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Geomorphometric Analysis of a Milli-Watershed Using GIS: A Case of Agalambe Watershed in Khadakwasla Dam Catchment Area, Pune District, Maharashtra

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Abstract

Geomorphometry, a specialized field within Geomorphology, focuses on the quantitative measurements and mathematical evaluation of Earth's surface features and landform dimensions. In hierarchical hydrological classifications, a milli-watershed (area of 10 to 100 square kilometres) represents the second smallest unit and a micro-watershed is the smallest unit (area of 1 to 10 square kilometres). Traditional, manual techniques for extracting quantitative watershed parameters such as utilizing planimeters, dot grids, or graphical approaches for area estimation, and rotameters or curvimeters for measuring perimeters and stream lengths are notoriously labour-intensive and prone to human error. To overcome these limitations in this work, stream lengths, catchment area, and perimeter were precisely extracted from the Survey of India (SOI) toposheet number 47F/11/NE (1:25,000 map scale) using Global Mapper (version 22) GIS software. The investigation focuses on a milli-watershed situated within the Khadakwasla dam catchment, specifically located at Agalambe village within the Haveli Tahsil of Pune District, Maharashtra. The Agalambe watershed operates as a fifth-order drainage system that flows directly into Khadakwasla Lake. A comprehensive geomorphometric assessment of this milli-watershed was conducted by calculating its linear, relief, and areal characteristics. The key quantitative indices calculated for the Agalambe watershed include a mean bifurcation ratio of 4.01, a drainage density of 5.64 kilometre per square kilometre, a stream frequency of 15.75 streams per square kilometre, and a drainage texture of 13.02 streams per kilometre. Additionally, the infiltration number was determined to be 88.75, alongside a form factor of 0.32, an elongation ratio of 0.64, and a ruggedness number of 3.18. Collectively, these values of morphometric variables indicate a highly dissected and rugged topography characterized by mountainous relief, steep slopes, and a complex structural configuration. Furthermore, the high value of drainage density implies the presence of impermeable or weak subsurface geological strata coupled with sparse vegetative cover. Ultimately, geomorphometric analysis serves as a vital diagnostic tool for evaluating watershed erosion, providing critical data and offering valuable insights to guide decision-making in sustainable natural resource management.

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

Introduction

A watershed represents a distinct topographical and hydrological landscape unit, encompassing a specific land area where all surface runoff drains into a common stream, river, or water channel. Because it governs the surface processes that shape the terrain, a watershed provides an ideal framework for studying landscape development. These natural geohydrological units provide a highly efficient, systematic foundation for assessing local natural resources as well as designing and executing targeted environmental development initiatives within a catchment area. From a geomorphological perspective, a watershed is a distinct geomorphic entity containing a network of channels bounded by a ridge line or a natural drainage divide. Within the hierarchical classification of drainage basins, the micro-watershed represents the smallest distinct hydrological unit and the milli-watershed is the second smallest hydrological unit. Both micro- and milli-watersheds generally correspond to the catchments of small, local river tributaries. In terms of scale, a micro-watershed spans between 1 and 10 square kilometres area, while a milli-watershed encompasses an area ranging from 10 to 100 square kilometres.

Geomorphometry, a specialized branch of geomorphology, focuses on the precise measurement and mathematical evaluation of the Earth's surface variations, alongside the geometric dimensions of its landforms. To evaluate these landforms, researchers utilize geomorphometry dedicated to the quantitative measurement and mathematical analysis of Earth's surface configurations.

Traditionally, calculating the quantitative parameters needed for morphometric analysis relied on manual techniques such as tracking watershed boundaries with a planimeter, using dot grids, or utilizing curvimeters and rotameters to trace stream lengths and perimeters. However, these manual approaches are notoriously labour-intensive and prone to human error. To ensure precision, modern spatial assessments leverage Geographical Information System (GIS) tools to extract watershed attributes. To achieve maximum accuracy, modern geographic information system (GIS) software, specifically Global Mapper version 22, was utilized to extract critical watershed attributes such as stream length, total watershed area, and perimeter. These measurements were derived digitally from the Survey of India (SOI) topographical map sheet number 47F/11/NE at a larger map scale of 1:25,000.

