International Journal of Research Studies on Environment, Earth, and Allied Sciences (IJRSEAS)
| *Volume-3 Issue-2* | *April-2026* | *ISSN: 3066-0637* | *Website:* https://eesrd.us

Manuscript ID:
IJRSEAS-2026-030238

OPEN ACCESS

Quick Response Code:

Website: https://eesrd.us

DOI: 10.5281/zenodo.21544610

DOI Link:
https://doi.org/10.5281/zenodo.21544610

Volume: 3

Issue: 2

Pp. 225-231

Month: April

Year: 2026

E-ISSN: 3066-0637

Submitted: 14 Mar. 2026

Revised: 25 Mar. 2026

Accepted: 15 Apr. 2026

Published: 30 Apr. 2026

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How to cite this article:
Divekar, A. B. & Chavan, M. N. (2026). GIS-Based Geomorphometric Analysis of Kudje Micro-Watershed of Khadakwasla Dam Catchment Area, Pune District, Maharashtra. International Journal of Research Studies on Environment, Earth, and Allied Sciences, 3(2), 225–231. https://doi.org/10.5281/zenodo.21544610

GIS-Based Geomorphometric Analysis of Kudje Micro-Watershed of Khadakwasla Dam Catchment Area, Pune District, Maharashtra

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Abstract

Geomorphometry is a branch of Geomorphology which involves the measurements and mathematical analysis of the configuration of the Earth's surface, and dimensions of its landforms. A micro-watershed is the smallest hydrological unit in the hierarchical system of watersheds. Computations of the quantitative parameters required for geomorphometric analysis of a watershed using manual methods such as watershed area measurement using planimeter or dot grid method or graphical method and measurement of watershed perimeter and stream length using curvimeter or rotameter are considerably tedious and erroneous to a certain extent. Hence, the stream length, watershed area, watershed perimeter etc. have been accurately determined from SOI (Survey of India) toposheet number 47F/11/NE on 1:25000 map scale, using GIS (Geographical Information System) software - Global Mapper version 22. The study area is a small micro-watershed of the Khadakwasla dam catchment area. It is located near Kudje village in the Haveli Tahsil of Pune District in Maharashtra. The Kudje micro-watershed is a 4th order watershed draining directly into the Khadakwasla lake. Geomorphometric analysis of a watershed consists of calculation of linear, relief and areal parameters of the watershed. The important attributes of the watershed are mean bifurcation ratio (3.88), drainage density (5.68 km/sq.km), form factor (0.36), elongation ratio (0.67), ruggedness number (1.54) etc., which all together revealed the mountainous relief, steep slope, rugged and dissected topography, complex structure and shape of Kudje watershed. High drainage density indicated weak or impermeable subsurface materials and sparse vegetation. Geomorphometric analysis is a significant tool for assessment of erosion in micro-watersheds, which can help in decision making process for natural resources management.

Keywords: *GIS, Geomorphometric analysis, Micro-watershed, SOI toposheet, Drainage density*

Introduction

A watershed is defined as a natural topographical and hydrological unit that covers a specific area of land surface from which the surface runoff flows to a defined drain or stream or river channel. A watershed serves as an ideal unit for consideration of surface processes determining the formation of landscapes. Watersheds are natural geohydrological units that are highly efficient and most appropriate for the systematic assessment of available natural resources and subsequent planning and implementation of various development programmes in the catchment areas. A watershed is a geomorphic unit that consists of channel network which is demarcated by a drainage divide or a ridge line. A micro-watershed is the smallest hydrological entity in the hierarchical system of watersheds. Micro-watersheds are mostly pertaining to small local tributaries of a river. The area covered by a micro-watershed can range from 1 sq. km to 10 sq. km. Geomorphometry is a branch of Geomorphology which involves the measurements and mathematical analysis of the configuration of the Earth's surface, and shape and dimensions of its landforms. The computations of the quantitative parameters required for morphometric analysis of a watershed using manual methods such as watershed area measurement using planimeter or dot grid method or graphical method and measurement of watershed perimeter and stream length using curvimeter or rotameter are considerably tedious and erroneous to a certain extent. Hence, the stream length, watershed area, watershed perimeter etc. have been accurately determined from SOI (Survey of India) topographical map number 47F/11/NE on 1:25,000 map scale, using GIS (Geographical Information System) software Global Mapper version 22. Watershed attributes are accurately determined by using GIS tools.

