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Remote sensing and GIS-based morphometric analysis: a case study of the Mann river watershed

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Abstract
The Remote Sensing and Geographic Information System (GIS) has emerged as a highly efficient tool for collecting remotely sensed data over large areas in a periodic and systematic manner. One notable example is the globally available Digital Elevation Model (DEM), which is developed through various satellite missions. DEMs provide critical terrain elevation data that can be used to analyse and characterize watersheds of any size. This data is instrumental in estimating morphometric parameters, which play a vital role in watershed management and planning. The present study focuses on the Mann River watershed, and analyses its influence on the physical element responsible for key hydrological processes. Using a 30 m resolution CARTOSAT DEM, the drainage networks and other key morphometric features were extracted within a Geographic Information System (GIS) environment. This analysis provides valuable insights into how the shape and structure of the watershed impact water flow, erosion, and flood dynamics. Standard mathematical formulae were applied to compute parameters like linear aspects. Areal aspects and relief aspects. An analysis of these parameters gives tremendous insights into the shape of the watershed, its efficiency in drainage, and vulnerability to flooding and erosion. The results reveal that the Mann River watershed has characteristic features indicative of a dendritic drainage pattern and, therefore is subjected to moderate drainage density, which portrays this system as a well-drained one, prone to erosion and flash floods. This research holds significant implications for watershed management and planning. By understanding the morphometric behaviour of watersheds, it becomes possible to design effective conservation measures, implement flood control strategies, and plan sustainable land use and watershed development. Additionally, the study provides a framework for conducting further hydrological analyses and supports the effective management of riverine watersheds, particularly in semi-arid regions. The findings highlight that GIS-based morphometric analysis is a powerful tool for gaining insights into various characteristics of watershed while reducing time and cost, thereby enhancing the efficiency of watershed management efforts.

Keywords: Morphometric parameters, digital elevation model, remote sensing, geographic information system, watershed management, conservation measures

1. Introduction
Morphometric analysis of watersheds is a crucial technique for watershed management and planning, providing quantitative descriptions of river basins and insights into their behavior (Sukristiyanti *et al*., 2018; Maurya *et al*., 2016) [29, 16]. This method involves analyzing various parameters, including linear, areal, and relief aspects, to understand the relationship between different watershed characteristics (Gabale & Pawar, 2015) [7]. Digital Elevation Models (DEMs) and Geographic Information Systems (GIS) are commonly used tools for conducting morphometric analyses (Maurya *et al*., 2016) [16]. While numerous studies have been conducted in this field, there is a need for standardized classification and interpretation of morphometric parameters to facilitate consistent evaluation and comparison across watersheds (Sukristiyanti *et al*., 2018; Sondarva *et al*., 2023) [29, 25].
Morphometric analysis of watersheds using geospatial techniques plays a crucial role in the effective management of water resources and sustainable development. These techniques provide valuable insights into geo-hydrological behavior, climate, geology, and geomorphology (Bhatt, 2020; Hajam *et al*., 2013) [4, 10]. Parameters such as drainage area, stream order, and relief aspects help identify potential water zones and locations suitable for water harvesting. The use

of geospatial technologies like Remote Sensing and Geographic Information Systems (GIS) enables faster and more accurate analyses, particularly in regions lacking adequate hydrological data (Sondarva *et al*., 2023) [25]. GIS and remote sensing have proven effective in morphometric analysis, allowing easy delineation and computation of watershed parameters (Hajam *et al*., 2013; Gosavi *et al*., 2018) [10, 8]. These studies are essential for watershed assessment, management, and development projects (Soni, 2017; Bhatt, 2020) [26, 4]. Key parameters such as runoff, soil erosion, flood risk, and water resource capacity both surface and underground are directly influenced by morphometric characteristics (Hajam *et al*., 2013; Gosavi *et al*., 2018) [10, 8]. Understanding the behavior of drainage networks is critical for interpreting watershed dynamics and planning interventions, especially in mountainous regions prone to high runoff and erosion (Gosavi *et al*., 2018) [8].

