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Gis-Based Prioritisation of Pennar Watershed in Bapatla District: A Combined Morphometric and Land Use/Land Cover Approach

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Abstract

Effective watershed prioritisation is essential for sustainable resource management in vulnerable regions. This study presents an integrated multi-criteria assessment to prioritise sub-watersheds within the Pennar basin of Bapatla District, Andhra Pradesh, a semi-arid coastal area facing significant anthropogenic and climatic pressures. The methodology synergistically combines geospatial analysis of quantitative morphometric parameters with qualitative thematic layers of Land Use/Land Cover (LULC), slope, soil, and rainfall. A comprehensive set of linear, areal, and relief parameters, derived from a CartoDEM and analysed in a GIS environment, characterised the inherent geomorphic and hydrological susceptibility of ten sub-watersheds (SW-1 to SW-10).

The analysis uncovered significant heterogeneity, with sub-watersheds like SW-5 and SW-7 showing high drainage density, complex networks, and elevated ruggedness indices, indicating a tendency for rapid runoff and severe soil erosion. These inherent vulnerabilities were then considered within the human-modified landscape; areas with high morphometric risk that coincide with agricultural dominance, erodible soils, and steeper slopes were prioritised for intervention. The resulting prioritisation ranks SW-7 and SW-5 as very high priority, followed by SW-10 and SW-9 as high priority, offering a clear, evidence-based framework for conservation planning. This research illustrates that a holistic approach, combining the static controls of basin morphology with dynamic land-use factors, is essential for identifying critical erosion hotspots and strategically allocating resources for soil and water conservation in developing coastal agro-ecosystems.

Keywords: Watershed Prioritisation, Morphometric Analysis, Geographic Information System (GIS), Land Use/Land Cover (LULC), Drainage Density, Erosion Susceptibility, Bapatla District, Pennar Basin, Integrated Watershed Management

Introduction

Watershed management serves as an interdisciplinary approach for sustainable water resource development and environmental protection. It is especially significant for rapidly developing countries facing dual challenges of water scarcity, soil erosion, and substantial land-use changes [1]. Typically, a watershed or drainage basin is the core geohydrological unit, encompassing all land and water components within a specified topographic boundary that drains to a single outlet; thus, it is central to integrated resource management [2-4]. Ranking sub-watersheds at different levels using quantitative morphometric analysis is now an established scientific method for identifying areas that need the most conservation efforts; this approach is especially applicable to regions with pronounced geomorphological variation and shifting land-use patterns.

This approach relies on the integrated use of geospatial technologies, especially Geographic Information Systems (GIS) and remote sensing, along with traditional morphometric analysis to ensure dependable, scientifically sound decision-making in watershed management [5-7]. These technologies enable comprehensive, cost-effective, and precise analysis of large areas—something that would have been very costly and perhaps even unfeasible if conducted solely on the ground [8-10].

The Pennar watershed in Bapatla District, situated in the coastal region of Andhra Pradesh, India, exemplifies typical semi-arid area complexities and hydrogeological conditions largely caused by sharp seasonal rainfall variation, diverse

topography, and extensive land-use changes driven by intensified agriculture and expanding urban areas [11,12]. By assessing these parameters, morphometric characterisation can effectively reveal the basin's vulnerability to erosion, its hydrological behaviour, infiltration capacity, and overall geomorphological development, which naturally guides prioritisation as a scientific process [13-15]. However, recent research has highlighted that relying solely on morphometric parameters can lead to an overemphasis on topography and overlook the significant impact of land surface modifications caused by human activities [16-18].

Thoroughly ranked watersheds are thus expected to buffer in the Land Use and Land Cover (LULC) study because LULC changes are primarily the result of human-nature interactions, which directly influence hydrological processes, sediment delivery to rivers, and groundwater recharge [19-21]. Remote sensing has revolutionised LULC mapping and change detection, making accurate, multi-temporal monitoring of landscape alterations such as deforestation, agricultural expansion, and urbanisation possible, factors that significantly impact watersheds [22,23,11]. The integration of multi-temporal satellite imagery and elevation data models (DEMs) within a GIS environment enhances the capacity for high-level spatial analysis, enabling the assessment of relationships among land cover, topography, and hydrological processes [24-26]. Therefore, combining morphometric and LULC analyses in a GIS framework has become a recommended, multi-criteria, holistic approach for watershed assessment and prioritisation [16,27,28].

