

Manuscript ID:
IJRSEAS-2025-020625



Quick Response Code:



Website: <https://eesrd.us>



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DOI: 10.5281/zenodo.23080072

DOI Link:
<https://doi.org/10.5281/zenodo.23080072>

Volume: 2

Issue: 6

Pp. 146-153

Month: December

Year: 2025

E-ISSN: 3066-0637

Submitted: 10 Nov. 2025

Revised: 16 Nov. 2025

Accepted: 15 Dec. 2025

Published: 31 Dec. 2025

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How to cite this article:

Divekar, A. B., & Chavan, M. N. (2025). Assessment of Geomorphometric Parameters and Erosion Vulnerability of a Coastal Watershed Using GIS: A Case of Karde Watershed, Konkan Coast, Maharashtra. International Journal of Research Studies on Environment, Earth, and Allied Sciences, 2(6), 146–153. <https://doi.org/10.5281/zenodo.23080072>

Assessment of Geomorphometric Parameters and Erosion Vulnerability of a Coastal Watershed Using GIS: A Case of Karde Watershed, Konkan Coast, Maharashtra

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Abstract

A watershed represents a distinct geomorphological unit defined by a stream network and bounded by a topographic drainage divide. Geomorphometric assessment provides a quantitative framework to measure and analyze these landform dimensions. The present work utilizes Geographical Information System (GIS) tools to evaluate the erosion susceptibility of the Karde watershed, located in the Konkan coastal belt along India's western coast. Spatial dimensions including total stream length, watershed area, watershed perimeter, and watershed length were extracted from the Survey of India (SOI) topographical sheets 47G/1 and 47G/2 (1:50,000 map scale) using Global Mapper software (version 22). The investigation focuses on a fourth-order watershed spanning 7.684 square kilometres within the Karde and Chandranagar villages of Dapoli Tahsil, situated in the Ratnagiri District of Maharashtra. Geographically, the Karde watershed is bounded by latitudes 17°44'07" N to 17°46'02" N and longitudes 73°07'20" E to 73°09'30" E. The fourth-order stream flows westward, discharging directly into the Arabian Sea. The Karde watershed is characterized by a dense and dendritic drainage network. The study area sits within the Konkan coastal plains, where torrential downpours during the southwest monsoon drive severe landscape degradation. The geomorphometric evaluation involved calculating the linear, areal, and relief characteristics of the watershed. Key quantitative indices computed for the Karde watershed include mean bifurcation ratio (3.25), drainage density (3.42 km/sq.km), stream frequency (5.34/sq.km), infiltration number (18.23), form factor (0.54), elongation ratio (0.83) and ruggedness number (0.85). Collectively, these morphometric variables indicate a mountainous terrain marked by steep gradients, highly dissected topography, and a complex structural configuration. Furthermore, the high drainage density value implies the presence of impermeable or highly consolidated subsurface geologic formations with sparse vegetative cover. The evaluation of linear, areal, and relief parameters of a watershed helps evaluate erosion risks and guides natural resource planning.

Keywords: Geomorphometry, Watershed, GIS, Erosion vulnerability assessment, linear parameters, Relief parameters, Areal parameters

Introduction

A watershed represents a distinct topographical region where all surface runoff drains into a specific river or stream channel. As natural geohydrological units, watersheds provide an ideal framework for evaluating natural resource availability and executing developmental initiatives within a catchment area. To analyze watershed areas, researchers utilize geomorphometry — a subfield of geomorphology focused on quantifying the dimensions, shapes, and structural configurations of Earth's terrain. In the present work, spatial parameters such as stream length, watershed area, and watershed perimeter were derived from Survey of India (SOI) topographical sheets (47G/1 and 47G/2) at a 1:50,000 map scale. By utilizing Global Mapper (version 22) GIS software, the linear, relief, and areal characteristics of the Karde watershed were precisely evaluated.