Objectives:

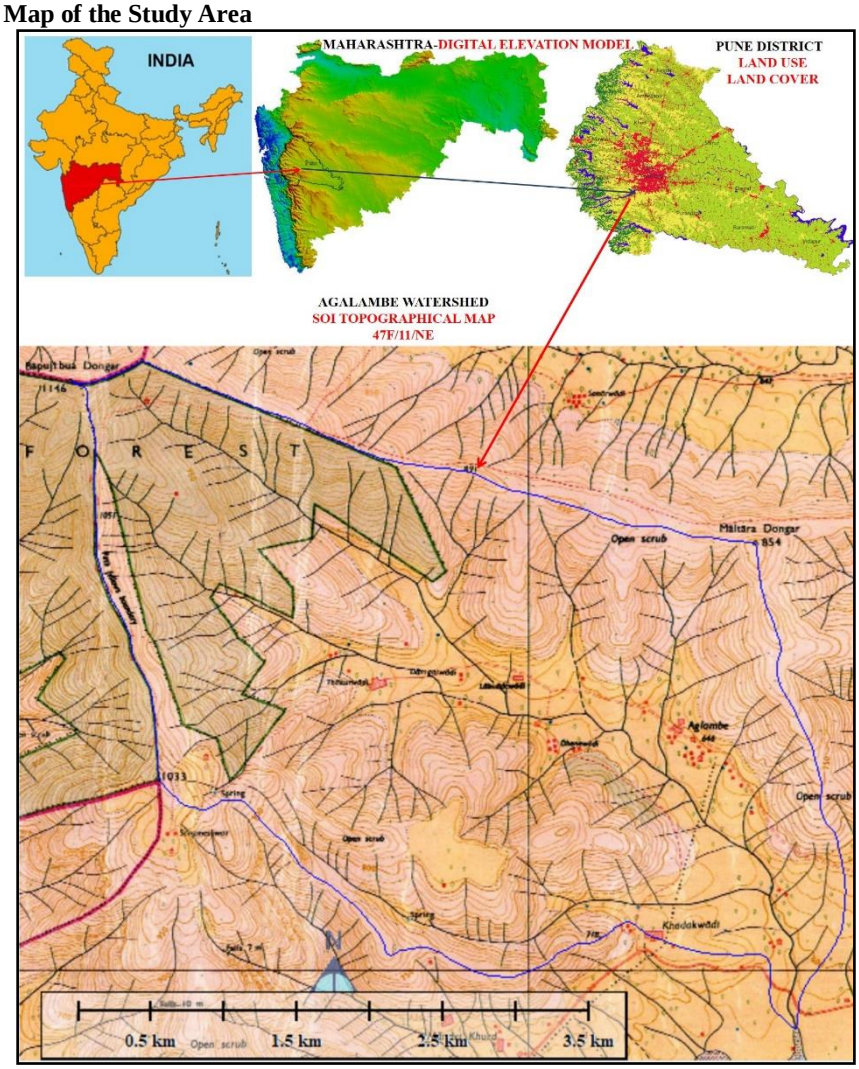
Specific objectives of the present research work are:

1. To measure and analyze the geomorphometric attributes of the selected milli-watershed.
2. To assess the susceptibility to erosion within the milli-watershed using geomorphometric variables.

Study Area

The present research focuses on a small milli-watershed situated within the Khadakwasla dam catchment area at Agalambe village (Haveli Tahsil, Pune district, Maharashtra). The Agalambe watershed covers a total geographical area of 13.59 square kilometres. Geographically, the milli-watershed is bounded by latitudes 18°24'47.5" N to 18°27'16" N and longitudes 73°40'48" E to 73°43'40" E. Characterized by a typical hot tropical climate, the study area experiences the bulk of its precipitation during the southwest monsoon, leaving a majority of the terrain classified as wasteland. Hydrologically, the Agalambe watershed features a dense, well-developed dendritic drainage pattern. The Agalambe watershed is a 5th order watershed, comprising 177 first-order, 26 second-order, 8 third-order, and 2 fourth-order streams feeding into a single fifth-order mainstream which is draining directly into the Khadakwasla lake. While the primary fifth-order channel functions continuously, the lower-order streams (first through fourth) are seasonal and dry up outside the monsoon period.