This comprehensive method considers watershed vulnerability as the combined effect of inherent geomorphological features and current land use practices [29,18,30]. It has been validated through studies on Indian river basins such as the Cauvery, Betwa, and Godavari, which have led to the identification of priority sub-watersheds for conservation [2,8,31]. The Pennar watershed in Bapatla District exemplifies the applicability of this integrated approach. Situated in the highly vulnerable coastal zone of Andhra Pradesh, the district faces multiple pressures, including water demands for agriculture, groundwater depletion, urban expansion, and increasing climate variability [32,12]. Its sub-watersheds exhibit marked differences in geomorphology, drainage systems, and land cover, necessitating a geographically explicit, numerical assessment to facilitate rational resource allocation [33,15].

A GIS-based prioritisation such as this offers more than academic insights; it provides crucial data for developing district-level agricultural policies, water resource planning, and targeted soil and water conservation initiatives [13,34,35]. This research focuses on an integrated approach that utilises cutting-edge remote sensing data, GIS tools for analysis, comprehensive morphometric parameterisation, and LULC change studies to rank sub-watersheds within the Pennar basin of Bapatla District. The goal is to improve the management of semi-arid coastal watersheds in India through a reproducible model that combines natural landscape components with human influences for sustainable resource planning.

Study Area

Bapatla District lies in the south of Andhra Pradesh, a State renowned for its agricultural products located in the south-eastern part of India. The district extends between 15°40'N and 16°15'N latitude and 80°00'E and 80°50'E longitude. It is a seaside district with the Bay of Bengal as its climate moderator and an inland mountain range. The Bapatla district area is geologically northern and eastern parts consist of metamorphic rock/rock types, e.g., Migmatite Gneiss and charnockite which are located in the west-central parts of the district, along with high-grade sedimentary rock to the East and the Bapatla seabed.

Coastal and delta plains of the Bapatla district are the result of a combination of human (digging) and natural (fluvial and marine) processes; thus, forming the geomorphology of the region. The district itself comprises mainly two soil types that are very productive: Black cotton soil and Sandy loamy soil. The first type accounts for 70% of the total land area and the second one comprises 30%.

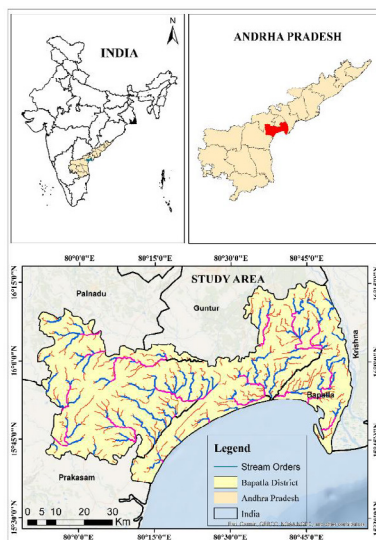


Figure 1: Location Map of the Study Area

The district is predominantly a rural setting with a local population that majorly depends on agriculture to make a living and their choice of living is in proximity to the environmental conditions described. This population is very susceptible to the changes that take place in the hydrological and climatic parameters due to their economic well-being being heavily dependent on the availability of water and soil fertility. The use of irrigation water in agriculture might lead to the contamination of freshwater sources and the intrusion of saline or oceanic water into less saline parts of the aquifers may increase, thus, the essential drinking water sources of the local communities are threatened.

Less reliable precipitation is the expected trend and therefore, climatic drought will become more and more prominent, which can be a reason for significant agricultural vulnerability. Furthermore, coastal erosion will become increasingly problematic as it directly threatens settlements and coastal infrastructure; also, the temperature is bound to rise. The rainfall pattern shows that Bapatla's northern regions in the east and west get more precipitation, whereas the shallowest groundwater levels are found in the south-western part of Bapatla. Both of these result in a spatial water access disparity and further deepen the vulnerabilities of the communities in these areas, which mainly depend on the mentioned shallow aquifers for their water needs

Data And Methodology

Data

Sl. No.	Data	Parameter	Source
	CartoDEM	Drainage Map Slope Map	Indian National Digital Elevation Model
	Sentinel 2A	LULC	European Space Agency (ESA)
	Soil	Soil Map	https://apsac.ap.gov.in/dashboard-staging/ap-geoportal/
	Rainfall	Rainfall Map	https://www.city-facts.com/ (A

Table 1: Data Used for Prioritisation of Sub-Watersheds

Methodology

The prioritisation of sub-watersheds (SW-1 to SW-10) in Bapatla District is carried out using an integrated multi-criteria approach that combines morphometric, physiographic, and climatic factors. The method involves analysing quantitative morphometric parameters from the dataset, including drainage density, stream frequency, bifurcation ratio, relief, ruggedness index, and shape factors to evaluate the inherent erosion and runoff potential. This geomorphic analysis is then complemented with qualitative thematic layers: Land Use/Land Cover (LULC December 2024) to assess human activity and surface permeability; Slope to understand terrain steepness and runoff speed; Soil type to consider erodibility and infiltration capacity; and Rainfall distribution to account for precipitation. The Stream Order extracted from CartoDEM from the Indian National Digital Elevation Model 2025 and the map provides a spatial validation of the drainage network structure. Each watershed is ranked by interpreting the convergence of high-risk morphometric traits with adverse conditions on other thematic maps, such as steep slopes, erodible soils, intense rainfall zones, and agricultural or barren land covers, to identify areas most vulnerable to soil erosion, flash floods, and land degradation.