Objectives:

The primary aims of this study are structured as follows:

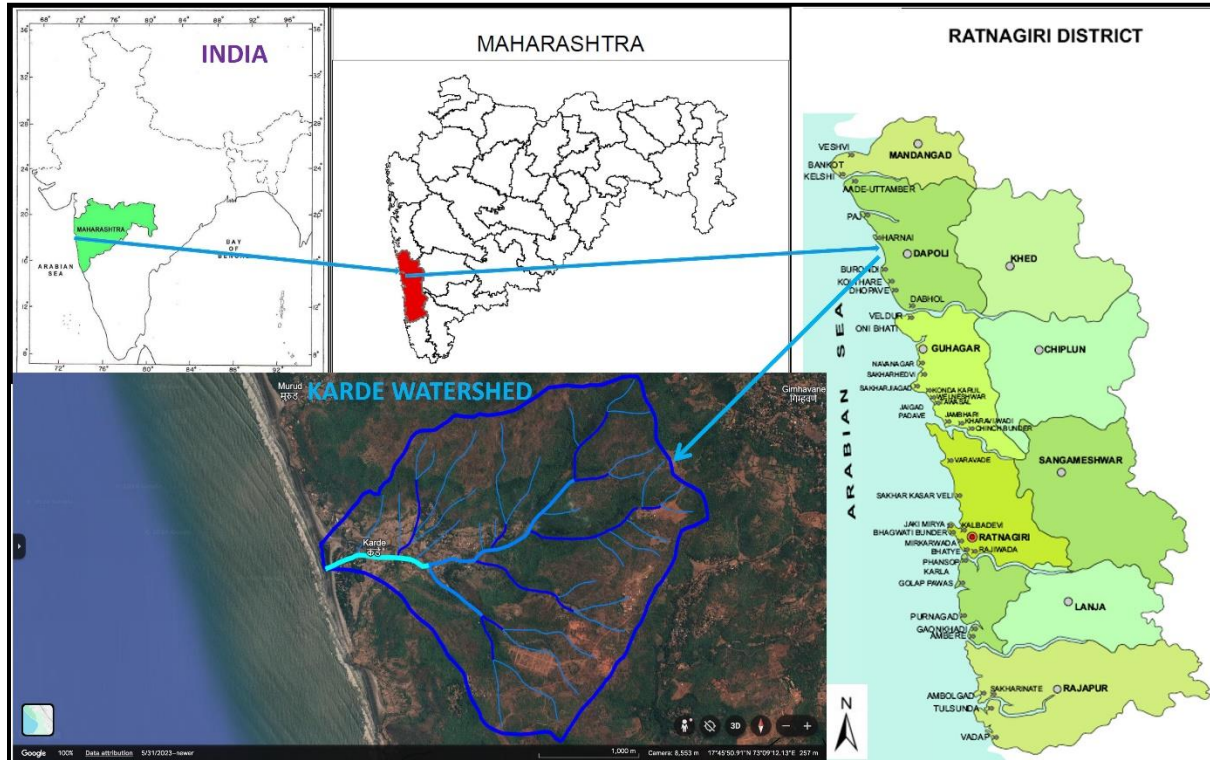
1. To calculate key geomorphometric characteristics of the watershed.
2. To evaluate watershed susceptibility to erosion utilizing morphometric data.

Study Area

The present research work focuses on a 7.684 square kilometres coastal catchment spanning the Karde and Chandranagar villages within the Dapoli Tahsil of Ratnagiri District, Maharashtra (Figure 1). Geographically bounded by latitudes 17°44'07" N to 17°46'02" N and longitudes 73°07'20" E to 73°09'30" E, this watershed lies within the Konkan coastal plains.

The region experiences a tropical hot climate characterized by intense southwest monsoon precipitation, which drives severe landscape erosion. This seasonal monsoon supplies the vast majority of the region's annual rainfall. Wastelands dominate the local topography. The drainage network of the Karde watershed is highly dense, well-defined, and dendritic, comprising 30 first-order, 8 second-order, and 2 third-order streams that feed into a single central fourth-order stream. This fourth-order stream flows westward and debouches into the Arabian Sea, whereas the lower-order tributaries are ephemeral, remaining dry outside the monsoon season.

Figure 1: Location Map of the Study Area



Database and Methodology

(I) Toposheets: The base map has been prepared with the help of SOI (Survey of India) toposheets - 47G/1 and 47G/2 on 1:50000 map scale. The watershed boundaries, stream networks, and watershed length were digitized utilizing Survey of India (SOI) toposheets 47G/1 (B3 Quadrant) and 47G/2 (B1 Quadrant) at a scale of 1:50,000.