Objectives:

Specific objectives of the present research work are:

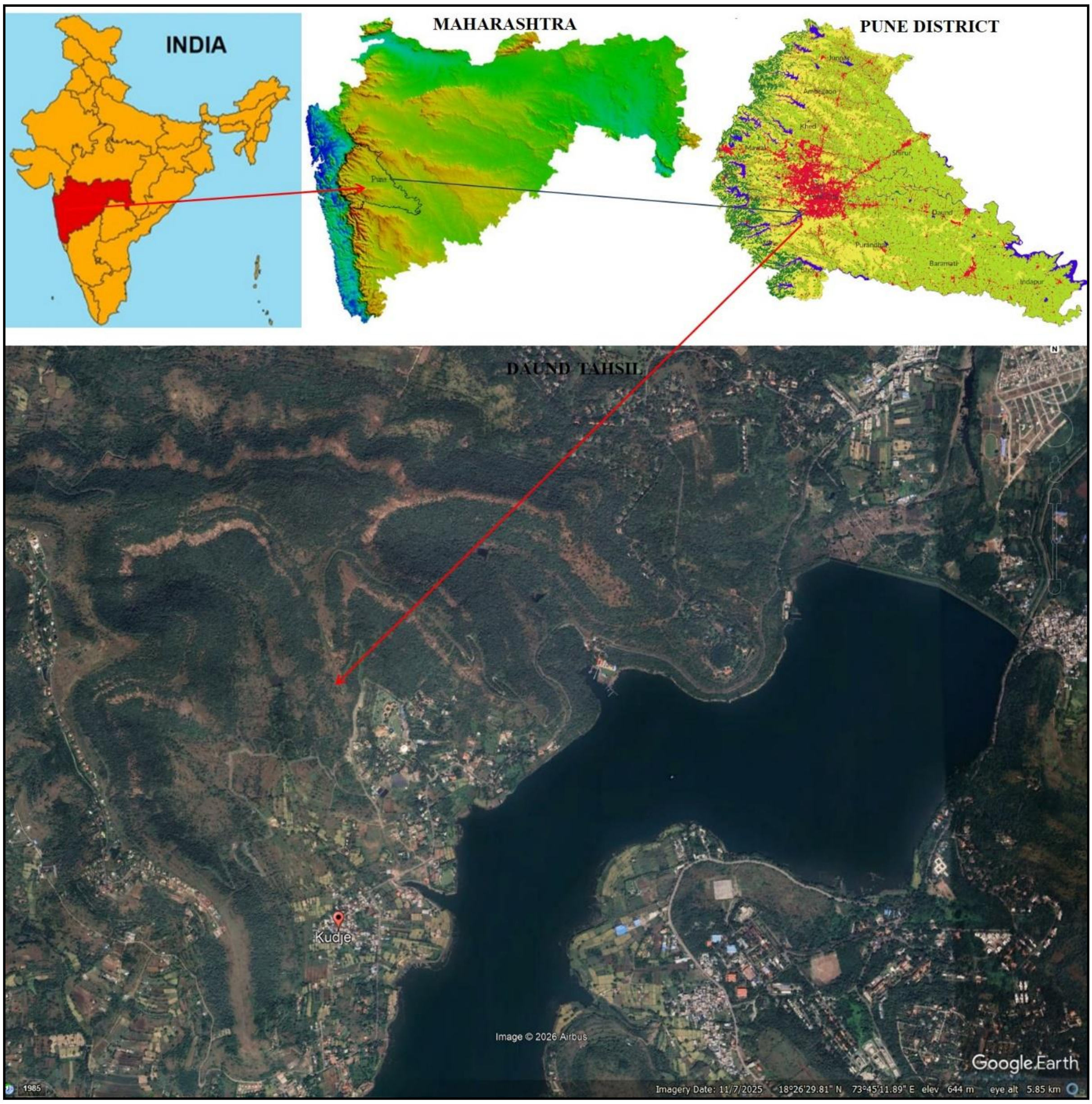
1. To quantify the geomorphometric characteristics of the micro-watershed.