Morphometric parameters provide crucial insights into watershed features and hydrological behavior, aiding in water resource management (Shekar & Mathew, 2023; Dash *et al*., 2023) [23, 5]. For instance, drainage density and stream frequency reflect watershed permeability and slope, which are vital for predicting runoff patterns (Dash *et al*., 2023) [5]. GIS and Digital Elevation Models (DEMs) enhance the accuracy of morphometric analyses, enabling detailed mapping of watershed characteristics (Arya *et al*., 2023; Aguiar, 2024) [3, 1]. Research indicates that morphometric analysis reveals relationships among watershed attributes, improving water resource planning, rainwater harvesting, and groundwater recharge strategies, particularly in semi-arid regions (Dash *et al*., 2023) [5]. These findings also inform land-use planning to mitigate flood risks, especially in urbanizing watersheds (Aguiar, 2024) [1]. However, challenges remain in standardizing parameters and ensuring data quality, which can affect the reliability of hydrological predictions (Shekar & Mathew, 2023; Ramatal *et al*., 2023) [23, 20].

In addition to watershed management, geospatial tools facilitate the prioritization of sub-catchments based on natural resource availability and erosion factors, which is critical for soil and water conservation planning (Faye & Ndiaye, 2021) [6]. They also support urban morphology studies, enabling town-plan analysis, meteorological assessments, and 3D visualization of urban forms and functions (Lo, 2007) [14]. Morphometric parameters serve as indicators of hydrological and morphological characteristics in different morpho-climatic settings, helping to assess flood potential, basin shape, and geomorphic development stages (Mahala, 2020) [15]. Also the findings from morphometric studies can guide local governments in making informed decisions about irrigation and water resource infrastructure (Reddy *et al*., 2024) [21].

Thus, the objective of this study was to analyze the linear, areal, and relief morphometric characteristics of the Mann river watershed, located in Akola and Buldana districts of the Maharashtra state, using geospatial technology. By employing morphometric techniques within a GIS framework, the study aims to provide insights into the watershed's geo-hydrological features.

2. Materials and Methods

2.1 Study Area

The Mann River Watershed lies in the Vidarbha region of Maharashtra state and lies between 20°54'59" N and 76°41'23" E. The river originates in the Malegaon block of Washim district and flows through Khamgaon, Chikli, Mehekar, Patur, and Shegaon before joining the Purna River near Manasgaon village in the Balapur block of Akola district. The Mann River, together with tributaries such as Aama, Pendhi, Uma, Katepurna, Shahanur, Chandrabhaga, Morna, and Vaan, forms a significant part of the Purna River system, which ultimately feeds into the Tapi River. The Mann river basin spreads over parts of Khamgaon, Chikli, Shegaon, Mehekal, Balapur, Pattur and Malegaon talukas and encompasses areas within Akola and Buldhana districts of Maharashtra.The study area is represented on Survey of India toposheets 55D/7, 55D/9, 55D/11, 55D/13, 55D/14 and 55D/15 at a scale of 1:50,000.