(II) Digital Terrain Elevation data: Topographic variations across the study area were extracted using the Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM), which features a 30-metre spatial resolution.

Figure 2: Karde Watershed (SOI Toposheet No. 47G/1 and 47G/2)

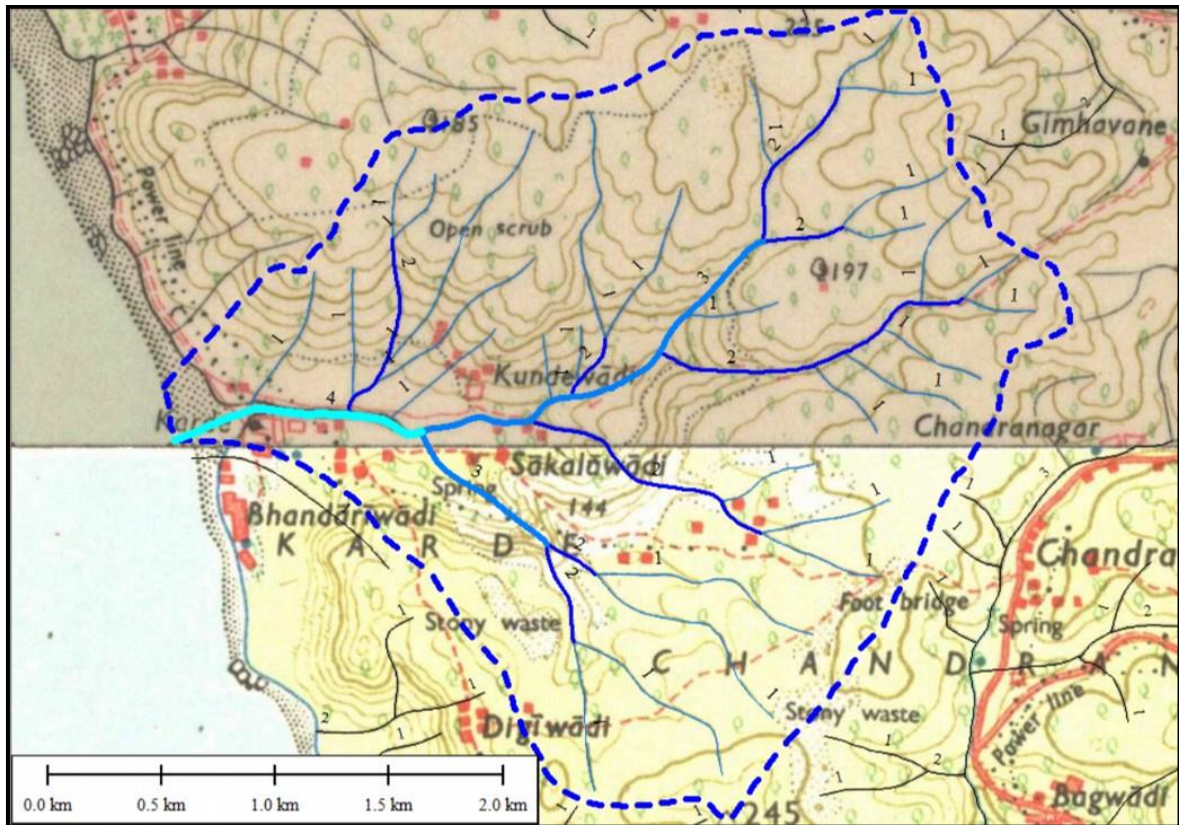
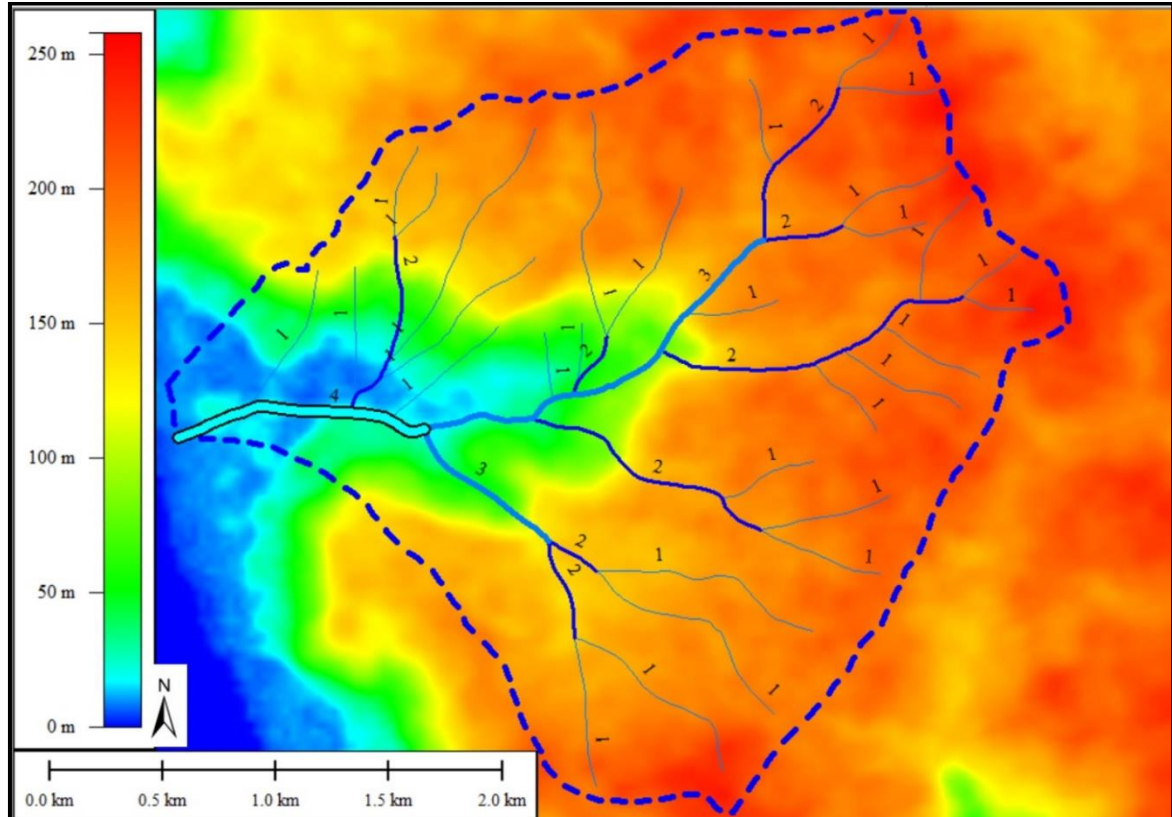