Figure 1: Location Map of the Study Area



Database and Methodology

1. Toposheets: The stream network and watershed boundaries were digitized using the Survey of India (SOI) toposheet number 47F/11/NE (1:25000 map scale) as the base map.

2. Digital Elevation data: The terrain elevation data for the milli-watershed was obtained from the ASTER (Advanced Space borne Thermal Emission and Reflection Radiometer) Global Digital Elevation Model, which features a 30 metres spatial resolution.

Methodology:

To perform the geomorphometric analysis of the selected milli-watershed, the Survey of India (SOI) toposheet number 47F/11/NE (1:25,000 scale) was first georeferenced and projected using the WGS (World Geodetic System) 1984 datum and UTM (Universal Transverse Mercator) Zone 43N coordinate system. The milli-watershed boundary was then delineated using contour line patterns, while the drainage network of the milli-watershed was manually digitized directly from the SOI topographical map. Stream ordering was assigned according to Strahler's (1964) system, assigning first-order rank to unbranched tributaries, which then combine to form second-order channels. The overall methodology evaluates the milli-watershed across three primary geomorphometric dimensions:

I. Linear parameters: Linear parameters evaluate stream length and the bifurcation ratio.

II. Areal parameters: Areal parameters examine drainage density, stream frequency, drainage texture, form factor, elongation ratio, and the compactness constant.

