factor (Ff), Shape Factor (Fs), Constant of channel maintenance (C), and Ruggedness number (Rn). The SRTM DEM was employed to estimate the Basin relief (R) and Relief ratio (Rr) [4,7,14,15]. The specific formulas for calculating these morphometric parameters are outlined in Table 1. The entire analysis was carried out within the Geographical Information System (GIS) environment using ArcGIS software.

5. Results and discussions

The subbasins within the Kali River basin, which are the focus of this study, collectively cover an approximate area of 1175.45 km^2. Factors such as climate, geological conditions, and topography influence the development of drainage systems [7]. The stream exhibits a dendritic pattern and the study area has been classified as a 7th order basin. To comprehend the hydrological characteristics of the study area, morphometric parameters have been computed, taking into account the

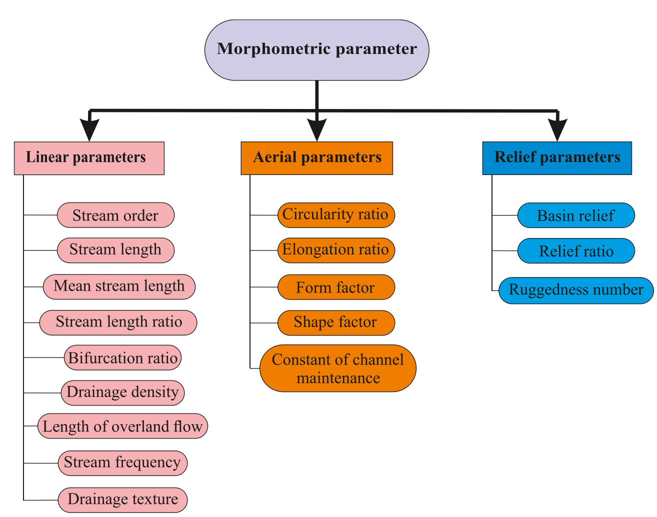

Fig. 3. The methodology adopted for the study.

Table 1
Formulae used for computation of morphometric parameters.

SI. No	Morphometric parameters	Formula & Definition	References
1	Stream order (u)	Hierarchical rank	Strahler[41]
2	Stream number (Nu)	Number of streams in each order	Horton[13]
3	Stream length (Lu)	Total Length of the stream segments of a particular order	Horton[13]
4	Mean stream length (Lsm)	Lsm = Lu/Nu	Strahler[41]
5	Stream length ratio (RL)	RL = Lsm/Lsm − 1	Horton[13]
6	Bifurcation ratio (Rb)	Rb = Nu/Nu+ 1	Schumm[32]
7	Drainage density (Dd)	Dd = Σ Lu /A	Horton[12]
8	Length of overland flow (Lo)	Lo = 1/(2Dd)	Horton[13]
9	Stream frequency (Sf)	Sf = Σ Nu /A	Horton[13]
10	Drainage texture (T)	T = Dd × Sf	Horton[13]
11	Circularity ratio (Rc)	$Rc = 4\pi A/P^2$	Miller[21]; Strahler[41]
12	Elongation ratio (Re)	$Re = D/L = 1.128 \sqrt{A} /L$	Schumm[32]
13	Form Factor (Ff)	$Ff = A/L^2$	Horton[12,13]
14	Shape Factor (Fs)	$Fs = L^2 /A$	Horton[12]
15	Constant of channel maintenance (C)	C = 1/Dd	Schumm[32]
16	Basin relief (R)	R = H − h	Hadley and Schumm[11]
17	Relief ratio (Rr)	Rr = R/L	Schumm[32]
18	Ruggedness number (Rn)	Rn = R × Dd	Schumm[32]

stream network and basin properties.

5.1. Estimation of linear parameters

5.1.1. Stream order (u)

Stream order is a term employed in hydrology and geomorphology to categorize and characterize the hierarchical arrangement of streams and rivers within a drainage network or river basin. The initial step in morphometric studies involves the analysis of stream ordering [15]. The Strahler stream order system [41], created by American geologist Arthur Strahler in the mid-1950s, was employed in this study. It has been noted that the study area exhibits stream orders up to the 7th order as their highest stream orders (Fig. 4). Observations indicate that as the stream order increases, the stream number tends to decrease (Table 2). Nevertheless, the 1st order streams displayed the highest drainage density (Fig. 5).