2. To infer the erosion vulnerability of the micro-watershed based on geomorphometric parameters.

Study Area

The study area is a small micro-watershed of the Khadakwasla dam catchment area, covering a total geographical area of 3.12 sq. km. It is located near Kudje village in the Haveli Tahsil of Pune district in Maharashtra. The study area has a typical tropical hot climate. The study area receives most of the rainfall in the southwest monsoon season. Most of the part of the study area is covered by wastelands. The Kudje micro-watershed extends from 18°25'24" N to 18°26'40" N latitudes and 73°43'20" E to 73°44'36" E longitudes. The Kudje micro-watershed is a 4^{th} order watershed draining directly into the Khadakwasla lake. The drainage network of the Kudje watershed is dense and well-developed. The drainage pattern is of dendritic type. The Kudje watershed has 43 first order streams, 7 second order streams, 2 third order streams linked to a fourth order stream. The 1^{st}, 2^{nd}, 3^{rd} and 4^{th} order streams are mostly seasonal in nature and remain dry in non-rainy seasons.

Figure 1: Location Map of the Study Area



Database and Methodology

1. **Toposheets** SOI (Survey of India) toposheet number 47F/11/NE on 1:25000 map scale has been used as a base map for digitization of stream network and watershed boundary.
2. **Digital Elevation data:** The elevation data of the micro-watershed has been acquired from ASTER GDEM (Advanced Space borne Thermal Emission and Reflection Radiometer – Global Digital Elevation Model) with a spatial resolution of 30 meters.

Figure 2: Kudje Micro-watershed (SOI Toposheet No. 47F/11/NE)

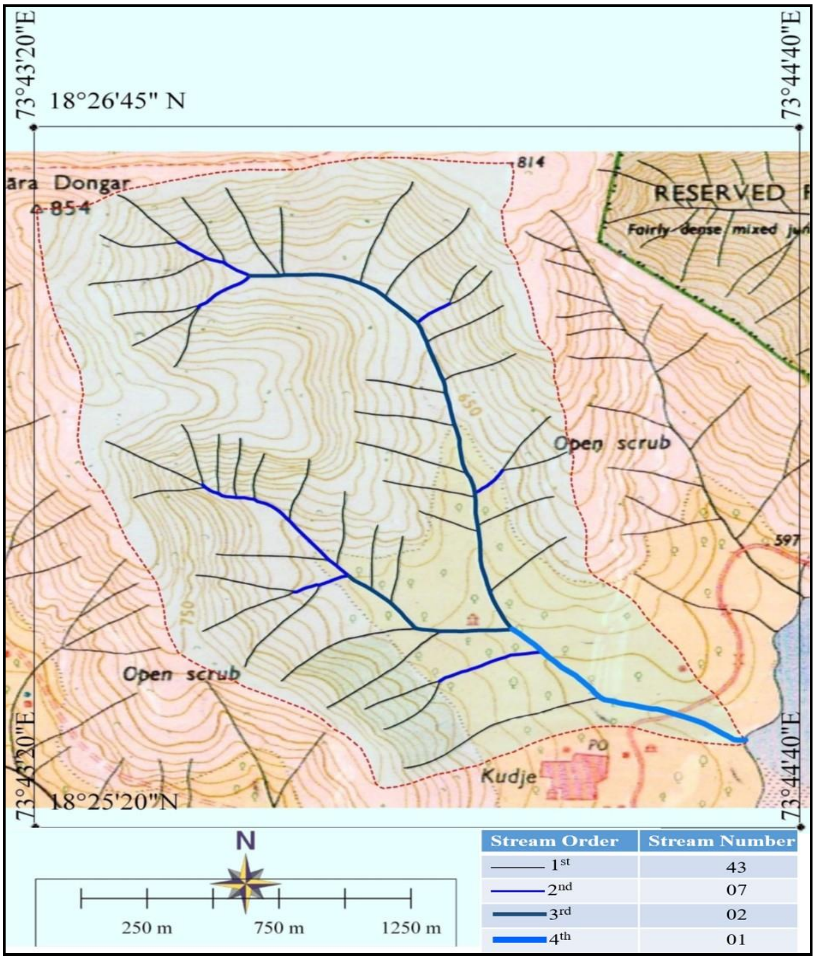
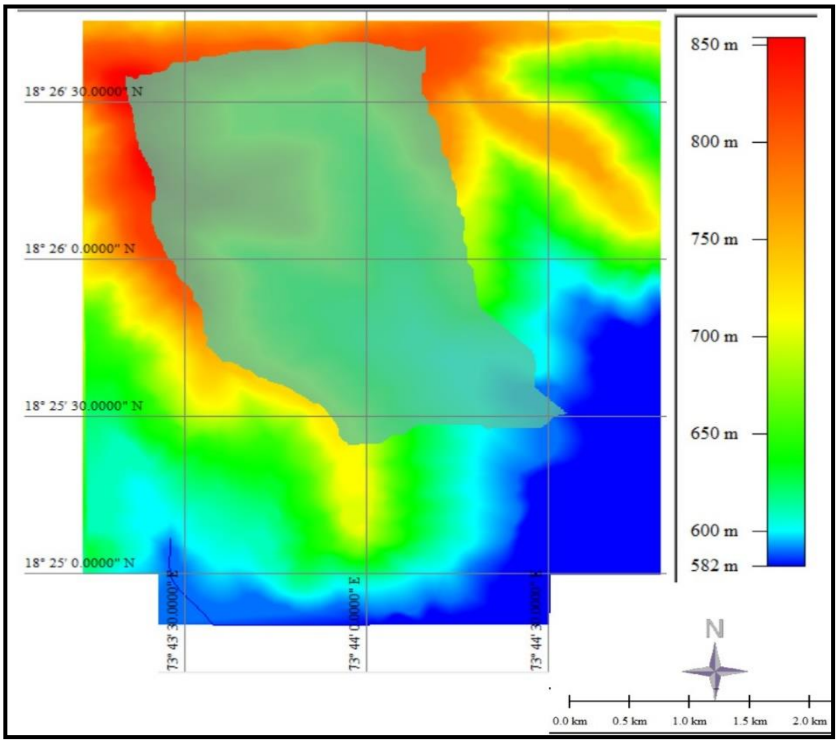