III. Relief parameters: Relief parameters analyze the total watershed relief and the ruggedness number.

IV. **Figure 2: Agalambe Watershed – Stream Ordering**

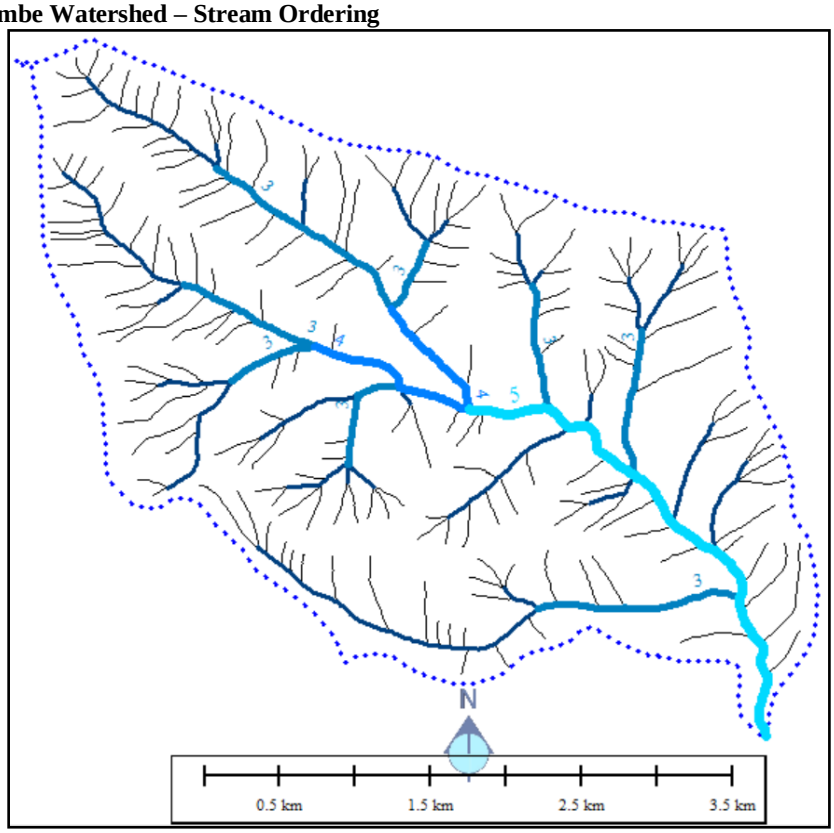
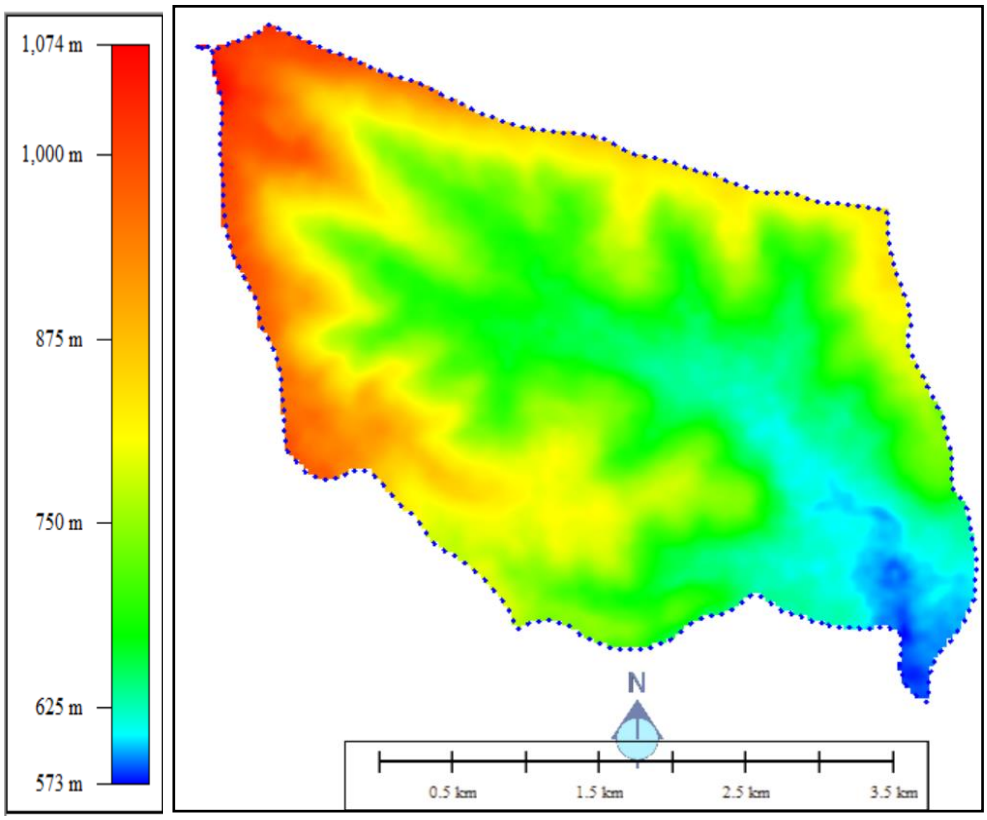


Figure 3: Agalambe Watershed - Digital Elevation Model (DEM)



Results and Interpretation:

Geographical Information System (GIS) software, specifically Global Mapper version 22, was utilized to compute the stream length, watershed area, watershed length and watershed perimeter. The geospatial technology ensures the extraction process is both efficient and highly accurate. The outputs are summarized as follows:

1. Total Stream Length (L) = 76.59 km
2. Watershed Area: A = 13.59 km^2
3. Watershed Perimeter: P = 16.44 km

The geomorphometric analysis of the Agalambe watershed involved the calculation and interpretation of linear, relief and areal morphometric parameters of the milli-watershed.

(I) Linear Aspects of Watershed:

(1) Stream Length: The total length of all rivers and stream segments within a specific watershed is known as the stream length (L). In watershed analysis, stream length (L) is defined as the cumulative linear distance (in kilometres) of the drainage network. It is calculated by adding together the individual lengths of every stream segment found within the catchment area of that specific drainage basin.