5.1.2. Stream length (Lu)

Stream length refers to the measurement of the linear distance or total length of a river or stream from its source to its mouth, where it flows into a larger body of water, such as an ocean, sea, lake, or another river. It is a fundamental parameter used in hydrology and geography to describe the physical characteristics of a river or stream [16,28]. The occurrence of streams with relatively shorter lengths is characteristic of regions exhibiting steeper slopes and finer soil textures [29,42]. Conversely, the presence of longer streams typically indicates areas with more gradual gradients. Horton's second law [13] proposes that as stream order decreases, stream length increases. 1st order streams exhibit the greatest stream length, measuring 2162.57 kilometres (Table 2). The cumulative stream length within the study area amounts to 3354.108 kilometres.

5.1.3. Mean stream length (Lsm)

The mean stream length is a characteristic attribute associated with the drainage network components of drainage basins [41]. Lsm has been calculated by dividing the total length of a stream within a specific order by the total count of streams within that same order [15]. Lsm values vary depending on the specific basins, with a direct correlation to the size and topography of each basin [30]. Within the study area, the Lsm values range from 0.557 km to 64.146 km (Table 2). Strahler [41] emphasized that Lsm is an intrinsic property linked to the dimensions of a drainage network and its corresponding surface.

5.1.4. Stream length ratio (RL)

The stream length ratio (RL) can be defined as the proportion of the average length of streams from one order to the succeeding order [13]. Fluctuations in the RL values across the examined river basins are illustrated in Table 2. The variation could have arisen due to differences in slope and lithological changes in the basin's topography [15,16]. Upon close examination, it becomes evident that there is an increasing trend in the stream length ratio from lower order to higher order in the study area, indicating a matured topographical condition.

5.1.5. Bifurcation ratio (Rb)

The bifurcation ratio (Rb) can be defined as the ratio of the number of streams in a particular order to the number of streams in a higher order within the drainage basin [15,32,36]. This dimensionless property serves as an indicator of the connectivity level between streams of different orders within a drainage basin. Theoretically, a bifurcation ratio is expected to be 2.0, whereas natural drainage systems typically range from 3.0 to 5.0, provided that geologic structures do not disrupt the drainage pattern. An Rb exceeding 5 signifies significant structural disturbances and a pronounced influence of geological features on the drainage network [41]. In the study area, the bifurcation ratio (Rb) varies from 4.396 to 3 on the order of 1st to 6th respectively, as detailed in Table 2. A lower bifurcation ratio suggests a relatively flat terrain with permeable and soft bedrock, facilitating increased water infiltration and creating favourable conditions for groundwater potential in the area. Variations in the Rb values also indicate differences in the morphology of the stream network [29,35,42]. Elevated Rb values in the examined region suggest a significant structural influence on the drainage pattern, while lower values indicate that the sub-basins are relatively less affected by structural disturbances.

5.1.6. Drainage density (Dd)

Drainage density is a measure of the total length of all streams and rivers in a drainage basin divided by the total area of that drainage basin [12]. It is used to indicate the proximity or density of channels within the area [16,36]. High drainage density indicates a well-developed and closely spaced network of streams and rivers, which is often associated with areas of high precipitation and relief, such as mountainous regions. Low drainage density, on the other hand, indicates a less developed and sparsely distributed stream network, which is common in arid or flat regions [7]. A high drainage density results in a fine drainage texture, whereas a low drainage density leads to a coarse drainage texture. Typically, drainage density is categorized into four classes: low (< 2), moderate (2−4), high (4−6), and very high (> 6) [4]. The drainage density in the study area is measured at 2.853 km/km^2 (Table 3). Fig. 5 illustrates the variations in drainage density throughout the study area, and from the observations, it's evident that the areas with lower-order streams exhibit higher drainage density.

5.1.7. Length of overland flow (Lo)

The length of overland flow refers to the distance that water travels across the land surface as it flows over the ground, rather than following established channels like rivers or streams [13]. The length of overland flow (Lo) is defined as one-half of the reciprocal of drainage density, as proposed by Horton in 1945. In the study area, the length of overland flow is determined to be 0.175 (Table 3). The length of overland flow is an important factor in hydrology and watershed management, as it affects the transport of sediments, nutrients, and pollutants, which can impact water quality and the stability of landscapes.