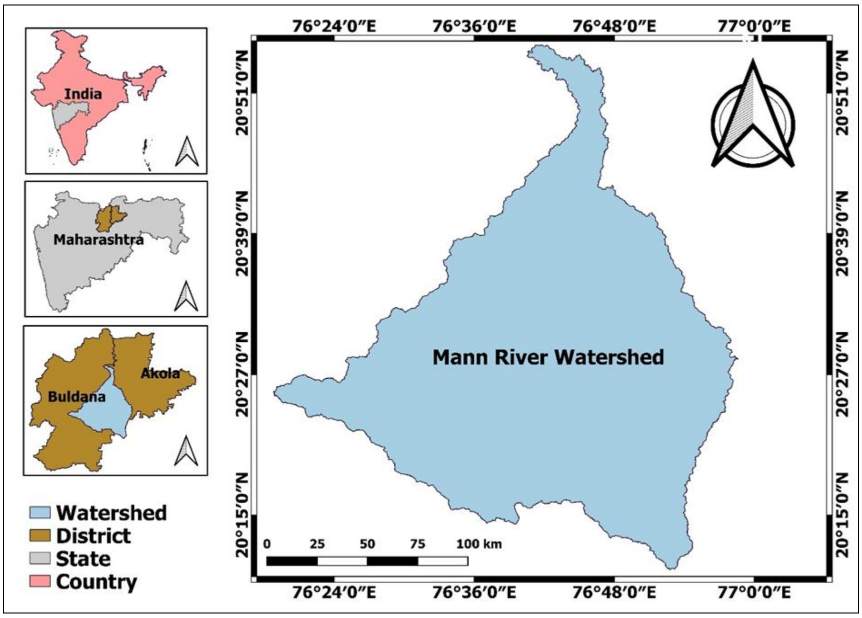

Fig 1: Location Map of the study area

2.2 Data Sets Utilized

The datasets employed in this study to achieve the objectives are as follows:

(i) CARTOSAT DEM with a 30-meter spatial resolution which was downloaded from National Remote Sensing Research Centre (NRSC) Bhuvan.

(ii) Topographical maps at a 1:50,000 scale which was downloaded from Survey of India (SOI).

2.3 Delineation of watershed and morphometric analysis
The study area, located within UTM zone 43, covers multiple scenes and was mosaicked and clipped using SAGA GIS software to create a unified mosaic. The Mann river watershed was automatically extracted from the CARTO DEM (30m) using pour point identification and geoprocessing tools in ArcGIS 10.8, and verified against georeferenced SOI Topo sheets (1:50,000) for accuracy. The basic watershed parameters, such as watershed area, watershed perimeter, length of the watershed, maximum elevation, and minimum elevation, were calculated first using ArcGIS 10.8 software. Various morphometric parameters, including linear, relief, and areal aspects, were then calculated using CARTOSAT DEM 30m data and ArcGIS 10.8, employing standard formulae to understand the study area's characteristics.

Table 1: Basic, linear, areal and relief morphological parameters and equations

Sr. no.	Parameters	Formulae	Reference
Linear Parameters			
1	Stream Order (U)	Hierarchical rank	Strahler (1964) [28]
2	Stream number (Nu)	Total number of stream segments of the order "u"	Strahler (1957) [27]
3	Stream Length (Lu)	$L_u=Lu_1+Lu_2......Lu_n$	Horton (1945) [12]
4	Mean Stream length (Lsm)	Lsm=Lu/Nu,	Strahler (1964) [28]
5	Stream Length Ratio (RL)	RL=Lu/N(u-1)	Horton (1945) [12]
6	Bifurcation Ratio (Rb)	Rb=Nu/N(u+1)	Schumm (1956) [22]
Areal Parameters			
1	Drainage Density (Dd)	Dd=Lu/A	Horton (1945) [12]
2	Stream Frequency (Fs)	$Fs=(\sum Nu)/A$	Horton (1945) [12]
3	Drainage Texture (Dt)	Dt=Nu/P	Smith (1950) [24]
4	Form Factor (Ff)	$Ff=A/(Lb^2)$	Horton (1945) [12]
5	Elongation Ratio (Re)	$Re=2\times(\sqrt{A/\pi})/Lb$	Schumm (1956) [22]
6	Circulatory Ratio (Rc)	$Rc=4\pi A/P^2$	Strahler 1964[28]
7	Length of overland flow (Lg)	Lg=1/2Dd	Horton (1945) [12]
8	Constant of channel maintenance (C)	C=1/Dd	Strahler 1964[28]
Relief Aspects			
1	Basin Relief (R)	R=H-h	Hadley and Schumm (1961) [9]
2	Relief Ratio (Rr)	Rr=R/L	Schumm (1956) [22]
3	Relative relief (RR)	$RR=(R/P)\times100$	Schumm (1956) [22]
4	Ruggedness number (Rn)	$Rn=R\times Dd$	Strahler (1964) [28]

3. Results and Discussion
The stream network was generated from the CARTOSAT DEM using the 'Spatial Analyst' and 'Hydrology' toolboxes in ArcGIS 10.8. The basic characteristics of the drainage basin was first calculated and then the aspect-wise morphometric parameters of the Mann River basin were analysed, and classified as :1. Linear aspect 2. Areal aspect 3. Relief aspect.