Figure 3: Karde Watershed - Digital Elevation Model (DEM)



Methodology

Survey of India (SOI) toposheets 47G/1 and 47G/2 at a 1:50,000 map scale were georeferenced in Global Mapper software (version 22) to digitize the stream network and delineate the watershed boundary along the contour-defined ridge line. Stream ordering was determined using Strahler's (1964) classification system. Under this hierarchical stream ordering method, initial fingertip tributaries with no branches are classified as first-order streams. The stream order advances only when two channels of equal rank intersect. The confluence of two identical orders increments the downstream channel to the next higher order (e.g., two first-order streams form a second-order stream and two second-order streams form a third-order stream). The quantitative morphometric analysis covers three distinct dimensions:

(I) Linear Metrics: These include stream lengths and bifurcation ratios.

(II) Areal Metrics: These include drainage density, stream frequency, drainage texture, compactness constant, channel maintenance constant, form factor, elongation ratio, and circularity ratio.

(III) Relief Metrics: These include watershed relief and the ruggedness number.

Results and Interpretation

Global Mapper (Version 22), a GIS platform, served as the tool for extracting key morphometric parameters of the watershed, such as its perimeter, area, and stream length. The results are summarized as follows:

1. Watershed Area: $A = 7.684 \text{ km}^2$
2. Watershed Perimeter: $P = 11.502 \text{ km}$
3. Total Stream Length (L) = 26.259 km

The geomorphometric analysis of the Karde watershed involves evaluating and interpreting its linear, relief, and areal characteristics.

(I) Linear Aspects of the Karde Watershed:

(i) Stream Length: Total channel length represents the cumulative distance of all stream segments within a watershed. This value is determined by summing the lengths of every individual channel found inside the watershed boundaries.