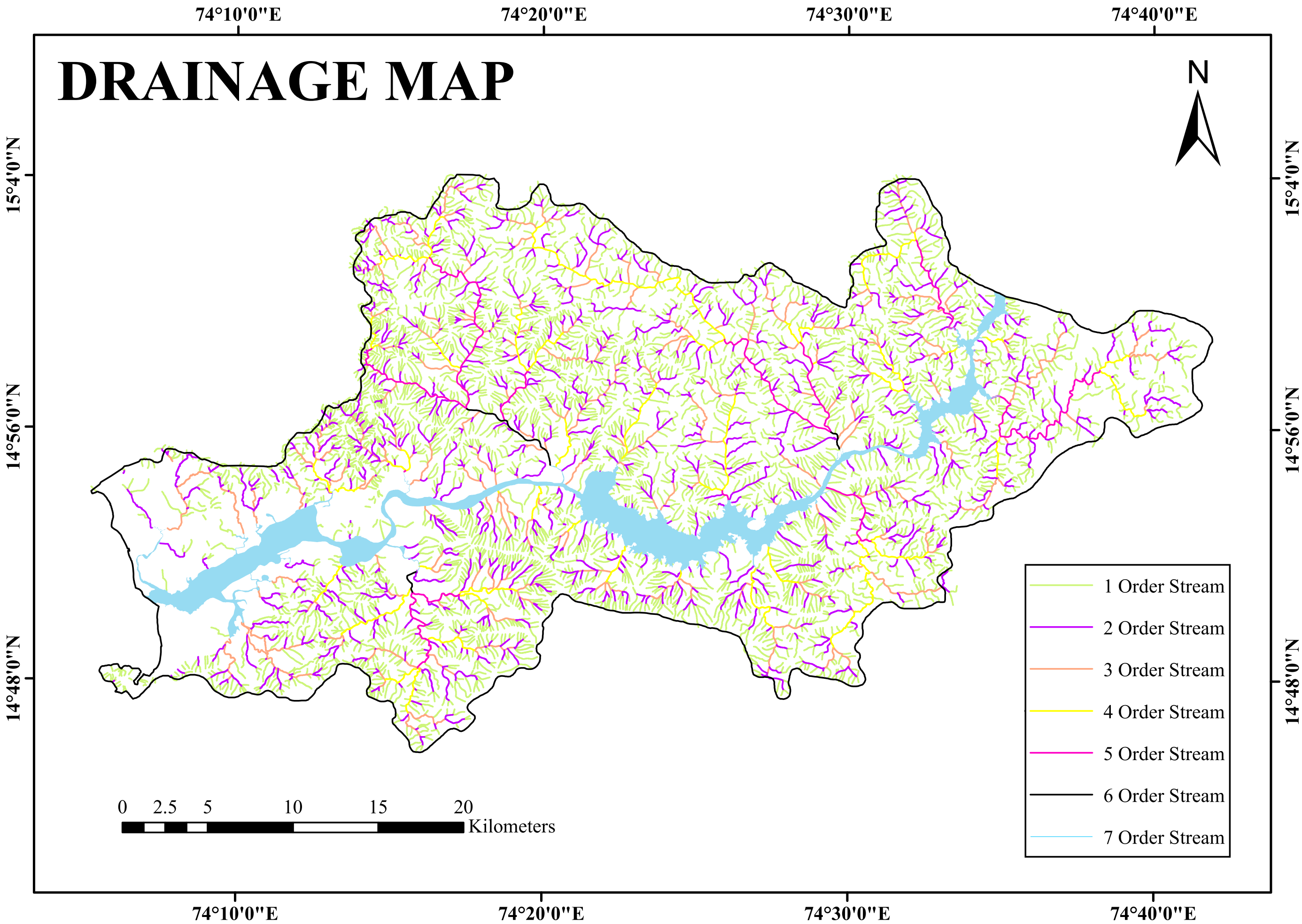

Fig. 4. Drainage map.

Table 2
Drainage network properties of the study area.

