OPEN ACCESS
Quick Response Code:
Website: https://wgges.us

Manuscript ID:
IJWGAFES-2025-021102

DOI: 10.5281/zenodo.17760144

DOI Link:
https://doi.org/10.5281/zenodo.18067284

Volume: 2
Issue: 11
November
Year: 2025
E-ISSN: 3066-1552

Submitted: *05 Oct.2025*
Revised: *10 Oct.2025*
Accepted: *05 Nov. 2025*
Published: *30 Nov. 2025*

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How to cite this article:
Khandare, R. P., & Shinde, P. S. (2025). Morphometric Analysis of the Tulsi River Basin, Kolhapur District, Maharashtra for Hydrological Assessment. International Journal of World Geology, Geography, Agriculture, Forestry and Environment Sciences, 2(11), 5–12.
https://doi.org/10.5281/zenodo.18067284

Morphometric Analysis of the Tulsi River Basin, Kolhapur District, Maharashtra for Hydrological Assessment

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Abstract

The Tulsi River Basin in Kolhapur represents a critical basin within the Western Ghats and requires detailed geomorphological assessment for sustainable resource management. This study conducted a comprehensive quantitative morphometric analysis utilizing geospatial techniques to evaluate the hydrological characteristics of the basin. Linear, areal, and relief parameters were derived from ALOS PALSAR DEM data and analyzed using GIS. The results revealed a mature, 6th-order dendritic drainage network comprising 730 streams with a mean bifurcation ratio of 3.74, indicating geological homogeneity and structural stability. The basin exhibits strong elongation (Form Factor: 0.09; Elongation Ratio: 0.34), which significantly influences hydrological behavior by moderating flood peaks and extending concentration time. Moderate drainage density (2.95 km/km^2) combined with high stream frequency (4.49 streams/km^2) reflects well-developed drainage texture, while gentle slopes (10.75%) and moderate ruggedness (1.32) suggest controlled erosion potential. The analysis concludes that the basin's inherent morphometric characteristics provide natural resilience to extreme flooding and severe erosion. These findings establish crucial baseline data for prioritizing sub-watersheds and formulating effective soil conservation, water harvesting, and flood mitigation strategies, thereby contributing to sustainable watershed management in this ecologically significant region.

Keywords: *Morphometric Analysis, Tulsi River Basin, GIS, Watershed Management.*

Introduction

Watersheds function as fundamental units for hydrological study and management, where the interplay of linear, aerial, and relief characteristics dictates the movement and availability of water resources. The quantitative examination of these properties, known as morphometric analysis, provides a valuable tool for evaluating the structure and process of a drainage basin. As a systematic mathematical description of the Earth’s surface configuration and drainage network, morphometry offers essential insights into the influence of geology, soil, temperature, and structural constraints on the hydrological behavior of a region (Horton, 1945; Strahler, 1964).

The advent and integration of Geospatial Technologies, particularly Geographic Information Systems (GIS) and remote sensing, has revolutionized morphometric studies. These tools enable the efficient extraction, calculation, and analysis of a vast array of morphometric parameters from Digital Elevation Models (DEMs), allowing for more precise and comprehensive watershed characterization (Nag & Chakraborty, 2003). This methodological advancement is crucial for understanding complex land-surface processes, including runoff generation, sediment transport, and groundwater potential, which are foundational to sustainable watershed management (Pande & Moharir, 2015).

The utility of this approach has been well-documented across diverse geographical settings. Numerous studies have established strong correlations between morphometric parameters and hydrological outcomes at the global and national levels. For instance, high drainage density and stream frequency are frequently linked to increased runoff potential and soil erosion susceptibility (Sutradhar, 2020), whereas elongated basin shapes tend to moderate flood peaks (Bogale, 2021). Within the Indian context, and more specifically, the Deccan Trap terrain of Maharashtra, researchers such as Shinde and Telore have been instrumental. Their geospatial morphometric analyses of basins, including Banganga (Nimbalkar & Shinde, 2022; Telore & Shinde, 2020), provide a valuable regional framework that demonstrates how parameters such as bifurcation ratio and relief can be used to prioritize sub-watersheds for conservation in semi-arid to semi-humid environments.