Total Stream Length (L) = 26.259 km

(ii) Bifurcation Ratio: As defined by Schumm (1956), the bifurcation ratio (R_b) represents the relationship between the stream count of a specific order (N_u) and that of the subsequent higher order (N_{u+1}) within a watershed. Generally, average bifurcation ratios range from 2 in flat or mildly sloping terrains to between 3 and 5 in highly dissected, mountainous landscapes.

Formula for calculation of Bifurcation ratio (R_b):

$$R_b = N_u / N_{u+1} \dots (\text{Schumm, 1956})$$

where,

N_u = Total number of stream segments of order 'u'

N_{u+1} = Number of segments of the next higher order 'u+1'

Formula for calculation of Mean Bifurcation ratio (R_{bm}):

R_{bm} = Average of bifurcation ratios of all orders ... (Strahler, 1957)

Table 1: Bifurcation Ratio of Karde Watershed

S.No.	Stream Orders	Bifurcation Ratio (R_b)
1	1 st / 2 nd	$R_b = N_1/N_2 = 30/8$ $R_b = 3.75$
2	2 nd / 3 rd	$R_b = N_2/N_3 = 8/2$ $R_b = 4.00$
3	3 rd / 4 th	$R_b = N_3/N_4 = 2/1$ $R_b = 2.00$
4	Mean Bifurcation Ratio (R_{bm})	$R_{bm} = (3.75 + 4.00 + 2.00) / 3 = 9.75 / 3$ $R_{bm} = 3.25$

With a mean bifurcation ratio of 3.25, the Karde watershed features a mature, well-developed, and moderately dissected hilly stream network. Ratios near 3.0 typically signify uniform underlying lithology and soil compositions. Consequently, this region exhibits a highly normal, well-integrated dendritic drainage pattern, suggesting homogeneous rock structures and negligible structural disruptions. However, this high value of bifurcation ratio also correlates with an increased susceptibility to soil erosion.

(II) Areal Aspects of the Karde Watershed:

(i) Drainage Density: Drainage density (D_d) measures how closely a landscape's stream channels are spaced. It is calculated by dividing the cumulative length of all stream segments within a watershed by the watershed's total surface area.

Formula for calculation of Drainage density (D_d):

$$D_d = L / A \dots (\text{Horton, 1932})$$

where,

L = Total stream length of all orders (km)

A = Area of the watershed (km²)

$$D_d = L / A = 26.259 \text{ km} / 7.684 \text{ km}^2 = 3.42 \text{ km/km}^2$$

The Karde watershed exhibits a drainage density of 3.42 km/km², signifying a densely packed network of stream channels. This high value reflects a deeply dissected topography characterized by rapid surface runoff and minimal groundwater absorption. Typically, such a high drainage density develops in areas featuring impermeable geological formations, limited vegetation cover, and rugged, mountainous terrain. This structural layout also generates a fine drainage texture and a highly fragmented landscape. Consequently, the high drainage density elevates both soil erosion risks and flooding susceptibility within the Karde watershed.

(ii) Stream Frequency: Drainage frequency or stream frequency (F_s) measures the count of all streams of all orders per unit area of the watershed.

Formula for calculation of Stream frequency (F_s):

$$F_s = N / A \dots (\text{Horton, 1932})$$

where,

N = total number of streams of all orders

A = Area of the watershed (km²)

$$F_s = N / A = 41 / 7.684 \text{ km}^2 = 5.34 \text{ streams / km}^2$$

The Karde watershed exhibits a stream frequency of 5.34 streams per square kilometre, indicating a dense network of surface channels per unit area. This high drainage density value is responsible for rapidly speeding up surface runoff, which severely drives soil erosion. Consequently, the high value of channel concentration directly amplifies both soil erosion rates and flood susceptibility within the watershed.

(iii) Drainage Texture: Impermeable surfaces exhibit a higher density of drainage lines compared to permeable zones. Drainage texture (D_t) represents the ratio of the total number of stream segments across all orders to the watershed's perimeter. According to Smith's (1950) classification, drainage texture is divided into five distinct groups: very coarse drainage texture (less than 2), coarse drainage texture (2 to 4), moderate drainage texture (4 to 6), fine drainage texture (6 to 8), and very fine drainage texture (exceeding 8).