Stream order (u)	Stream number (Nu)	Stream length (Lu) (km)	Mean stream length (Lsm) (km)	Stream length ratio (RL)	Bifurcation ratio (Rb)
1	3886	2162.57	0.557	-	4.396
2	884	583.074	0.660	1.185	4.398
3	201	309.029	1.537	2.331	4.188
4	48	146.243	3.047	1.982	3.692
5	13	79.42	6.109	2.005	4.333
6	3	9.626	3.209	0.525	3
7	1	64.146	64.146	19.991	-

5.1.8. Stream frequency (Sf)

Stream frequency (Sf) is a measure that represents the total number of stream segments of all orders within a specific area [12]. High stream frequency indicates a densely dissected and well-developed network of streams, while low stream frequency suggests a less developed and sparser network [36]. The stream frequency value for the study area is calculated to be 4.284 (Table 3). Sf is influenced by the lithology of the basin, and it has an impact on the overall drainage texture [30]. Sf value in the basin demonstrates a direct correlation with the drainage density value of the area. This suggests that as drainage density increases, there is a corresponding rise in the population of streams within the region.

5.1.9. Drainage texture (T)

The concept of drainage texture refers to the relative spacing of drainage lines, as described by Smith in 1950. Drainage texture (T) varies depending on numerous factors, including climate, lithology, relief, infiltration capacity, vegetation cover, and the stage of drainage development [13,36,38]. Massive and resistant rock formations exhibit a coarse drainage texture, while areas underlain by soft or weak rock tend to display a finer drainage texture. As per Smith's classification from 1950, drainage basins are categorized into four groups: coarse (< 4 per km), intermediate (4–10 per km), fine (10−15), and ultra-fine (> 15 per km), based on their drainage texture. The drainage texture of the study area is calculated to be 12.225 (Table 3). Drainage texture provides insights into permeability and the potential for groundwater recharge. A higher drainage texture implies greater permeability and better groundwater recharge potential [4].

5.2. Estimation of aerial parameters

5.2.1. Circularity ratio (Rc)

The circulatory ratio is defined as the ratio of the basin's area to the area of a circle with an equivalent perimeter (P) to that of the basin [21]. A circularity ratio of 1 indicates a perfect circle, while values less than 1 suggest increasing irregularity or deviation from a circular shape [37]. For irregular shapes, the circularity ratio approaches 0 as the shape becomes more complex or elongated. The circulatory ratio for the study area is 0.298 (Table 3) which indicates the basin is not circular in shape. The circularity ratio is affected by geological structures, climate, relief, land cover, as well as the length and slope of the streams within the basin.