Sl. No.	Variable	Formula	Reference
A. Linear parameters			
1	Stream order (u)	Hierarchical rank	Strahler (1952)
2	Stream number (Nu)	Total number of streams of order u	Horton (1945)
3	Stream length (Lu), km	Total stream length of order u	Strahler (1952)
4	Mean stream length (Lsm)	Lu / Nu	Strahler (1952)
5	Stream length ratio (Lur)	$Lu / Lu-1$	Strahler (1952)
6	Bifurcation ratio (Rb)	$Nu / Nu+1$	Strahler (1952)
7	Length of overland flow (Lo), km	$1 / (2 * Dd)$	Horton (1945)
8	Basin length (Lb), km	GIS software analysis	Schumm (1956)
B. Areal parameters			
9	Basin area (A), km ²	GIS software analysis	Schumm (1956)
10	Basin perimeter (P), km	GIS software analysis	Schumm (1956)
11	Form factor (Rf)	A / Lb^2	Horton (1932)
12	Shape factor (Sf)	Lb^2 / A	—

13	Elongation ratio (Re)	$1.128 * \sqrt{A} / L_b$	Schumm (1956)
14	Circularity ratio (Rc)	$4\pi A / P^2$	Miller (1953)
15	Drainage texture (Dt)	Nu / P	Smith (1950)
16	Stream frequency (Fs)	Nu / A	Horton (1932)
17	Drainage density (Dd), km/km ²	Lu / A	Horton (1932)
C. Relief parameters			
18	Height of basin mouth (H), m	GIS analysis/DEM	—
19	Maximum height of the basin (Z), m	GIS analysis/DEM	—
20	Total basin relief (R), m	$H = Z - h$	Strahler (1952)
21	Relief ratio (Rh)	R / L_b	Schumm (1956)
22	Ruggedness number (Rn)	$Dd * R$	Chorley (1972)
23	Basin ruggedness index (Bri)	$Dd * (H/1000)$	Chorley (1972)

Table 2: Method Adopted for the Computation of Morphometric Parameters

Result And Discussion

Morphometric Analysis

The morphometric analysis is studied under three different categories: (i) linear aspects (ii) areal aspects, and (iii) relief aspects, which are discussed below.

Linear Aspects

The linear aspects include stream order, stream number, stream length, mean stream length, stream length ratio, bifurcation ratio, Length of overland flow and Basin length which were determined and their results have been presented in the following table 3.

Linear Aspects								
Sub-Watershed	Stream order (u)	Stream number (Nu)	Stream length (Lu), km	Mean stream length (Lsm)	Stream length ratio (Lur)	Bifurcation ratio (Rb)	Length of overland flow (Lo), km	Basin length (Lb), km
SW-1	41.00	145.24	15.03	0.12	3.58	6.42	0.39	4.06
SW-2	27.00	89.90	20.15	0.12	4.68	9.33	0.30	4.01
SW-3	25.00	88.69	20.78	0.10	4.58	8.80	0.27	4.77
SW-4	36.00	132.09	14.78	0.13	3.13	6.05	0.41	4.00
SW-5	122.00	507.79	44.46	0.12	6.71	10.64	0.64	4.28
SW-6	33.00	106.52	8.11	0.13	1.44	6.93	0.25	3.83
SW-7	58.00	232.74	30.35	0.14	5.22	11.50	0.36	3.65
SW-8	17.00	77.14	24.09	0.10	4.63	7.33	0.21	4.80
SW-9	86.00	371.98	41.76	0.13	6.09	11.00	0.43	3.85
SW-10	41.00	146.91	18.48	0.13	4.27	6.42	0.30	3.79

Table 3: Linear Aspects of Sub-Watersheds

- **The Stream Order (u):** for each sub-watershed, ranging from 17 (SW-8) to 122 (SW-5), establishes a hierarchical framework for drainage network analysis. The presence of higher-order streams, as seen in SW-5, indicates a more integrated and mature hydrological system, while lower-order networks suggest simpler, less developed drainage. This hierarchical classification is fundamental for assessing relative geomorphic development and prioritising sub-watersheds based on their structural complexity and influence on sediment and water delivery dynamics.