The Tulsi River Basin, a vital right-bank tributary of the Krishna River located entirely within the Kolhapur district, has emerged as a critical area for such investigations. Originating in the ecologically sensitive and high-rainfall Sahyadri ranges (a part of the Western Ghats biodiversity hotspot), the basin's health is paramount for water security and agricultural productivity of the region.

The geology of the basin, dominated by the Deccan Traps basalts, and its significant topographic gradient from the Ghats to the plains present a dynamic and potentially vulnerable landscape. Despite its importance, a comprehensive and contemporary GIS-based morphometric characterization of the entire Tulsi Basin is lacking in scientific literature.

Objectives

To address this gap, the present study conducted a detailed quantitative morphometric analysis of the Tulsi River Basin. The specific objectives are:

1. To delineate the basin boundary was delineated and the drainage network was extracted using high-resolution DEM data in a GIS environment.
2. To Compute and analyze a comprehensive set of linear, aerial, and relief morphometric parameters.
3. To synthesize these quantitative results, we inferred the hydrological behavior, erosion susceptibility, and flood potential of the basin.
4. To provide science-based recommendations for watershed prioritization and sustainable resource management within the basin.

The findings of this study are expected to establish a crucial baseline database for hydrologists, geomorphologists, and planners, enabling informed decision making for soil conservation, water harvesting, and flood mitigation in the Tulasi River Basin.

Study Area

The Tulsi Basin is located in the Maharashtra state's Kolhapur district's Karvir and Radhanagari tehsils of Maharashtra state. Geographically, it ranges from 16°27′ to 16°39′ North latitude and 73°57′ to 74°08′ East longitude, encompassing an area of approximately 165 km². The basin is located in the southern part of Maharashtra, which is known for its fertile soils and well-watered agricultural lands (refer to the Location Map).

Physiographically, the Tulsi Basin exhibits an undulating topography with a combination of plains and gently sloping areas that support intensive agriculture. The region benefits from favorable climatic conditions, ensuring productive agricultural activities throughout most of the year. The presence of irrigation facilities and fertile alluvial soils further enhances the agricultural potential of the basin.

Administratively, the basin encompasses several villages distributed across the head, middle, and tail reaches of the command area, reflecting the variations in irrigation access and cropping patterns. Therefore, the study area represents a typical example of a semi-humid agricultural region of southern Maharashtra, where both natural and human factors play a crucial role in determining the socio economic and agricultural characteristics of the local population.