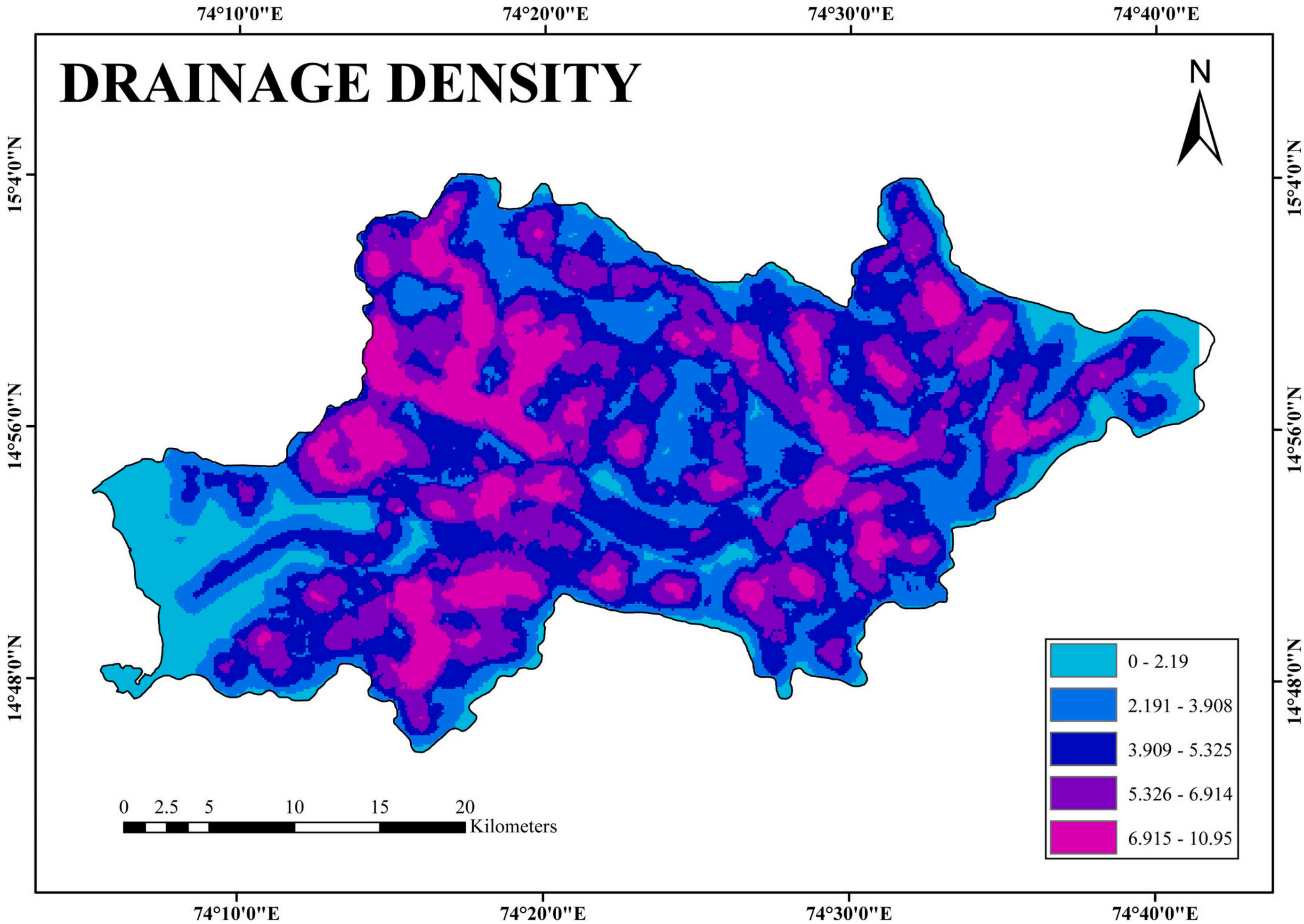

Fig. 5. Drainage density.

Table 3
Morphological parameters.

Basin area (A)(km^2)	1175.45
Basin perimeter (P)(km)	222.468
Basin length (L)(km)	64.012
Drainage density (Dd)(km/km^2)	2.853
Length of overland flow (Lo)	0.175
Stream frequency (Sf)	4.284
Drainage texture (T)	12.225
Circularity ratio (Rc)	0.298
Elongation ration (Re)	0.604
Form factor (Ff)	0.287
Shape factor (Fs)	3.486
Constant of channel maintenance (C)	0.351
Basin relief (R) (m)	901
Relief ratio (Rr)	14.075
Ruggedness number (Rn)	2.570

5.2.2. *Elongation ratio (Re)*

The elongation ratio is defined as the ratio of the diameter of a circle with an equivalent area to that of the drainage basin, divided by the maximum length of the basin [32]. The elongation ratio is a measure of the river basin's shape, and it is influenced by both climatic and geological factors. The Re value will be 1 for a perfectly circular basin. As Re decreases, it indicates that the river basin is becoming more elongated in shape (Table 4) [7,16]. With a Re value of 0.604, the study area exhibits an elongated oval shape (Table 3). Higher values of the elongation ratio indicate a high infiltration capacity and low runoff, while lower Re values are associated with a higher susceptibility to erosion and sediment load [31,36].

Table 4
Elongation Ratio (Re) classification based on [32].

Basin shape	Range
Highly Elongated	< 0.5
Less Elongated	0.5 - 0.6
Elongated Oval	0.6 - 0.7
Semicircular	0.7 - 0.8
Circular	> 0.8

5.2.3. *Form factor (Ff)*

The form factor (Ff) can be defined as the ratio of the total drainage area to the square of the basin length [12]. Smaller values of the Ff signify a more elongated basin with a lower peak flow that lasts for a longer duration. Conversely, higher Ff values indicate a more circular basin [16] with the potential for flash floods due to a higher peak flow that occurs over a shorter duration. In the case of the study area, with an Ff value of 0.287 (Table 3), it exhibits an elongated shape.

5.2.4. *Shape factor (Fs)*

The shape factor is defined as the ratio of the square of the basin length to the area of the basin [12]. The shape factor of a basin is a valuable tool for analysing the irregularity of the drainage basin's shape [4,44]. The shape factor for the study area is evaluated to be 3.486 (Table 3).