Total Stream Length (L) = 76.59 km

(2) Bifurcation Ratio: Bifurcation ratio (R_b) represents the relationship between the number of streams in a specific order (N_u) and those in the immediately higher order (N_{u+1}), a concept introduced by Schumm (1956). This metric reflects the branching structure of a watershed's drainage network. Typically, average bifurcation ratios range from 2 to 3 for flat topographies, whereas mountainous, hilly, and highly eroded basins generally exhibit values between 3 and 5.

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 Agalambe Watershed

S.No.	Stream Orders	Bifurcation Ratio (R_b)
1	1st / 2nd	$R_b = N_1/N_2 = 177/26 = 6.81$
2	2nd / 3rd	$R_b = N_2/N_3 = 26/8 = 3.25$
3	3rd / 4th	$R_b = N_3/N_4 = 8/2 = 4.00$
4	4th / 5th	$R_b = N_4/N_5 = 2/1 = 2.00$
5	Mean Bifurcation Ratio (R_{bm})	R_{bm}=(6.81+3.25+4.00+2.00) / 4 = 16.06 / 4 R_{bm}= 4.015

With a mean bifurcation ratio of 4.015, the Agalambe watershed exhibits characteristics typical of a highly dissected, mountainous, rugged and hilly terrain. Because this value is relatively high, it indicates that the watershed has an increased susceptibility to soil erosion.

(II) Areal Aspects of Watershed:

(1) Drainage Density: To quantify the spacing of stream channels, Horton introduced the concept of drainage density (D_d), which represents the total length of all stream orders divided by the total 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 = 76.59 km / 13.59 km^2 = 5.636 km/km^2

For the Agalambe watershed, the drainage density is 5.636 kilometre per square kilometre area, signaling a highly concentrated, closely spaced network of streams. This characteristic is typically accelerated by mountainous terrain, minimal plant cover, and impermeable underlying geology (Nag, 1998), culminating in a highly fragmented landscape and fine drainage texture. Consequently, this elevated drainage density exposes the Agalambe watershed to a substantially greater risk of both soil degradation and flooding.

(2) Stream Frequency: Stream frequency (F_s) or drainage frequency, defined as the total number of stream segments across all orders within a specific area, was originally established by Horton (1932).

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 = 214 / 13.59 km^2 = 15.747 streams / km^2

The Agalambe watershed features a high stream frequency of 15.747 streams per square kilometre area, indicating a dense concentration of stream channels. This dense network of stream channels is responsible for generation of rapid surface runoff, triggering greater soil degradation than in neighboring areas. Because of this high drainage frequency, the watershed faces a significantly elevated risk of soil erosion and flooding.

(3) Drainage Texture: Horton (1945) identified infiltration capacity as the primary determinant affecting drainage development, noting that impermeable zones typically support a higher concentration of streams compared to permeable regions. Horton defined drainage texture (T) as the ratio of total stream segments across all orders to the watershed's perimeter. This metric was later categorized into five distinct classes by Smith (1950): very coarse (<2), coarse (2–4), moderate (4–6), fine (6–8), and very fine (>8).

Formula for computation of Drainage texture (T):

$T = N / P$ … (*Horton*, 1945)

where,

N = total number of streams of all orders

P = watershed perimeter (km)

T = N / P = 214 / 16.44 km = 13.017

The Agalambe watershed exhibits a high drainage texture (13.017), signalling a very fine-textured and largely impermeable terrain. This high value directly correlates with a greater susceptibility to soil erosion in the catchment area.

(4) Drainage intensity: Drainage intensity (D_i) is defined mathematically as the ratio of the drainage frequency (Fs) to the drainage density (D_d) of the watershed, or directly as the total number of streams in the watershed divided by the total stream length. This metric was introduced by geomorphologist Faniran in 1968 for measuring the operational efficiency and level of denudation (erosion) of a drainage basin network.