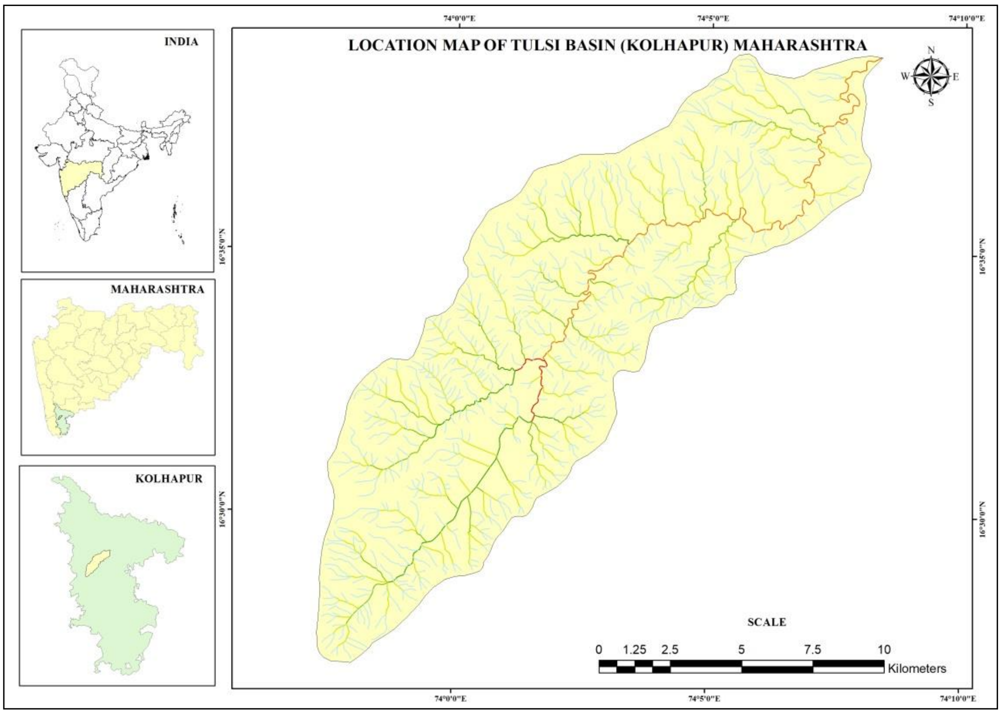

Figure 1. Location Map

Materials And Methodology

A morphometric investigation of the Tulsi River Basin was undertaken using a thorough geospatial methodology. The main source of data was the 12.5-meter spatial resolution ALOS PALSAR Digital Elevation Model (DEM), which was acquired from the Alaska Satellite Facility portal and used as the basis for terrain analysis. For validation, reference data were obtained from the 1:50,000 scale Survey of India topographic maps (sheets 47 L/2, 47 L/3, 47 H/14, 47 H/15), accessed via the SOI Naksha portal. All spatial data were standardized to the WGS-1984 UTM Zone 43N coordinate system to maintain projection consistency throughout the analysis. The analytical procedures were implemented using ArcGIS 10.8 software with the Arc Hydro tools extension. The process began with DEM pre-processing, involving sink filling and computation of the flow direction and flow accumulation rasters. The drainage network was extracted using a threshold-based approach followed by stream ordering according to Strahler's (1957) classification system. Basin delineation was performed by identifying the pour point at the confluence with the Bhogawati River.

Table 1: Quantitative Morphometric Analysis.

Category	Parameter	Description & Formula	Reference
I. Linear Aspects	Stream Order (U)	Hierarchical rank of streams.	Strahler (1964)
	Stream Number (Nu)	Total stream segments for a given order.	Horton (1945)
	Stream Length (Lu)	Total length of all streams for a given order (km).	Horton (1945)
	Mean Stream Length (Lsm)	$Lsm = Lu / Nu$	Horton (1945)
	Stream Length Ratio (RL)	$RL = Lu / Lu-1$	Horton (1945)
	Bifurcation Ratio (Rb)	$Rb = Nu / Nu+1$	Schumm (1956)
	Mean Bifurcation Ratio (Rbm)	Average Rb for all orders.	Strahler (1957)
	Main Channel Length (Lm)	Length of the longest stream (km).	Horton (1945)
	Basin Perimeter (P)	Total length of the watershed boundary (km).	(GIS Derived)
	Sinuosity Index	$SI = Cl / Vl$	Schumm (1963)
	Rho Coefficient (ρ)	$\rho = RL / Rb$	Horton (1945)
II. Areal Aspects	Basin Area (A)	Total projected area of the basin (km²).	Strahler (1964)
	Drainage Density (Dd)	$Dd = \Sigma Lu / A$ (km/km²).	Horton (1945)
	Stream Frequency (Fs)	$Fs = \Sigma Nu / A$	Horton (1945)
	Drainage Texture (T)	$T = \Sigma Nu / P$	Horton (1945)
	Form Factor (Ff)	$Ff = A / Lb^2$	Horton (1945)
	Constant of Channel Maintenance (C)	$C = 1 / Dd$	Horton (1945)
	Circularity Ratio (Rc)	$Rc = 4\pi A / P^2$	Miller (1953)
	Compactness Coefficient (Cc)	$Cc = P / (2\sqrt{(\pi A)})$	Horton (1945)
	Elongation Ratio (Re)	$Re = (2\sqrt{(A/\pi)}) / Lb$	Schumm (1956)
	Length of Overland Flow (Lg)	$Lg = 1 / (2 * Dd)$	Horton (1945)
	Infiltration Number (If)	$If = Dd * Fs$	Faniran (1968)
	Shape Index (Sw)	$Sw = Lb^2 / A$	Horton (1932)
	Drainage Intensity (Di)	$Di = Fs / Dd$	Faniran (1968)
III. Relief Aspects	Basin Relief (Bh)	$Bh = Z - z$	Schumm (1956)
	Relief Ratio (Rr)	$Rr = Bh / Lb$	Schumm (1956)
	Ruggedness Number (Rn)	$Rn = Bh * Dd$	Patton & Baker (1976)
	Dissection Index (DI)	$DI = Bh / Z$	Magesh et al. (2011)
	Basin Slope (Sb)	$Sb = Bh / Lb$	Miller (1953)