5.2.5. Constant of channel maintenance (C)

The constant of channel maintenance is the reciprocal of drainage density [32]. In general, lower C values for a watershed suggest lower rock permeability, and conversely, higher C values indicate greater rock permeability [36]. The constant of channel maintenance for the basin is 0.351 (Table 3) which indicates moderate to high permeability, moderate slope and moderate surface runoff.

5.3. Estimation of relief aspects

5.3.1. Basin relief (R)

Basin relief refers to the topographical or elevation variations within a geographical basin. Basin relief refers to the tangible variation in elevation between the highest and lowest points within a drainage basin [15]. This is a critical parameter that aids in comprehending the erosional traits of the drainage basin. It plays a significant role in determining the stream's slope, consequently impacting surface runoff, sediment volume, and the flooding pattern within the basin [11,37,44]. The basin's highest elevation is 901 m, and its lowest point is 0 (Fig. 6) (Table 3). A substantial relief in these basins suggests a steep terrain where hillslope processes predominate, coupled with high-velocity runoff and limited infiltration potential across the basin's expanse.

5.3.2. Relief ratio (Rr)

The relief ratio is defined as the maximum difference in elevation in relation to the horizontal distance along the longest dimension of the basin, which runs parallel to the principal drainage line [32]. Rh serves as an indicator of the overall steepness and erosional potential within the drainage basin [16,32]. The relief ratio of the study area is evaluated to be 14.075 (Table 3), which implies that the study area exhibits very steep slopes and a high-intensity erosional mechanism.

5.3.3. Slope

Slope refers to the steepness or incline of a terrain's surface. It is a measure of how much elevation changes over a specified horizontal distance. The slope of the study area can be determined by utilizing the SRTM DEM dataset through the ArcGIS software. It varies from 0° to 72.0978° (Fig. 7). A significant variation in slope in the study area indicates the presence of steep scarps, which often lead to rapid runoff and increased susceptibility to erosion.

5.3.4. Ruggedness number (Rn)

The ruggedness number (Rn) is defined as the product of basin relief and drainage density [40,16]. Ruggedness number is a quantitative measure used to assess the roughness or ruggedness of a terrain or land surface. It can be computed by multiplying the maximum basin relief (R) by the drainage density (Dd). The study area exhibits a ruggedness number of 2.570 (Table 3). A significantly high ruggedness number is observed when both of these variables are large, signifying the presence of steep slopes [32,41].

6. Conclusions

Morphometric analysis is a quantitative method used to measure and analyse the geometric characteristics of landforms and natural features on the Earth's surface. Remote sensing and Geographic Information