- **Stream Number (Nu):** representing the total count of channels, shows significant variation, from approximately 77 (SW-8) to over 507 (SW-5). This parameter quantifies the drainage network's branching density, where higher numbers, as in SW-5 and SW-9, indicate a finely dissected landscape with numerous tributaries. This high degree of dissection typically correlates with greater surface runoff generation and a more rapid hydrological response, making such sub-watersheds critical for flood risk assessment and erosion control prioritisation.

- **Stream Length (Lu):** measured cumulatively in kilometres, reveals the total linear extent of channels within each order. Sub-watersheds like SW-5 (44.5 km) and SW-9 (41.8 km) exhibit the greatest cumulative channel lengths, signifying extensive drainage networks that efficiently collect and convey surface runoff. The spatial distribution of

these lengths directly influences sediment transport capacity and hydrograph timing, with longer networks generally contributing to more attenuated but sustained flow peaks at the outlet.

- **Mean Stream Length (Lsm):** averages the length of channels within specific orders, with values across the sub-watersheds ranging from 0.104 to 0.137 km. This metric normalises channel development, where deviations from theoretical norms can indicate geological controls. For instance, relatively consistent mean lengths across orders, as observed in several sub-watersheds, may suggest homogeneous lithology, while significant variations could point to structural influences affecting channel formation and elongation.

- **The Stream Length Ratio (Lur):** which compares mean lengths between successive stream orders, shows values from 1.44 (SW-6) to 6.71 (SW-5). This ratio reflects hydrological and erosional transitions within the network. A higher ratio, as in SW-5, suggests a pronounced increase in channel length with increasing order, indicative of efficient flow integration and potential for higher erosive energy in lower-order streams, which is a key consideration for identifying sediment source areas.

- **Bifurcation Ratio (rb):** a measure of branching complexity, varies from 6.05 (SW-4) to 11.5 (SW-7). This dimensionless index indicates the degree of geological control; lower, more consistent ratios suggest a dendritic pattern in homogeneous terrain, while higher or variable ratios, as seen in SW-5, SW-7, and SW-9, often reflect structural disturbances. Sub-watersheds with high Rb values may experience more synchronised tributary convergence, potentially leading to sharper flood hydrographs and warranting higher priority for hydrological modelling.

- **The Length of Overland Flow (Lo):** quantifies the average distance water travels as sheet flow before entering a channel, with values between 0.205 km (SW-8) and 0.642 km (SW-5). A shorter Lo, as in SW-6 and SW-8, implies a well-dissected terrain with rapid runoff concentration and higher erosion potential on hillslopes. Conversely, a longer Lo, notably in SW-5, indicates greater opportunity for infiltration, which can delay peak discharge but may also signify less efficient surface drainage.

- **Basin Length (Lb):** the longest dimension parallel to the main drainage line, ranges from approximately 3.65 km (SW-7) to 4.80 km (SW-8). This fundamental linear scale parameter influences the shape of the runoff hydrograph; longer basins typically produce more attenuated flood peaks due to longer travel times. It also serves as a critical denominator for calculating other shape and relief indices, providing a baseline for comparing the longitudinal development of each sub-watershed.

Areal Aspects

The Areal aspects includes Basin area (A), km², Basin perimeter (P), km, Form factor (Rf), Shape factor (Sf), Elongation ratio (Re) Circularity ratio (Rc) Drainage texture (Dt) Stream frequency (Fs) and Drainage density (Dd), km/km² which were determined and their results have been presented in the following table 4.

Areal Aspects									
Sub-Watershed	Basin area (A), km ²	Basin perimeter (P), km	Form factor (Rf)	Shape factor (Sf)	Elongation ratio (Re)	Circularity ratio (Rc)	Drainage texture (Dt)	Stream frequency (Fs)	Drainage density (Dd), km/km ²
SW-1	332.83	105.18	0.35	2.85	0.67	0.38	0.39	0.123	0.44
SW-2	216.77	89.16	0.40	2.51	0.71	0.34	0.30	0.125	0.41
SW-3	238.66	93.77	0.31	3.19	0.63	0.34	0.27	0.105	0.37
SW-4	287.66	86.86	0.48	2.10	0.78	0.48	0.41	0.125	0.46
SW-5	1044.29	190.06	0.42	2.38	0.73	0.36	0.64	0.117	0.49
SW-6	252.60	132.61	0.14	7.29	0.42	0.18	0.25	0.131	0.42
SW-7	422.83	161.08	0.26	3.84	0.58	0.20	0.36	0.137	0.55
SW-8	163.34	82.83	0.28	3.63	0.59	0.30	0.21	0.104	0.47
SW-9	663.06	200.30	0.39	2.56	0.71	0.21	0.43	0.130	0.56
SW-10	310.39	136.09	0.19	5.29	0.49	0.21	0.30	0.132	0.47