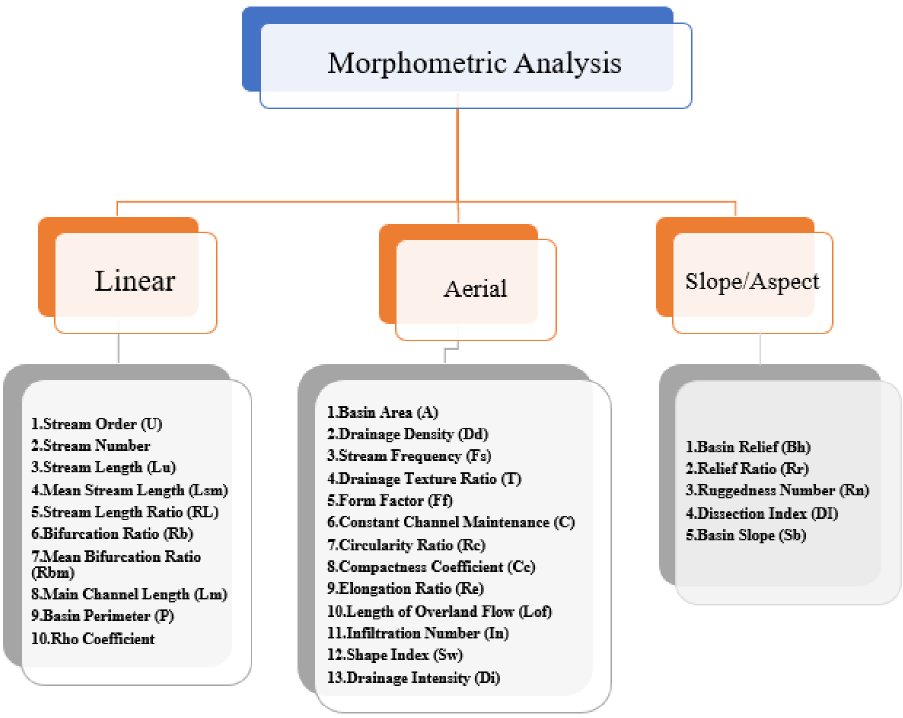

Figure 2. Methodological Flowchart

Results And Analysis

Table 2: Linear Morphometric Parameters of the Tulsi River Basin.

Basin	Stream Order	No of Streams	Stream Length (km)	Mean Stream Length (km)	Stream Length Ratio	Bifurcation Ratio	Basin Perimeter (km)	Main stream length (km)	Rho Coefficient
Tulsi	1	567	281.17	0.50	0.37	4.57	67.77	41.63	--
	2	124	104.99	0.85	0.43	4.13			0.081
	3	30	45.13	1.50	0.39	5.00			0.104
	4	6	17.66	2.94	0.22	3.00			0.078
	5	2	3.93	1.97	6.89	2.00			0.073
	6	1	27.08	27.08	--	--			3.445
	Total	730	479.96	--	8.31	18.71	--		--
	Mean	--	--	--	1.39	3.74	--	1.66	0.756

Linear Parameters

1. **Stream Order Analysis**

The Tulsi Basin demonstrates a hierarchical stream order system following Strahler's classification method. The basin contains 567 first-order streams, 124 second-order streams, 30 third-order streams, six fourth-order streams, two fifth-order streams, and one sixth-order stream, totaling 730 streams. This distribution exhibits a steady decline in stream count with increasing stream order in accordance with Horton's law of stream numbers. This suggests a well-developed dendritic drainage pattern, typical of homogeneous geological formations.

2. **Stream Length Analysis**

The total stream length within Tulsi Basin measures 479.96 kilometers, distributed across different stream orders as follows: 281.17 km in first-order streams, 104.99 km in second-order streams, 45.13 km in third-order streams, 17.66 km in fourth-order streams, 3.93 km in fifth-order streams, and 27.08 km in the sixth-order stream. A main stream length of 41.63 kilometers serves as the principal drainage conduit, influencing the basin's hydrological response characteristics and flood propagation patterns.