Figure 3: Kudje Micro-watershed Digital Elevation Model (DEM)



Methodology:

SOI Toposheet number 47F/11/NE on 1:25000 map scale is georeferenced and projected into a standard coordinate system - WGS 1984 datum and UTM Zone 43N. The watershed boundary is delineated based on contour patterns, and the stream network is digitized from the toposheet. Streams are ordered following the Strahler (1964) method, where unbranched streams are first-order, and two first-order streams join to form a second-order stream. The methodology of the present study involves the analysis of linear, relief and areal parameters of the micro-watershed.

1. **Linear Aspects:** Stream length and Bifurcation ratio.
2. **Areal Aspects:** Drainage density, Stream frequency, Drainage texture, Compactness Constant, Watershed shape indices (form factor and elongation ratio).
3. **Relief Aspects:** Watershed relief and Ruggedness number.

Results and Interpretation:

The stream length, watershed area, watershed perimeter etc. are computed using GIS (Geographic Information System) software - Global Mapper version 22. The use of GIS makes this task relatively easy and accurate as well. The results are summarized as follows:

1. Total Stream Length (L) = 17.62 km
2. Watershed Area: A = 3.1 km^2
3. Watershed Perimeter: P = 7.6 km

The geomorphometric analysis of Kudje micro-watershed involves the calculation and interpretation of linear, relief and areal parameters of the micro-watershed.

(I) Linear Aspects of Watershed:

Stream Length: Stream Length (L) is the total length (in kilometers) of all the rivers or stream segments in a given watershed. The total stream length (L) is computed by summing the length of all stream segments within the contributing drainage area.

Total Stream Length (L) = 17.62 km

Bifurcation Ratio: Bifurcation ratio is defined as the ratio of number of streams of a given order (N_u) to number of streams of next higher order (N_{u+1}), (*Schumm*, 1956). It is related to the branching pattern of a drainage network. The value of mean bifurcation ratio varies from about 2 for flat basins and 3 to 5 for mountainous, hilly and dissected basins.

Formula for computation of Bifurcation ratio (R_b):

$\mathbf{R_b = N_u / N_{u+1}}$ …(*Schumm*, 1956)

Where,

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

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

Table 1: Bifurcation Ratio of Kudje Micro-watershed

S.No.	Stream Orders	Bifurcation Ratio (R_b)
1	1st / 2nd	$R_b = N_1/N_2 = 43/7$ $R_b = 6.14$
2	2nd / 3rd	$R_b = N_2/N_3 = 7/2$ $R_b = 3.50$
3	3rd / 4th	$R_b = N_3/N_4 = 2/1$ $R_b = 2.00$
4	**Mean Bifurcation Ratio (R_{bm})**	$R_{bm} = (6.14+3.50+2.00) / 3 = 11.64 / 3$ $R_{bm} = 3.88$

The value of mean bifurcation ratio is 3.88 which indicates that Kudje micro-watershed is mountainous, hilly and dissected. As the bifurcation ratio is higher, the erosion vulnerability is also higher for Kudje micro-watershed.