3.1. Linear Aspect
Linear aspect include Stream order (U), Stream number (Nu), Stream length (Lu), Mean stream length (Lsm), Stream length ratio (Rl) and Bifurcation ratio (Rb) which are presented in table 2:

Table 2: Stream Order Wise Stream number, Stream length and Mean stream length:

Stream Order (U)	Stream number (Nu)	Stream Length (Lu) (kilometer)	Mean Stream Length (Lsm) (kilometer)
I	1931	1931	1
II	430	860	2
III	91	273	3
IV	34	136	4
V	6	30	5
VI	3	18	6
VII	1	7	7
Total	2496	3255	28
Mean	-	465	2.71

3.1.1. Stream order (U)
The stream order of the Mann River watershed was analyzed using Strahler's (1964) [28] method, and the results were summarized in Table 1. In the Mann River watershed, the most prevalent stream orders were lower orders (1st, 2nd, and 3rd), reflecting the dominance of smaller tributaries in the drainage network. These lower-order streams were associated with steep slopes, rapid surface runoff, and higher erosion rates. In contrast, higher stream orders (4th and above) occurred in flatter regions with slower runoff and more significant sediment deposition. This stream order distribution suggested a dendritic drainage pattern, typical in regions with homogeneous lithology and moderate relief. The dominance of lower-order streams indicated the watershed's tendency for quick hydrological responses, especially in the upper reaches, making stream order a critical factor in understanding and managing the watershed's hydrology. This pattern was consistent with previous studies that suggested a direct relationship between stream order and the watershed's hydrological response (Ali and Khan, 2013) [2].

3.1.2 Stream number (Nu)
The number and length of streams by stream order in the Mann River watershed is presented in Table 2. There were 2,496 streams in total, with 1,931 being 1st order, which dominated both in number and length (1,931 units). As stream order increased, the number and length of streams decreased, aligning with Horton's laws. For example, 2nd order streams numbered 430 with 860 units in length, and by the 7th order, there was only one stream of 7 km. The predominance of lower-order streams indicated a high drainage density, contributing to rapid surface runoff, increased erosion potential, and higher flood risks. This suggested that the watershed was in a youthful geomorphic stage with complex drainage patterns.

3.1.3. Stream length (Lu)
The total stream length for the Mann River watershed, measured

using GIS software is presented in Table 2. The stream length (Lu) of the Mann River watershed, totalling 3,255 km, reflected an extensive and well-developed drainage network. This long cumulative stream length indicated high drainage efficiency and the capacity to transport significant water and sediment. The watershed's stream length distribution suggested prolonged water movement, which might have reduced peak flows during storm events and contributed to moderate flood intensity. Higher-order streams, with longer lengths and gentler slopes, regulated flow, while shorter, lower-order streams contributed to rapid runoff. The substantial total stream length highlighted the watershed's potential for efficient water conveyance, aligning with typical drainage patterns in similar regions. These characteristics were important for understanding water retention, runoff rates, and erosion potential within the watershed. These findings aligned with those observed by Ali and Khan (2013) [2].

3.1.4. Mean stream length (Lsm)

The Mean Stream Length (Lsm) in the Mann River watershed ranged from 1 km for 1st-order streams to 7 km for 7th-order streams, as shown in Table 3, indicating a typical hydrological pattern where stream length increased with order. This followed Horton's law, which suggested that higher-order streams, with longer lengths, drained larger areas and had gentler gradients, while lower-order streams, with shorter lengths, were found in steeper areas and contributed to rapid runoff.