3. **Bifurcation Ratio (Rb)**

The bifurcation ratios calculated between successive stream orders were Rb(1-2) = 4.57, Rb(2-3) = 4.13, Rb(3-4) = 5.00, Rb(4-5) = 3.00, and Rb(5-6) = 2.00. The mean bifurcation ratio was 3.74 indicates geological homogeneity and uniform rock resistance to erosion. These values, within the optimal 3-5 range suggest minimal structural control and a mature drainage system that has achieved dynamic equilibrium between erosional forces and rock resistance.

4. **Stream Length Ratio (Rl)**

The stream length ratios across successive orders were Rl(1-2) = 0.37, Rl(2-3) = 0.43, Rl(3-4) = 0.39, Rl(4-5) = 0.22, and Rl(5-6) = 6.89. Although the unusually large ratio between the fifth and sixth orders reveals particular geomorphological controls or data properties in higher-order stream segments, a mean stream length ratio of 1.66 demonstrates the presence of geometric similarity in the basin's stream network development.

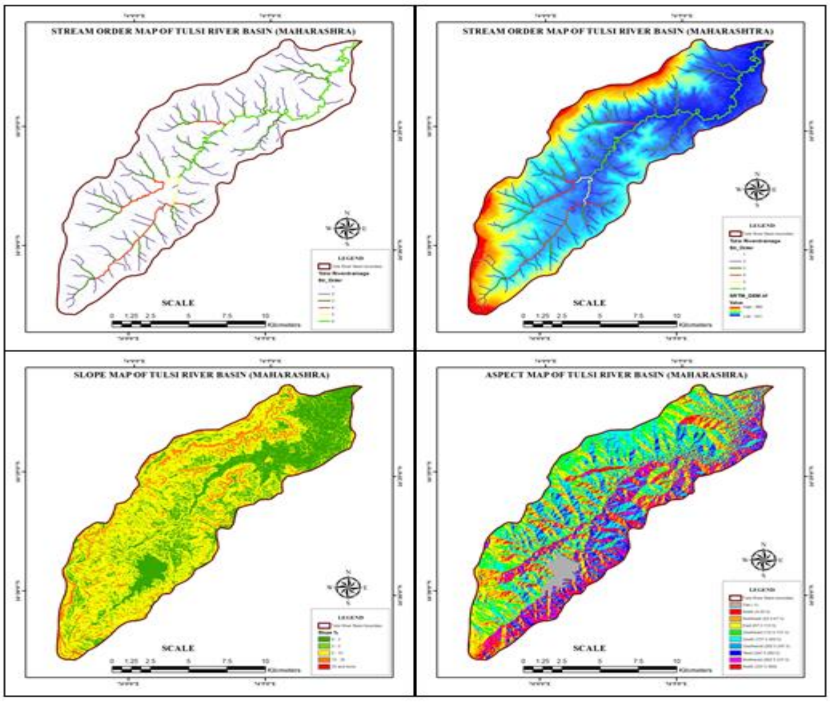

Figure 4. Stream order, DEM, Slope and Aspect Map of the study region

5. **Rho Coefficient Analysis**

The Rho Coefficient values across stream orders showed significant variation, ranging from 0.073 to 3.445, with a mean value of 0.756. The Rho Coefficient represents the ratio of the stream length ratio to the bifurcation ratio (Rl/Rb), indicating the relationship between channel storage capacity and drainage efficiency. Values below 1.0 generally suggest efficient drainage systems with good sediment transport capacity, while values above 1.0 indicate higher storage potential and reduced drainage efficiency.

Rho Coefficient Interpretation

- **Orders 2-5**: Rho values ranged from 0.073 to 0.104, indicating highly efficient drainage systems with excellent sediment transport capacity and minimal storage potential in these intermediate stream orders.
- **Order 6**: An exceptionally high Rho value of 3.445 suggests significant storage capacity and reduced drainage efficiency in the highest-order stream, potentially indicating floodplain development, sediment deposition zones, or anthropogenic influence.
- **Mean Rho (0.756)**: The overall basin average below 1.0 suggests a drainage network that is generally efficient in water and sediment conveyance with moderate storage characteristics.