Formula for calculation of Drainage texture (D_t):

$$D_t = N / P \dots (\text{Horton, 1945})$$

where,

N = total number of streams of all orders

P = watershed perimeter (km)

$$D_t = N / P = 41 / 11.502 \text{ km} = 3.57 \text{ per km}$$

The Karde watershed exhibits a coarse texture, evidenced by a drainage texture of 3.57 per kilometre. This moderately high texture value directly correlates with an increased susceptibility to soil erosion within the watershed.

(iv) Compactness Constant: The compactness constant or coefficient (C_c) of a catchment measures the relationship between the watershed's perimeter and the circumference of a theoretically circular watershed that shares the exact same drainage area. This morphometric index is completely unaffected by the physical size of the watershed, varying instead based on its geometric shape and structural slope.

Formula for calculation of Compactness Constant (C_c):

$$C_c = 0.2821 \times P / A^{0.5} \dots (\text{Horton, 1945})$$

where,

A = area of the watershed (km²) and

P = watershed perimeter (km)

$$C_c = 0.2821 \times P / A^{0.5} = 0.2821 \times 11.502 / 7.684^{0.5} = 3.2447 / 2.7720 = 1.17$$

Because the compactness constant is greater than unity, the Karde watershed is less circular. A compactness constant exceeding 1 signifies that the watershed deviates significantly from a circular shape. Consequently, this elongation extends the time of concentration required to reach peak runoff.

(v) Constant of Channel Maintenance: The constant of channel maintenance (C) quantifies the minimum catchment area needed to develop a unit length of a channel. Calculated as the inverse of drainage density (D_d), this metric directly influences hydrological behaviour. Watersheds characterized by a low constant of channel maintenance often exhibit rapid responses to rainfall, resulting in accelerated peak discharge. Consequently, these watersheds experience rapid storm runoff, heightened flood potential, and severe vulnerability to soil erosion.

Formula for calculation of Constant of Channel Maintenance (C):

$$C = 1 / D_d \dots (\text{Schumm, 1956})$$

where,

D_d = drainage density of the watershed (km/km²)

$$C = 1 / D_d = 1 / 3.42 \text{ km/km}^2 = 0.2926 \text{ km}^2/\text{km}$$

A channel maintenance constant of 0.2926 indicates that every linear kilometre of stream channel requires about 0.2926 square kilometres of contributing watershed area. This specific value characterizes a highly dissected terrain with a dense drainage network. Such landscapes typically feature high erodibility, rapid surface runoff, and minimal groundwater infiltration.

(vi) Length of Overland Flow: Horton (1945) introduced the length of overland flow (L_g), a geomorphometric metric representing the average distance rainwater flows across the land before entering a distinct stream channel. This value is mathematically calculated as roughly half of the inverse of drainage density (D_d).

Formula for calculation of Length of Overland Flow (L_g):

$$L_g = 1 / 2 \times D_d \dots (\text{Horton, 1945})$$

where,

D_d = drainage density of the watershed (km/km²)

$$L_g = 1 / 2 \times D_d = 1 / 2 \times 3.42 = 0.1463 \text{ km}$$

A short overland flow length of 0.1463 km reflects a watershed characterized by steep slopes, high relief, and a dense drainage network. From a geomorphometric standpoint, this indicates that surface runoff travels only a brief distance before discharging into an established stream channel, resulting in a rapid hydrological response. Short and fast-moving surface flows on steep slopes generally generate higher kinetic energy, increasing the vulnerability of the topsoil to sheet and rill erosion.

(vii) Infiltration Number: The infiltration number (I_f), calculated as the product of drainage density (D_d) and stream frequency (F_s), serves as a quantitative geomorphometric metric to evaluate a landscape's permeability. High infiltration numbers signify increased surface runoff and diminished groundwater absorption. Consequently, catchments featuring high infiltration number (I_f) values typically demonstrate lower infiltration capacities and accelerated overland flow.

Formula for calculation of Infiltration Number (I_f):

$$I_f = D_d \times F_s \dots (\text{Faniran, 1968})$$

where,

D_d = drainage density of the watershed (km/km²)

F_s = stream frequency of the watershed (streams/ km²)

$$I_f = D_d \times F_s = 3.42 \times 5.34 = 18.23$$

An infiltration number of 18.23 far exceeds the critical threshold of 10.0, signalling exceptionally poor ground permeability. Because the underlying soil or bedrock prevents rainfall from absorbing effectively, water quickly collects on the surface to establish new drainage channels. This process results in a highly dissected terrain with a dense network of streams. Since subsurface absorption is minimal, nearly all precipitation translates directly into immediate surface runoff. Consequently, the watershed outlet experiences rapid, sharp peak discharges that trigger flash floods. Furthermore, the sheer volume and velocity of this runoff generate immense stream power, severely elevating the risk of soil erosion and land degradation across the catchment area.