The variation in stream length revealed the distinct roles streams played in managing runoff and erosion. Lower-order streams responded quickly to rainfall and contributed to faster runoff and higher erosion rates, while higher-order streams acted as main channels, modulating flow and aiding sediment deposition, reducing peak discharges over time. With an overall mean stream length of 3.8 km, the watershed exhibited a well-developed drainage system.

Table 3: Stream order wise Stream Length Ratio and Bifurcation Ratio

Stream Length Ratio	Value	Bifurcation Ratio	Value
II/I	0.45	I/II	4.49
III/II	0.32	II/III	4.73
IV/III	0.50	III/IV	2.68
V/IV	0.22	IV/V	5.67
VI/V	0.60	V/VI	2.00
VII/VI	0.39	VI/VII	3.00
Mean Stream Length Ratio	0.41	Mean Bifurcation Ratio	3.76

3.1.5. Stream Length Ratio (RL)

It refers to the ratio relating total stream length of a given order to the total stream length of the next lower order and it relates strongly to surface flow and discharge. Values for Stream length ratio (RL) of this study, as shown in Table 3, are 0.45 (1st to 2nd order), 0.32 (2nd to 3rd order), 0.50 (3rd to 4th order), 0.22 (4th to 5th order), 0.60 (5th to 6th order), and 0.39 (6th to 7th order). The fluctuations in the Stream Length Ratio (RL) indicated an early stage of geomorphic development in the area and were most likely to change frequently in the near future. This also demonstrated uneven hydrological behavior in the watershed area. The average stream length ratio for the watershed was found to be 0.41.

3.1.6 Bifurcation Ratio (Rb)

The bifurcation ratio (Rb) is the ratio of the number of streams of a given order to the number of streams of the next higher order (Schumm, 1956) [22]. Horton (1945) [12] viewed the bifurcation ratio as an index of relief and dissection, and it is a dimensionless parameter. Strahler (1957) [27] noted that the bifurcation ratio typically shows minimal variation across different regions or environments, except where strong geological controls are present. Variations in the bifurcation ratio between orders can indicate geological and lithological influences on the drainage basin (Strahler, 1964) [28]. Generally, bifurcation ratios ranges from 2.0 to 5.0 in sub-basins where geological structure did not dominate the drainage pattern, suggesting a normal basin category (Strahler, 1964) [28]. In this study, the bifurcation ratio ranged from 2 to 5.67, as presented in Table 3. The mean bifurcation ratio was 3.76, suggesting that the area had experienced significant structural disturbance (Nag and Chakroborty, 2003) [18].

3.2. Areal Aspects

Areal aspects include Drainage Density (Dd), Stream Frequency (Fs), Drainage Texture (T), Form Factor (Ff), Elongation Ratio (Re), Circularity Ratio (Rc), Constant of channel maintenance (C), Length of overland flow (Lg) which are presented in table 4:

Table 4: Results of the Morphometric Analysis of Areal Aspects

Sr. no	Parameter	Unit	Value
1	Drainage Density (Dd)	km/km^2	1.35
2	Stream Frequency (Fs)	km^{-2}	0.22
3	Drainage Texture (T)	km^{-1}	1.21
4	Form Factor (Ff)	Unitless	0.34
5	Elongation Ratio (Re)	Unitless	0.37
6	Circulatory Ratio (Rc)	Unitless	0.16
7	Constant of channel maintenance (C)	km^2/km	0.74
8	Length of overland flow (Lg)	Km	0.37

3.2.1. Drainage Density (Dd)

Drainage density is defined as the total length of all streams in a basin divided by the basin's area (Strahler, 1957) [27]. It reflects the spacing of channels within the basin. A low drainage density (Dd) indicates permeable subsoil material under vegetative cover and low relief (Strahler, 1964) [28], while a high Dd is associated with weak or impermeable subsurface materials, sparse vegetation, and mountainous relief (Nag, 1998) [17]. Low drainage density results in a coarse drainage texture, whereas high drainage density leads to a finer texture. The watershed had a drainage density of 1.35, as shown in Table 4. This low drainage density indicated highly permeable subsoil.