(II) Areal Aspects of Watershed:

Drainage Density: Horton introduced drainage density (D_d) as an expression to indicate the closeness of spacing of channels. Drainage density is defined as the total length of streams of all orders per unit watershed area.

Formula for computation of Drainage density (D_d):

$D_d = L / A$ … Horton (1932)

where,

L = Total stream length of all orders

A = Area of the watershed (km^2)

$Dd = L / A = 17.62 \text{ km} / 3.1 \text{ km}^2 = 5.68 \text{ km/km}^2$

The value of drainage density for Kudje micro-watershed is 5.68 km/sq.km which indicates that the stream channels are closely spaced.. High drainage density is favoured in regions of impermeable subsurface materials, sparse vegetation and mountainous relief (Nag, 1998). High drainage density leads to fine drainage texture and highly dissected landscape. As the drainage density is higher, the soil erosion and flood vulnerability is also higher for Kudje micro-watershed.

Stream Frequency: Horton (1932) introduced stream frequency (F_s) or drainage frequency which is the total number of stream segments of all orders per unit area.

Formula for computation of Drainage/ Stream frequency (F_s):

$F_s = N / A$ … Horton (1932)

where,

N = total number of streams of all orders

A = Area of the watershed (km^2)

$F_s = N / A = 53 / 3.1\ km^2 = 17.1$ streams / km^2

The value of stream frequency is 17.1 streams per km^2 which indicates that the number of stream channels is higher per unit area. A high value of drainage frequency produces more surface runoff and leads to increased soil loss in comparison to others. As the drainage frequency is higher, the soil erosion and flood vulnerability is also higher for Kudje micro-watershed.

Drainage Texture: Horton recognized infiltration capacity as the single important factor which influences drainage. Drainage lines are numerous over impermeable areas than permeable areas. Drainage texture is the total number of stream segments of all orders per perimeter of that area (Horton, 1945). Smith, (1950) has classified drainage texture into five different textures i.e., very coarse (<2), coarse (2 to 4), moderate (4 to 6), fine (6 to 8) and very fine (>8).

Formula for computation of Drainage texture (T):

$T = N / P$ … Horton (1945)

where,

N = total no. of streams of all orders

P = watershed perimeter (km)

$T = N / P = 53 / 7.6\ km = 6.97$

The value of drainage texture is 6.97 which indicates mostly impermeable and fine textured watershed area. As the drainage texture is higher, the soil erosion vulnerability for watershed is also higher for Kudje micro-watershed.

Compactness Constant: According to Gravelius (1914), compactness coefficient of a watershed is the ratio of perimeter of watershed to circumference of circular area, which equals the area of the watershed. The compactness constant is independent of size of watershed and dependent only on the slope.

Formula for computation of Compactness Constant (Cc):

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

where,

A = area of the drainage basin and

P = watershed perimeter (km)

$C_c = 0.2821 \times P / A^{0.5} = 0.2821 * 7.6 / 3.1^{0.5} = 2.14396 / 1.76068 = 1.22$

As the compactness constant is more than 1, it indicates more deviation from the circular nature of the watershed. It will have a long time of concentration before peak flow occurs in the micro-watershed.

Form Factor: According to Horton (1932), form factor (R_f) is defined, as the ratio of basin area (A) to square of the watershed or basin length (L_b^2). The values near to 0 indicate highly elongated shape and those near to 1 indicate perfectly circular shape of the drainage basin. Smaller the value of form factor, more elongated will be the watershed. The elongated watershed with low value of form factor indicates that the watershed will have a flatter peak flow for longer duration. The watersheds with high form factors have high peak flows of shorter duration. The shape indices have an inverse relationship with soil erosion.

Formula for computation of Form factor (F_f):

$F_f = A / L_b^2$ … Horton (1932)

where,

A = area of the watershed (km^2)

L_b^2 = square of the length of the drainage basin / watershed (km^2)

$F_f = A / L_b^2 = 3.1\ km^2 / (2.95\ km)^2 = 0.36$

The value of form factor for the Kudje micro-watershed is 0.36. As the form factor is lower, the soil erosion vulnerability is higher for Kudje micro-watershed.