Hydrological Implications of Rho Coefficient

The Rho Coefficient pattern indicates that the Tulsi Basin maintains efficient drainage through most of its network (orders 1-5) while the highest-order stream (order 6) serves as a significant storage component. This configuration supports flood attenuation during high-flow events, while ensuring efficient drainage under normal flow conditions. The low Rho values in intermediate orders suggest a well-maintained channel capacity and minimal sedimentation issues, contributing to the basin's overall hydrological stability.

Aerial Parameters

1. **Basin Geometry**

The Tulsi Basin encompasses a total area of 162.70 square kilometers with a perimeter of 67.77 kilometers. The area-perimeter relationship provides the fundamental basis for calculating various shape parameters that influence the basin's hydrological behavior, sediment yield, and flood characteristics. The compactness of the basin affects the runoff concentration time and peak discharge rates.

2. **Form Factor (Rf)**

A substantially elongated basin shape is indicated by a form factor of 0.0939, which is determined by dividing the basin size by the square of the main stream length. This low value significantly influences hydrological processes by increasing the concentration time, reducing peak discharges, and extending the duration of flood flows. The elongated morphology suggests that the basin developed under structural or lithological control that favored longitudinal extension.

3. **Elongation Ratio (Re)**

With an elongation ratio of 0.3459, the Tulsi Basin entered the strongly elongated group. The Ratios below 0.7 indicate significant elongation. This shape characteristic results in attenuated hydrographs and reduced flood peaks compared with more circular basins of equivalent area.

4. **Circularity Ratio (Rc)**

The circularity ratio of 0.4453 indicates a roughly circular basin with elongated inclinations.

5. **Drainage Density (Dd)**

The Tulsi Basin has a moderate drainage density of 2.95 km/km².

6. **Stream Frequency (Fs)**

High drainage dissection intensity was indicated by a stream frequency of 4.49 streams km^2.

7. **Drainage Texture (Dt)**

With a drainage texture of 10.77 streams per kilometer, Tulsi Basin demonstrates fine drainage texture.

8. **Constant of Channel Maintenance (C)**

The constant for channel maintenance (0.3390 km²/km) represents the basin area necessary to support a unit length (1 km) of the stream channel.

9. **Length of Overland Flow (Lg)**

The length of the overland flow is 0.1695 km, indicating that the average distance that water travels over land before entering a defined stream channel.

10. **Infiltration Number (If)**

An infiltration number of 13.25, calculated as the product of drainage density and stream frequency, suggests a limited infiltration capacity relative to the surface runoff in the basin. This elevated value indicates that surface runoff is the dominant hydrological process that negatively impacts groundwater recharge and the overall water balance.

Slope Aspect Parameters

Table 3: Relief Morphometric Parameters of the Tulsi River Basin.

Basin Relief (M)	Relief Ratio	Ruggedness Number	Dissection Index	Basin Slope %
447	0.0107	1.1318	0.491	10.75

1. **Basin Relief Analysis**

The Tulsi Basin exhibits significant topographic variation, with the highest elevation at 911 m and the lowest elevation at 464 m, resulting in a total basin relief of 447 m. This substantial elevation difference of nearly half a kilometer creates diverse microclimatic conditions and influences the hydrological processes across the basin. The Relief characteristics play a crucial role in determining rainfall distribution, temperature variations, and vegetation patterns throughout the watershed.

2. **Relief Ratio (Rh)**

The relief ratio was calculated to be 0.0107, derived from the basin relief of 447 m divided by the main stream length of 41,630 m. This low relief ratio indicates moderately steep to gentle slopes that prevail across the basin. This value suggests a mature landscape with balanced erosional processes where the basin has undergone significant denudation, resulting in moderate slope gradients that support stable hydrological conditions and controlled sediment transport rates.

3. **Ruggedness Number (Rn)**

Moderate topographic complexity and erosion potential were indicated by a roughness of 1.318. Calculated as the product of drainage density (2.9495 km/km²) and basin relief (0.447 km), this result is within a moderate range, suggesting balanced geomorphological conditions. The roughness number represents the combination of drainage texture and relief characteristics, indicating that the Tulsi Basin experienced erosion rates without excessive sediment yield or landscape instability.