Formula for computation of Drainage intensity (D_i):

$D_i = F_s / D_d$ … (*Faniran*, 1968)

where,

F_s = Stream frequency

D_d = Drainage density

$D_i = F_s / D_d$ = 15.747 / 5.636 = 2.794

In geomorphometric analysis of a watershed, drainage intensity of 2.794 is classified as high, indicating a highly responsive hydrological system with a dense network of short, frequent stream segments relative to its total channel length. This extensive channelization reduces overland flow travel distance, causing rapid runoff accumulation at the watershed outlet. Consequently, the watershed is highly vulnerable to flash floods during intense monsoon downpours. Geologically, this high value typically signifies impermeable or low-permeability underlying materials that restrict infiltration, forcing the landscape to generate surface streams to drain excess water. A value of 2.794 indicates that both stream frequency and drainage density are actively shaping the terrain and making the watershed highly susceptible to soil erosion, rill formation, and gully development, especially if the catchment area features steep relief or lack of thick vegetation cover.

(5) Infiltration number: Infiltration number (I_f) in geomorphometric analysis is the product of drainage density and stream frequency, acting as an indicator of the infiltration capacity and surface runoff potential of a watershed.

Formula for computation of Infiltration Number (I_f):

$I_f = F_s \times D_d$ … (*Faniran*, 1968)

where,

F_s = Stream frequency

D_d = Drainage density

$I_f = F_s \times D_d$ = 15.747 x 5.636 = 88.750

Because the infiltration number shares an inverse relationship with a soil's absorption or infiltration capacity, a value of 88.75 signifies that the watershed is highly impermeable. The majority of rainfall will instantly become surface runoff, sharply rising the threat of flash floods. This metric suggests the terrain is dominated by dense clay soils or hard rock layers, and sparse vegetation. Furthermore, these high infiltration number indicates heavily dissected terrains with dense stream networks that drive rapid channel cutting and severe soil erosion. An extreme outlier like 88.75 is typically exclusive to steep, barren mountain ranges or completely impermeable soil systems.

(6) Compactness Constant: The compactness coefficient (C_c) of a watershed, as defined by Gravelius (1914), represents the ratio between the watershed's perimeter and the circumference of a circle with an identical surface area. This dimensionless geomorphometric index remains completely unaffected by the overall size of the drainage basin, as it is determined solely by the watershed's configuration, slope and shape characteristics.

Formula for computation of Compactness Constant (C_c):

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

where,

A = area of the drainage basin and

P = watershed perimeter (km)

$C_c = 0.2821 \times P / A^{0.5} = 0.2821 * 16.44 / 13.59^{0.5} = 4.6377 / 3.6865 = 1.258$

A compactness constant greater than 1 signifies that the Agalambe watershed deviates significantly from a perfect circular shape. A compactness constant (also known as the *Gravelius Compactness Coefficient*) of 1.258 means that the watershed is moderately elongated and irregular in shape. Consequently, this elongated morphology extends the time of concentration, delaying the arrival of the peak flow.

(7) Constant of Channel Maintenance: To determine the minimum catchment area needed to support a unit length of a stream, hydrologists measure the constant of channel maintenance (C), which is the inverse of drainage density (D_d). This parameter significantly dictates watershed hydrology and plays a critical role in how a watershed responds to rain. When a watershed has a low channel maintenance constant, it reacts quickly to rainfall, causing peak discharge to happen much faster. As a result, these areas face rapid storm runoff, a higher risk of flash floods, and severe soil erosion.

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

$C = 1 / D_d$ … (*Schumm*, 1956)

where,

D_d = drainage density of the watershed (km/km^2)

$C = 1 / D_d = 1 / 5.636$ km/km^2 $= 0.177$ km^2/km

A channel maintenance constant of 0.177 reveals that approximately 0.177 square kilometres of watershed surface is necessary to sustain each linear kilometre of stream channel. This specific metric signifies a heavily dissected landscape featuring a dense network of streams. Terrains of this nature are generally characterized by high susceptibility to erosion, fast surface runoff, and very low levels of groundwater infiltration.

(8) Length of Overland Flow: The concept of overland flow length (L_g) was first established by Horton in 1945 to quantify the average distance rainwater travels over a hillslope before reaching a defined stream channel. This geomorphometric measurement is mathematically defined as approximately half the reciprocal of the watershed's drainage density (D_d).