3.2.2. Drainage Texture (T)

Drainage texture is defined as the total number of stream segments of all orders divided by the perimeter of the watershed (Horton, 1945) [12]. It describes the relative spacing of drainage lines, which are more pronounced in areas with impermeable materials compared to permeable ones (Ali and Khan, 2013) [2]. Drainage texture (T) is influenced by factors such as climate, rainfall, vegetation, lithology, soil type, infiltration capacity, relief, and stage of development (Smith, 1954) [24]. Soft or weak rocks without vegetation produce a fine texture, while massive and resistant rocks create a coarse texture In arid climates with sparse vegetation, textures are generally finer than those in humid climates with similar rock types. According to Smith (1954) [24], drainage textures are classified into five categories: very coarse (<2), coarse (2-4), moderate (4-6), fine (6-8), and very fine (>8). The study area had a drainage texture value of 4.38, indicating a moderate texture

3.2.3. Stream Frequency (Fs)

Stream frequency is defined as the total number of stream segments of all orders unit-1 area of the basin (Horton, 1932, 1945) [11, 12]. Basins with high drainage and stream frequency often experience frequent flooding (Howard, 1967) [13]. A higher stream frequency (Fs) indicates greater surface runoff and a steeper terrain, while lower Fs values suggest permeable subsurface materials and low relief. In the study area, the Fs value was 0.22, indicating low runoff potential, a permeable surface, and a low relief ratio.

3.2.4. Form factor (Ff)
Form factor is calculated by dividing the basin area by the square of the basin length (Horton, 1932) [11]. For a perfectly circular basin, the form factor would be approximately 0.7854. Basins with higher form factors tend to have higher peak flows with shorter durations. The study area had a form factor of 0.34, indicating an elongated shape.

3.2.5. Circularity Ratio (Rc)
The circularity ratio is the ratio of the basin area to the area of a circle with the same perimeter as the basin. This dimensionless measure reflects the degree of circularity of the basin. Value of Rc varies from '0' (minimum circularity) to '1' (Maximum circularity). In the present study, the Rc value was found to be 0.16, indicating semicircular characteristics

3.2.6. Elongation Ratio (Re)
The elongation ratio (Re) compares the diameter of a circle with the same area as the drainage basin to the basin's maximum length (Schumm, 1956) [22]. It varies from 0, representing a highly elongated shape, to nearly 1, representing a nearly perfect circle. With an elongation ratio of 0.37 in this study it exhibited that the watershed is slightly elongated in shape. It also helped to give the idea about hydrological character of a drainage basin. The elongated basin had a low peak discharge.

3.2.7. Constant of Channel Maintenance (C)
The constant of channel maintenance, which is the inverse of drainage density (Schumm, 1956) [22], assesses how various factors like lithology, permeability, infiltration capacity, climate, and vegetation affect channel sustainability. The erosion susceptibility is classified as follows: highly erosion prone for values between 0 and 0.2, moderate erosion prone for values between 0.2 and 0.5, slightly erosion prone for values between 0.5 and 1, and negligible erosion prone for values greater than 1. In the present study, the C value was found to be 0.71, meaning that 0.71 square kilometres of land area were required to support each kilometre of channel length. This value places the area in the "Slightly Erosion Prone" category, where values ranges from 0.5 to 1.

3.2.8. Length of Overland Flow (Lg)
The length of overland flow indicates the distance water travels over the ground before it flows into defined stream channels, similar to sheet runoff (Horton, 1945) [12]. It is approximately half of the reciprocal of the drainage density. The calculated length of overland flow (Lg) value for the study area was 0.146, suggesting high relief. According to Smith (1954) [24] lengths of overland flow are categorized into three classes: low values (>0.2), moderate values (0.2-0.3), and high values (>0.3).