Dissection Index (DI)

A dissection index of 0.491 reveals moderately dissected terrain with well-developed valley systems. Calculated as the ratio of relative relief to absolute relief (447m/911m), this value indicates that approximately 49% of the total elevation potential has been utilized in valley development. This moderate dissection suggests a landscape in the mature stage of geomorphological development, with balanced erosional and depositional processes that maintain landscape stability.

4. **Average Slope**

The average basin slope was approximately 6.14 °or 10.75%, indicating a gently sloping terrain conducive to sustainable agricultural practices and moderate runoff generation. This slope gradient supports adequate drainage while minimizing excessive erosion risk, creating favorable conditions for soil conservation and water resource management. The gentle slopes contributed to longer concentration times and attenuated flood peaks during rainfall events.

5. **Hypsometric Analysis**

The hypsometric curve, derived from the elevation distribution between 464m and 911m, suggests a mature basin in the equilibrium stage. The elevation distribution indicates a significant area at intermediate elevations, which is characteristic of well-developed basins that have undergone substantial landscape evolution. This hypsometric characteristic influences the water distribution, soil development, and ecological diversity across different elevation zones within the basin.

6. **Slope Aspect Distribution**

While specific aspect data are unavailable, the dendritic drainage pattern and elevation range suggest that varied slope aspects influence microclimatic conditions. North-facing slopes likely experience reduced solar radiation and higher moisture retention, whereas south-facing slopes receive more direct sunlight, affecting vegetation patterns and evaporation rates. This diversity creates ecological heterogeneity and influences hydrological responses across different slope orientations.

7. **Channel Slope Characteristics**

The main channel slope was calculated to be 1.07%, derived from the relief (447m) divided by the main stream length (41,630m). This gentle channel gradient supports efficient sediment transport without excessive erosion, maintains stable stream banks, and balances sediment loads. A moderate slope ensures adequate flow velocities for drainage while allowing sufficient infiltration opportunities along the channel network.

8. **Erosion Intensity and Sediment Yield**

The combination of moderate relief (447m) and gentle slopes (6.14°) suggests controlled erosion rates within sustainability limits. The morphometric characteristics of the basin indicate a landscape where erosional processes are balanced by depositional mechanisms, resulting in a moderate sediment yield that maintains ecological stability. This erosion pattern supports the long-term agricultural sustainability and water quality preservation in watersheds.

9. **Topographic Controls on Hydrology**

The elevation range of 447 m creates significant orographic effects on precipitation patterns, with higher elevations likely to receive enhanced rainfall. This topographic influence affects the runoff generation, soil moisture distribution, and groundwater recharge patterns across the basin. The varied elevation zones created distinct hydrological regimes that collectively contributed to the basin's overall water resource potential and flood response characteristics.

Conclusion

Based on a comprehensive morphometric analysis, the Tulsi River Basin is characterized as a mature and geomorphologically stable watershed. The basin exhibits a well-developed hierarchical dendritic drainage network, as evidenced by a total of 730 streams and a mean bifurcation ratio of 3.74, which indicates geological homogeneity and a drainage system in a state of dynamic equilibrium. A key defining feature is its highly elongated shape, reflected by a low Form Factor (0.09) and Elongation Ratio (0.34). This specific geometry plays a crucial role in moderating the hydrological response of the basin by attenuating flood peaks and extending the duration of runoff. Furthermore, the landscape demonstrates a fine drainage texture with a moderate drainage density (2.95 km/km²) and high stream frequency (4.49 streams/km²), facilitating efficient surface runoff. Importantly, this runoff potential is balanced by the basin's mature relief, characterized by gentle slopes (10.75%) and a moderate Ruggedness Number (1.32), which collectively suggests a controlled erosion environment. In summary, the morphometric structure of the Tulsi Basin confers natural resilience to extreme flooding and severe erosion. These findings provide a critical scientific foundation for formulating sustainable watershed management strategies, including soil conservation measures, water harvesting initiatives, and informed land use planning.

Acknowledgment
The authors express their sincere gratitude to the Groundwater Surveys and Development Agency (GSDA), Government of Maharashtra, for providing institutional support and a conducive research environment.
We are thankful to Shivaji University, Kolhapur, for academic guidance and research facilities extended during the course of this study.

Financial support and sponsorship
Nil.

Conflicts of interest
The authors declare that there are no conflicts of interest regarding the publication of this paper.

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