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

$L_g = 1 / 2 \times D_d$ … (*Horton*, 1945)

where,

D_d = drainage density of the watershed (km/km^2)

$L_g = 1 / 2 \times D_d = 1 / 2 \times 5.636 = 0.089$ km

A minimal overland flow distance of 0.089 km highlights a watershed defined by sharp elevation changes or steep slopes, rugged terrain, and a highly concentrated stream network. Structurally, this means rainwater and surface runoff quickly reach a defined channel, triggering a rapid hydrological response. Because these short, fast-moving flows gain significant speed on steep inclines, they generate substantial kinetic energy, greatly accelerating the risk of sheet and rill erosion on the topsoil.

(9) Form Factor: Horton (1932) defined the form factor (F_f) as the ratio of a watershed's area (A) to the square of its maximum length (L_b^2). This metric reflects the watershed's geometric shape, where values approaching 0 represent highly elongated drainage systems and values near 1 signify perfectly circular watersheds. Consequently, a lower form factor means greater elongation of the watershed, which leads to attenuated, longer-lasting flatter peak flows during storm events. Conversely, circular watersheds with higher form factors are characterized by sharper, rapid, short-duration peak discharges.

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)

$F_f = A / L_b^2 = 13.59$ km^2 / $(6.50$ km$)^2 = 0.322$

A watershed form factor of 0.322 reveals an elongated, narrow watershed geometry rather than a circular layout. Because this value is much closer to zero, runoff from the most hydraulically remote areas requires a longer travel time to reach the watershed outlet. Consequently, heavy rainfall events generate a delayed, more attenuated peak flow. Elongated watersheds naturally distribute the volume of water over time and are generally less prone to sudden, catastrophic flash flooding compared to circular watersheds.

(10) Elongation Ratio: The elongation ratio (R_e) is defined by Schumm (1965) as the relationship between the maximum length of a watershed and the diameter of a circle possessing the same area. According to Strahler, these values generally span from 0.6 to 1.0 across diverse geological and climatic environments. This ratio categorizes watershed shapes into specific

geometries: circular (0.9–1.0), oval (0.8–0.9), less elongated (0.7–0.8), elongated (0.5–0.7), and highly elongated (< 0.5). Lower relief terrains typically exhibit values approaching 1.0, while steeper slopes and high-relief landscapes generally yield ratios between 0.6 and 0.8. From a hydrological standpoint, circular watersheds demonstrate higher runoff discharge efficiency compared to their elongated counterparts.

Formula for computation of Elongation ratio (R_e):

$R_e = D_c / L_b$ … (*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 (km^2)

L_b = Length of the watershed or drainage basin (km)

$R_e = 1.1287 \times A^{0.5} / L_b = 1.1287 \times 13.59^{0.5} / 6.50 = 0.640$

With an elongation ratio of 0.64, the Agalambe watershed is classified as elongated under the morphological framework established by Pareta and Pareta (2011), which categorizes values between 0.50 and 0.70 under this specific shape. An elongation ratio of 0.64 is heavily associated with steep terrain and high relief. This elongated geometry, typically coupled with moderate-to-steep topography, directly influences the watershed's hydrology by extending the time of concentration. Consequently, runoff from the farthest ridges requires more time to reach the primary outlet. This prolonged travel time attenuates the hydrological response, resulting in a delayed, flattened flood peak rather than a rapid peak discharge. Such characteristics generally simplify flood mitigation and surface water management. Furthermore, a 0.64 ratio frequently points to geological and structural controls, suggesting that the drainage network has developed across complex lithologies or rugged, mountainous terrains.

(III) Relief Aspects of Watershed:

(1) Ruggedness Number: The ruggedness number serves as a metric to quantify the structural roughness of a terrain. Originally defined by Strahler (1968), this value is calculated by multiplying drainage basin or watershed relief (H) by drainage density (D_d), effectively integrating both the steepness and length of a slope. Consequently, exceptionally high ruggedness numbers are estimated only when a landscape features slopes that are simultaneously steep and long. Within a watershed, a high ruggedness number value indicates a higher susceptibility to soil erosion alongside structural complexities driven by the local topography and drainage network.