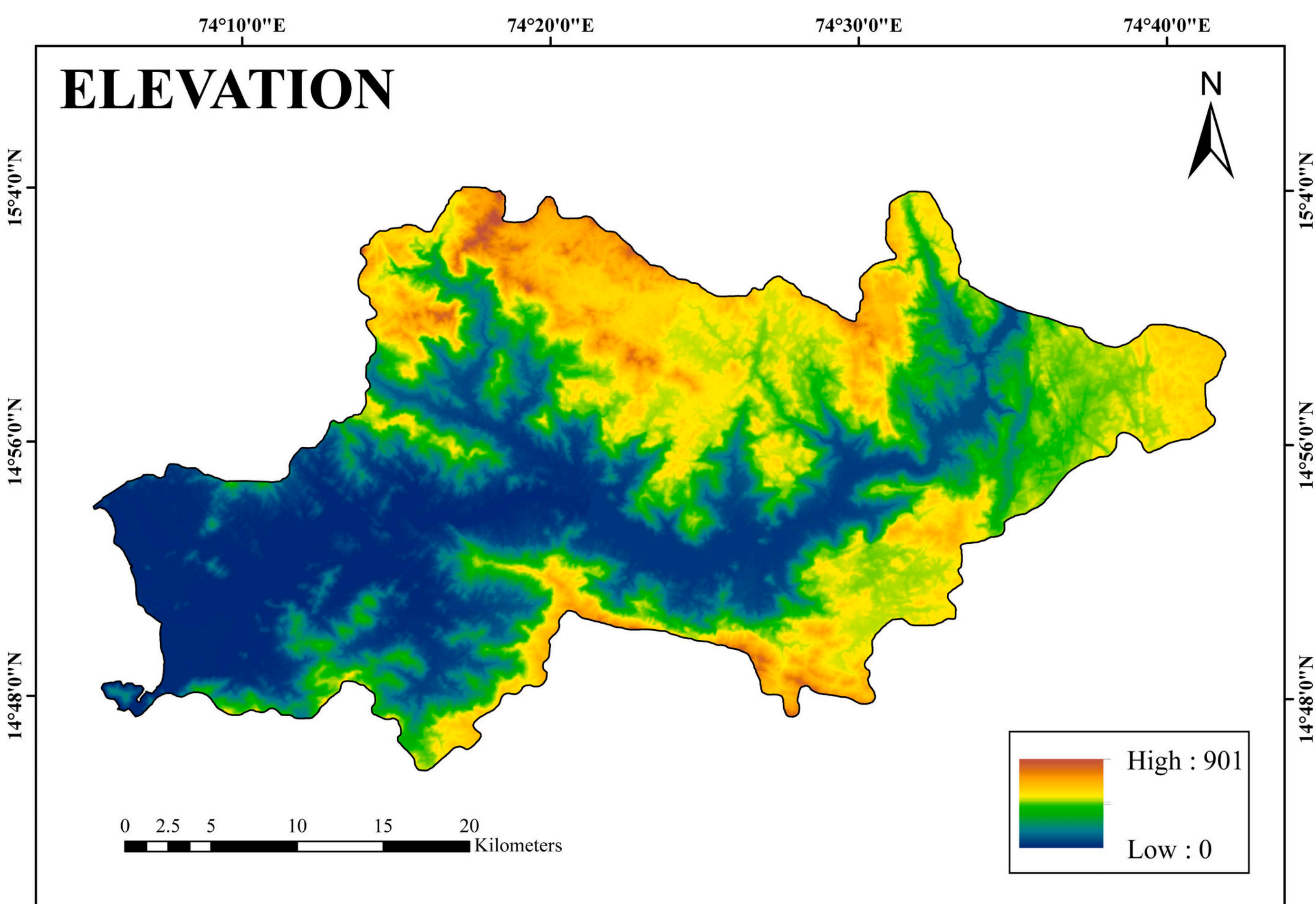

Fig. 6. Elevation map.