(viii) Form Factor: The form factor (F_f) measures watershed shape by calculating the ratio of the watershed area (A) to the square of its maximum length (L_b^2). Form factor values range from near 0 to 1, where lower values signify highly elongated watersheds and values approaching 1 represent nearly circular catchments. Consequently, a higher form factor corresponds to a more circular geometry. Shape characteristics directly influence hydrological responses. Circular watersheds possess high form factor values, meaning runoff from the outer boundaries reaches the main outlet almost simultaneously. This synchronization generates sharp, high-volume peak flows over a compressed timeframe, significantly elevating flash flood risks. Conversely, elongated watersheds feature low form factors, which distribute runoff arrival times to produce flatter, more prolonged peak flows.

Formula for calculation of Form factor (F_f):

$$F_f = A / L_b^2 \dots (\text{Horton, 1932})$$

where,

A = area of the watershed (km²)

L_b^2 = square of the length of the watershed (km²)

$$F_f = A / L_b^2 = 7.684 \text{ km}^2 / (3.78 \text{ km})^2 = 0.54$$

With a form factor of 0.54, the Karde watershed features a moderately elongated, oval shape. This intermediate geometry directly correlates to a moderate level of risk for soil erosion.

(ix) Elongation Ratio: The elongation ratio (R_e) quantifies catchment shape by comparing the diameter of an equivalent-area circle to the maximum watershed length. This metric categorizes drainage basins into distinct geometric profiles: circular (0.9–1.0), oval (0.8–0.9), moderately elongated (0.7–0.8), elongated (0.5–0.7), and highly elongated (< 0.5). Structurally, ratios approaching 1.0 signify flat terrains with minimal relief. Conversely, values between 0.6 and 0.8 typically indicate mountainous topography and steep gradients. Hydrographically, circular watersheds facilitate faster and more efficient runoff discharge compared to stretched or elongated configurations.

Formula for calculation of Elongation ratio (R_e):

$$R_e = D_c / L_b \dots (\text{Schumm, 1956})$$

$$R_e = 1.1287 \times A^{0.5} / L_b$$

where,

D_c = Diameter of the circle with the same area as that of the watershed (km)

A = Area of the watershed (km²)

L_b = Length of the watershed (km)

$$R_e = 1.1287 \times A^{0.5} / L_b = 1.1287 \times 7.684^{0.5} / 3.78 = 0.83$$

The Karde watershed features moderately high relief and a less elongated shape, as indicated by its 0.83 elongation ratio.

(x) Circularity Ratio: The watershed circularity ratio (R_c) is a dimensionless metric representing the ratio of a watershed's area to the area of a circle with the same perimeter. High circularity ratio (R_c) values point to a highly circular watershed, which generally reflects a mature or old geomorphic stage of landscape evolution. These variations stem from the unique structural conditions, slopes, and relief features of the specific watershed. While a perfectly round watershed carries a circularity ratio of one, comparing two watersheds of equal size reveals that the one with the lower ratio will generate greater runoff. Consequently, a lower circularity ratio signifies a higher susceptibility to soil erosion.

Formula for calculation of Circulatory ratio (R_c):

$$R_c = 4 * \pi * A / P^2 \dots (Miller, 1953)$$

where,

$$\pi = \pi \text{ value i.e., } 22 / 7 = 3.14$$

A = area of the watershed (km^2)

P^2 = square of the perimeter of the watershed (km)

$$R_c = (4 \times \pi \times A) / P^2 = (4 \times 3.14 \times 7.684) / 11.502^2 = 96.511 / 132.296 = 0.73$$

A circularity ratio of 0.73 reflects a moderately less-elongated watershed that approaches a circular geometry. Since this value exceeds 0.50, it signifies a high degree of circularity alongside uniform geological structures. Geomorphologically, this configuration points to a mature or late-maturity landscape with moderate relief, which generally elevates the risk of synchronized peak flood discharges.