Elongation Ratio: According to Schumm (1965), elongation ratio is defined as the ratio of diameter of a circle of the same area as the basin to the maximum basin length. Strahler states that this ratio runs between 0.6 and 1.0 over a wide variety of climatic and geologic types. The varying shapes of watershed can be classified with the help of the index of elongation ratio, i.e. circular (0.9-1.0), oval (0.8-0.9), less elongated (0.7-0.8), elongated (0.5-0.7), and more elongated (< 0.5). Values close to 1.0 are typical of regions of very low relief, whereas values in the range 0.6 to 0.8 are usually associated with high relief and steep ground slope. A circular basin is more efficient in the discharge of run-off than an elongated basin.

Formula for computation of Elongation ratio (R_e):

$Re = \left[(2 \times A) / \pi \right] / L_b$ … (Schumm, 1956)

where,

A = Area of the watershed (km^2)

$\pi = \pi$ value i.e., 3.14

L_b = Length of the watershed (km)

$R_e = [(2 \times A) / \pi] / L_b = [(2 \times 3.1) / 3.14] / 2.95 = 1.975 / 2.95 = 0.67$
The value of elongation ratio is 0.67 which indicates that the watershed is elongated in shape and is associated with high relief and steep ground slope.

(III) Relief Aspects of Watershed:
Ruggedness Number: Ruggedness number is a value for the measurement of ruggedness of the terrain. Strahler's (1968) ruggedness number is the product of the watershed / basin relief (H) and the drainage density (D_d) and it combines slope steepness with its length. Extremely high values of the ruggedness number occur when both variables are large, that is when slopes are not only steep but long as well. The high ruggedness value of watershed implies that area is more prone to soil erosion and have intrinsic structural complexity in association with relief and drainage density.
Formula for computation of Ruggedness Number:
$R_n = D_d \times H$ … Patton & Baker (1976)
where,
D_d = Drainage Density (km/km^2)
H = Total Drainage Basin Relief = Highest elevation – Lowest elevation (km)
$D_d = L / A = 17.62$ km / 3.1 km^2 = 5.68 km/km^2
H = Highest elevation – Lowest elevation = 814 – 582 = 232 m = 0.232 km
$R_n = 6.2$ km/km^2 x 0.232 km = 1.44
The value of ruggedness number for the micro-watershed is 1.44 which is high and implies that the micro-watershed area is highly prone to soil erosion.

Table 2: Linear, Areal and Relief Aspects of Kudje Micro-watershed

S.No.	Aspect	Value
1	Mean Bifurcation Ratio	6.14
2	Drainage Density	5.68 km/sq.km
3	Stream Frequency	17.1 streams / sq.km
4	Drainage Texture	6.97
5	Compactness Constant	1.22
6	Form Factor	0.36
7	Elongation Ratio	0.67
8	Ruggedness Number	1.44

Conclusion
The geomorphometric analysis of Kudje micro-watershed suggests that lower order streams dominate the catchment area, and the shape parameters influence the time of concentration for runoff to reach the Khadakwasla lake. As a 4th order drainage system with a dense and dendritic pattern, the micro-watershed exhibits a well-developed network that facilitates efficient surface runoff into the Khadakwasla dam. The analysis inferred that the high stream density coupled with the seasonal nature of the 53 identified streams and the presence of extensive wastelands renders the micro-watershed susceptible to soil erosion, making it a critical source of sediment for the Khadakwasla reservoir, particularly during the southwest monsoon. To minimize soil loss and ensure the sustainability of the Khadakwasla reservoir, immediate soil and water conservation measures, such as check dams, vegetative barriers, and contour bunding, should be implemented, particularly in the upper reaches of the micro-watershed. These findings provide a critical baseline for local authorities to implement targeted soil conservation and water management strategies to protect the Khadakwasla catchment. This study demonstrates that geomorphometric analysis using ASTER GDEM and GIS is an effective tool for identifying areas in the Kudje micro-watershed that are most vulnerable to soil erosion and flooding.

Acknowledgment
The authors express their sincere gratitude to the Survey of India for providing the topographical maps used in the present study. The authors are also thankful to the developers of Global Mapper and ASTER GDEM data providers for making spatial analysis and geomorphometric computations possible.
The authors extend heartfelt thanks to the Department of Geography of their respective institutions for providing academic support, guidance, and necessary facilities during the course of this research work. Special appreciation is conveyed to colleagues, researchers, and well-wishers who directly or indirectly contributed valuable suggestions and encouragement throughout the 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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