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)

$D_d = L / A = 76.59$ km / 13.59 $km^2 = 5.636$ km/km^2

H = Highest elevation – Lowest elevation = 1146 – 582 = 564 m = 0.564 km

$R_n = 6.636$ $km/km^2 \times 0.564$ km = 3.179

In watershed morphometric analysis, a ruggedness number (R_n) of 3.179 is considered high and it indicates a highly rugged terrain and heavily dissected watershed that combines steep, elongated slopes with a highly dense network of stream channels. Rainwater will move across the landscape quickly rather than infiltrating the soil. This indicates high peak runoff potential, high structural vulnerability to soil erosion, and a pronounced risk of flash floods during heavy rainfall.

Table 2: Linear, Areal and Relief Aspects of Agalambe Watershed

S.No.	Aspect	Value
1	Mean Bifurcation Ratio	4.015
2	Drainage Density	5.636 km/sq.km
3	Stream Frequency	15.747 streams / sq.km
4	Drainage Texture	13.017
5	Drainage Intensity	2.794
6	Infiltration Number	88.750
7	Compactness Constant	1.258
8	Constant of Channel Maintenance	0.177
9	Length of Overland Flow	0.089
10	Form Factor	0.322
11	Elongation Ratio	0.640
12	Ruggedness Number	3.179

Conclusion

Geomorphometric evaluation of the Agalambe watershed indicates a drainage network dominated by lower-order streams, where catchment shape directly affects the runoff concentration time into Khadakwasla Lake. Characterized as a fifth-order drainage basin with a high-density, dendritic pattern, the system possesses a mature network that accelerates surface runoff discharge into the Khadakwasla Dam. However, the combination of high drainage density, 177 seasonal streams, and vast degraded lands elevates the watershed's vulnerability to soil erosion. Consequently, it acts as a primary sediment contributor to the Khadakwasla Reservoir, especially during the southwest monsoon.

With a mean bifurcation ratio of 4.01, the Agalambe watershed features a mature, well-developed drainage network characteristic of hilly and moderately dissected landscapes. Its drainage density is 5.64 km/km², reflecting a highly efficient

surface runoff system. This rapid runoff dynamic is further supported by a high stream frequency of 15.75 streams/km², which significantly accelerates soil erosion across the watershed. The terrain demonstrates low permeability and a very fine texture, as indicated by a high drainage texture value of 13.02. This impermeability directly increases the catchment's vulnerability to soil degradation. Additionally, the channel maintenance constant of 0.18 highlights distinct watershed properties, including sparse vegetative cover, low ground infiltration, and high erodibility. The length of overland flow (0.09) further illustrates a structurally mature, rugged topography defined by steep gradients, dense drainage, and rapid runoff collection. Hydrologically, an infiltration number of 88.75 points to poor ground absorptive capacity, leading to an exceptionally high potential for surface runoff and soil loss. However, the watershed's form factor of 0.32 describes an elongated and narrow geometry, making it less susceptible to sudden, catastrophic flash floods than circular catchments. Despite this elongation, the ruggedness number of 3.18 warns of high peak discharge potential, severe structural erosion vulnerability, and a significant risk of flash flooding during intense precipitation events.

Watershed management in peripheral villages of Khadakwasla lake catchment area such as Agalambe is vital because Khadakwasla dam has experienced massive siltation over the decades and this has significantly reduced its storage capacity. Implementing active soil conservation prevents fertile topsoil from eroding and choking the Pune city's primary drinking water. To mitigate land degradation and safeguard the reservoir's capacity, targeted soil and water conservation interventions including continuous contour trenches (CCTs) or contour bunding, check dams, and vegetative buffers are urgently needed in the upper catchment area. These insights establish a vital framework for regional authorities designing targeted watershed management plans. Ultimately, this research highlights how integrating Survey of India (SOI) topographical maps, ASTER GDEM, and GIS tools provides an efficient approach to identifying flood-prone and erosion-prone catchments.

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Conflicts of interest

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

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