(III) Relief Aspects of the Karde Watershed:

(i) Ruggedness Number: The ruggedness number (R_n) is a terrain metric calculated by multiplying drainage density (D_d) by total watershed relief (H). By integrating slope gradient and length, it effectively quantifies landscape roughness. Consequently, peak values occur where steep slopes coincide with high drainage density values. Extremely high values of the ruggedness number are obtained when both variables are high, that is when slopes are not only steep but long as well. Watersheds exhibiting high ruggedness numbers generally feature complex structural geology and face a higher risk of accelerated soil erosion.

Formula for calculation of Ruggedness Number:

$$R_n = D_d \times H \dots (Patton and Baker, 1976)$$

where,

D_d = Drainage Density (km/km^2)

H = Total Watershed Relief = Highest elevation – Lowest elevation (km)

$$D_d = L / A = 26.259 \text{ km} / 7.684 \text{ km}^2 = 3.42 \text{ km}/\text{km}^2$$

$$H = \text{Highest elevation} - \text{Lowest elevation} = 257 - 7 = 250 \text{ m} = 0.25 \text{ km}$$

$$R_n = 3.42 \text{ km}/\text{km}^2 \times 0.25 \text{ km} = 0.85$$

With a moderately high ruggedness number of 0.85, the Karde watershed features a highly uneven topography. This specific terrain structure indicates that the watershed is highly susceptible to soil erosion.

Table 2: Linear, Areal and Relief Aspects of the Karde Watershed

S.No.	Aspect	Value
1	Mean Bifurcation Ratio	3.25
2	Drainage Density	3.42 km / sq.km
3	Stream Frequency	5.34 streams / sq.km
4	Drainage Texture	3.57 per km
5	Compactness Constant	1.17
6	Constant of Channel Maintenance	0.29 km^2/km
7	Length of Overland Flow	0.15 km
8	Infiltration Number	18.23
9	Form Factor	0.54
10	Elongation Ratio	0.83
11	Circularity Ratio	0.73
12	Ruggedness Number	0.85

Conclusion

An assessment of the Karde watershed's geomorphometric characteristics reveals a landscape dominated by lower-order channels, where shape-related variables dictate the concentration time for runoff flowing toward the Arabian Sea. Functioning as a fourth-order watershed with a moderately dense, dendritic configuration, the system possesses a mature network that promotes rapid surface drainage. Because the 41 streams are seasonal and the watershed contains vast tracts of degraded wasteland, this elevated drainage intensity aggravates land degradation. Consequently, the region serves as a major origin point for sediment yields, especially throughout the southwest monsoon period.

Specific quantitative indicators further define the watershed's hydrological behaviour:

1. **Mean Bifurcation Ratio (3.25)** confirms an advanced fluvial network spread across a hilly, moderately dissected topography.

2. **Drainage Density (3.42 km/km²)** demonstrates an extensive channel concentration that triggers highly effective surface drainage.
3. **Stream Frequency (5.34 streams/km²)** points to rapid runoff generation and intensified topsoil stripping.
4. **Channel Maintenance Constant (0.2926)** highlights distinct watershed attributes, including dense drainage, low ground permeability, limited plant cover, and high soil erodibility.
5. **Overland Flow Length (0.146)** reflects a geologically mature or rugged terrain defined by steep gradients, rapid water accumulation, and acute susceptibility to erosion.
6. **Infiltration Number (18.23)** proves that the watershed suffers from minimal water absorption capacity, causing extreme rates of overland flow and soil detachment.

To mitigate soil erosion within the Karde watershed, urgent intervention is required in its upper zones through the deployment of check dams, contour bunding, and vegetative barriers. This study highlights the high efficiency of geomorphometric analysis driven by GIS techniques, ASTER GDEM data, and SOI topographical maps in the erosion vulnerability assessment of the Karde watershed. The evaluation of geomorphometric parameters of the Karde watershed clearly indicate that the watershed faces greater risks of flooding and soil degradation.

Acknowledgement

The authors express their sincere gratitude to **Dr. Ashok B. Divekar** and **Dr. Mithilesh N. Chavan**, Department of Geography, for their valuable guidance, intellectual support, and encouragement throughout this study.

Financial Support and Sponsorship

Nil.

Conflict of Interests

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

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