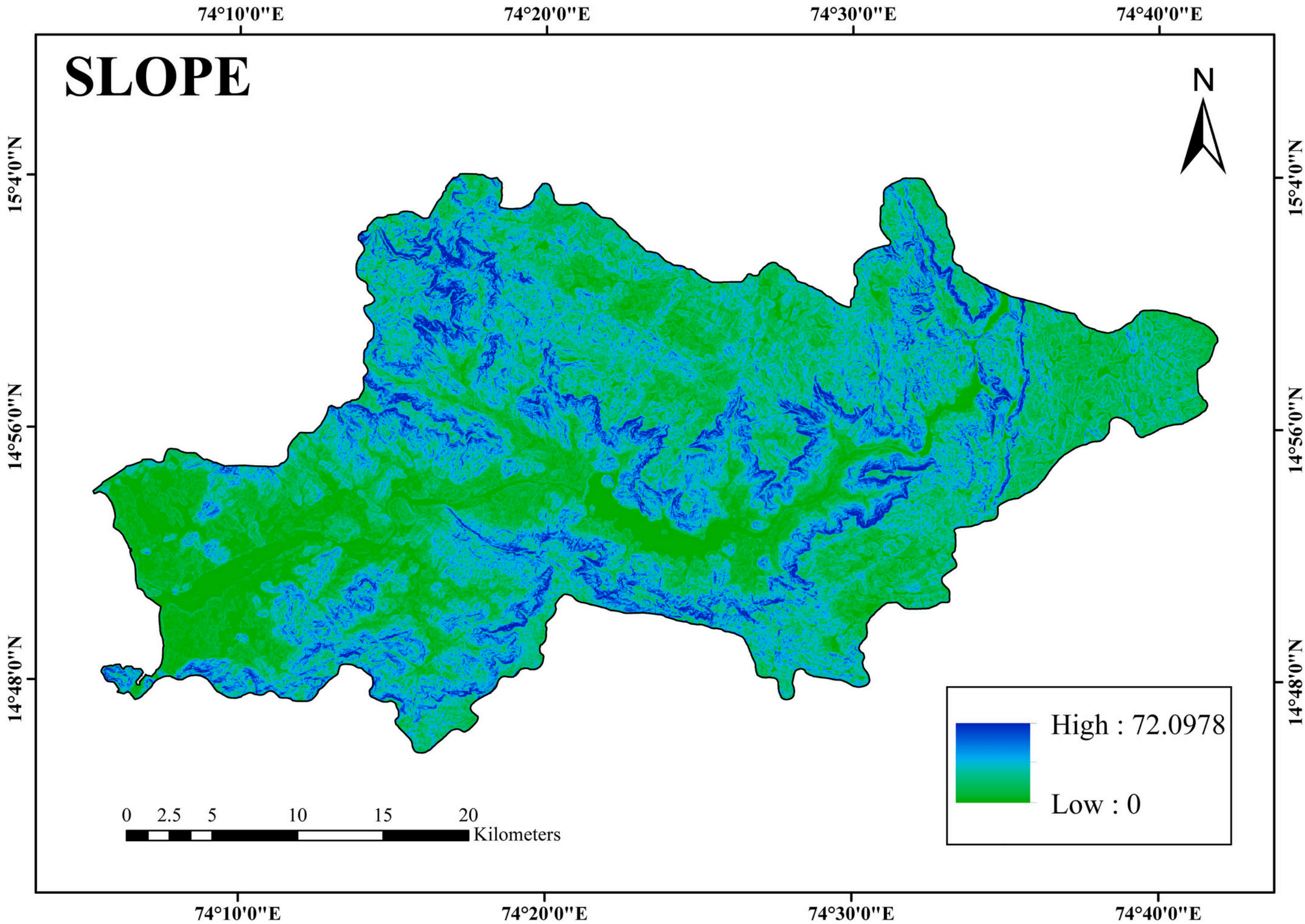

Fig. 7. Slope map.

Systems (GIS) are powerful tools that greatly facilitate the study of morphometric analysis such as satellite imagery, aerial photography, LiDAR, and radar, providing high-resolution data that can be used to extract information about the earth's surface. These data sources are essential for capturing the elevation, land cover, and topographic characteristics needed for morphometric analysis.

This study presents a morphometric analysis of the sub-basins of the Kali River basin, categorized as a 7th-order drainage basin, covering an area of 1175.445 km^2. The study area's drainage pattern is characterised by a dendritic nature. The bifurcation ratio of the study area suggests a low to moderate degree of structural control. Certain regions, exhibit elevated drainage density, signifying rapid runoff removal from these zones. The results suggest a substantial runoff generation in these areas due to their steep slopes and limited infiltration capacity. Both stream frequency and drainage texture indicate a very coarse spacing between streams in the area. The circularity ratio and elongation ratio, indicate an elongated oval shape for the study area, characterized by a moderate peak flow. The relief characteristics of the study area show significant fluctuations in altitude across the entire region, leading to intensified erosion and reduced infiltration in higher elevation areas. This, in turn, causes the accumulation of water in lower-lying regions, increasing the risk of flooding. Effective watershed management must address localized challenges such as flooding and soil erosion. Strategies to manage flooding include floodplain zoning, retention basins, and regular river maintenance. Soil erosion mitigation can be achieved through afforestation, terracing, and similar interventions, underscoring the importance of community engagement and multi-stakeholder collaboration in planning and execution. Furthermore, ongoing monitoring and adaptive management are imperative to ensure the efficacy of these strategies, necessitating coordinated efforts among governmental bodies, Non-Governmental Organizations (NGOs), and private sectors.

It is important to recognize that the morphometric characteristics of basins are subject to temporal changes driven by natural processes and human activities. Natural processes such as erosion and sedimentation can alter parameters like drainage density and stream frequency. Climatic variations can impact runoff, erosion, and drainage networks, while tectonic activities can modify the basin's topography. Additionally, human activities, including land use changes for urbanization and deforestation, as well as the construction of dams, can significantly influence morphometric parameters. This study provides valuable insights for decision-makers, planners, and governing authorities, facilitating informed decision-making and supporting sustainable flood management and mitigation strategies in the studied region. Understanding temporal changes in morphometric characteristics is essential for adaptive management and resilient planning in response to evolving natural and anthropogenic dynamics.

CRediT authorship contribution statement

S. Arjun: Supervision, Software, Methodology, Conceptualization. **Ananda Krishnan:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The authors are unable or have chosen not to specify which data has been used.

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