3.3. Relief Aspect
Relief aspect include Basin relief (R), Relief ratio (Rr), Relative relief (RR) and Ruggedness number (Rn) which are presented in Table 5:

Table 5: Results of the Morphometric Analysis of Linear Aspects

Sr. no	Parameter	Unit	Value
1	Basin Relief (R)	M	395.72
2	Relief Ratio (Rr)	Unitless	0.005
3	Relative Relief (RR)	Unitless	0.09
4	Ruggedness number (Rn)	Unitless	0.53

3.3.1. Basin Relief (R)
Basin relief refers to the elevation difference between the highest and lowest points within a basin. In the study area, the maximum elevation was 866 meters, and the minimum was 560 meters, giving a basin relief of 306 meters (Figure 3). This value indicates medium relief, characterized by steep water flow, low infiltration, and high runoff conditions. Basin relief is typically classified into four categories: low (0-200 meters), medium (200-500 meters), high (500-1000 meters), and very high (above 1000 meters). The study area's relief falls into the medium category.

3.3.2. Relief Ratio (Rr)
The relief ratio is calculated by dividing the basin relief by the basin length (Schumm, 1956) [22]. It serves as an indicator of the erosion intensity and sediment transport rate within the basin (Strahler, 1964) [28]. In the study area, the relief ratio was found to be 0.003. This very low Rr value of Mann watershed indicated elongated basin shape, low basin relief as well as maximum denudation stages of geomorphic evolution (Mahala, 2020) [15].

3.3.3. Relative relief (RR)
Relative relief (RR) is calculated by comparing the total elevation change within a watershed to its perimeter, providing a measure of the average elevation gradient from the highest peak to the outlet. It reflects the basin's vertical range, crucial for understanding its erosion characteristics (Rai *et al*., 2017) [19]. This factor plays a key role in landform development, influencing runoff, water transport, infiltration, and land degradation. In the present study, the relative relief was found to be 0.09. A low relative relief ratio indicates weak gravitational water flow, increased infiltration, and reduced runoff potential.

3.3.4. Ruggedness number (Rn):
The ruggedness number (Rn) is a dimensionless value obtained by multiplying the maximum basin relief by the drainage density. This number provides insight into the steepness of the basin's slopes and the overall length of the basin. In the study area, the Rn value was found to be 0.53. Very low Rn value of the watershed is indicative of mature and maximum denudation stages of erosion. (Mahala, 2020) [15].

4. Conclusion
A detailed morphometric analysis of the Mann River watershed was conducted to understand its drainage system and hydrological influences. By examining and quantifying the watershed's linear, areal, and relief components, the study highlights the use of the CARTO-DEM datas*et al*ongside geospatial technologies, such as Remote Sensing and GIS, to analyse the watershed's morphology. Classified as a seventh-order watershed, the Mann River basin is dominated by lower-order streams, with first-order streams making up the majority, indicating a network driven by smaller tributaries. The mean bifurcation ratio of 3.76 suggests a moderately branched drainage system. With a drainage density of 1.35, the watershed has highly permeable soil, leading to low runoff potential, supported by a form factor value of 0.22. This suggests significant groundwater recharge capacity, further reinforced by the low relief ratio. The elongated shape of the watershed, with a circularity ratio of 0.16 and an elongation ratio of 0.37, along with its medium relief, indicates a mature stage of geomorphic development. A low ruggedness number signifies extensive denudation, pointing to advanced erosion. These findings are vital for understanding the watershed's hydrological behaviour, particularly in water resource management and flood risk

mitigation. The elongated shape and mature erosion stage suggest slower surface runoff, reducing the likelihood of flash floods. However, the area's high permeability and low runoff potential emphasize the need for water conservation to maintain groundwater levels. Remote sensing and GIS techniques offer significant time and cost savings over conventional methods, providing a clearer understanding of hydrological behaviour and natural resource management challenges. However, the study has limitations, particularly its reliance on a 30 m resolution DEM, which may not capture finer topographical details.

Conflict of interest

The authors declare no conflict of interest.

Data availability

Data will be made available on request.

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