Table 4: Areal Aspects of Sub-Watersheds

- **Basin Area (A):** is the primary scale variable, showing a wide range from 163.34 km² (SW-8) to 1044.29 km² (SW-5). This parameter directly controls the total water yield and sediment production capacity of a catchment. Larger sub-watersheds like SW-5 and SW-9 represent major contributing zones within the larger Pennar system, making their management disproportionately important for downstream water resources and flood mitigation strategies.

- **Basin Perimeter (P):** defines the watershed boundary length, varying from 82.83 km (SW-8) to 200.30 km (SW-9). When considered relative to area, the perimeter reveals shape irregularity. A longer perimeter for a given area, as suggested for some sub-watersheds, indicates a more complex and elongated shape, which can influence groundwater interaction with adjacent basins and affect the pattern of tributary development.

- **Form Factor (Rf):** calculated as the ratio of basin area to the square of its length, indicates basin shape, with values from 0.137 (SW-6) to 0.476 (SW-4). A higher Rf, approaching 1.0, denotes a more circular shape, which theoretically leads to shorter concentration times and sharper flood peaks. The notably low Rf for SW-6 highlights its highly elongated nature, suggesting a very different and potentially delayed hydrological response compared to more circular sub-watersheds like SW-4.

- **Shape Factor (Sf):** the reciprocal of the form factor, provides an alternative expression of elongation, where higher values indicate greater elongation. SW-6 exhibits the highest Sf (7.29), confirming its pronounced linear form. This elongated geometry typically results in a longer lag time and reduced peak discharge for a given rainfall event, which must be factored into prioritisation for flood control infrastructure.

- **The Elongation Ratio (Re):** classifies basin shapes on a scale from highly elongated (low values) to circular (values near 1.0). The calculated ratios range from 0.418 (SW-6) to 0.778 (SW-4). Sub-watersheds with lower Re, such as SW-6 and SW-10, are characterised by elongated forms that tend to produce more subdued flood peaks, whereas those with higher Re values are more compact and prone to rapid runoff concentration, increasing their priority for flood hazard assessment.

- **Circularity Ratio (Rc):** measures the similarity of the basin's shape to a perfect circle, with values between 0.180 (SW-6) and 0.479 (SW-4). A higher Rc, as seen in SW-4, suggests a mature, structurally undisturbed basin with a well-integrated network. Lower values, prevalent in most sub-watersheds, indicate significant elongation or structural control, which compartmentalises flow paths and creates complex runoff patterns requiring detailed analysis.

- **Drainage Texture (Dt):** defined as stream frequency per unit perimeter, reflects the spacing of channels. Values range from 0.205 (SW-8) to 0.642 (SW-5). Finer texture (higher Dt), as in SW-5, implies closely spaced channels often associated with easily erodible material, steep slopes, or high runoff, marking these areas as highly susceptible to erosion and land degradation, thus prioritising them for conservation measures.

- **Stream Frequency (Fs):** the number of streams per unit area, varies from 0.104 (SW-8) to 0.137 (SW-7) streams/km². A higher Fs indicates a denser drainage network and a landscape with lower infiltration capacity, leading to greater surface runoff generation. Sub-watersheds like SW-7 and SW-10, with elevated Fs values, are likely characterised by impermeable surfaces or steep gradients, making them critical zones for managing runoff and non-point source pollution.

- **Drainage Density (Dd):** the total stream length per unit area, is a pivotal integrative measure of landscape dissection, with values from 0.372 (SW-3) to 0.561 (SW-9) km/km². Higher Dd, observed in SW-7, SW-9, and SW-10, signifies a well-developed channel network in response to impermeable lithology, steep relief, or intense rainfall, resulting in rapid hydrological response and high erosion potential. These sub-watersheds are therefore key targets for soil and water conservation interventions.

Relief Aspects

The Relief aspects includes Height of basin mouth (H), Maximum height of the basin (Z), Total basin relief (R), Relief ratio (Rh), Ruggedness number (Rn) and Basin ruggedness index (Bri) which were determined and their results have been presented in the following table 5.

Relief Aspects						
Sub-Watershed	Height of basin mouth (H)	Maximum height of the basin (Z)	Total basin relief (R), m	Relief ratio (Rh)	Ruggedness number (Rn)	Basin ruggedness index (Bri)
SW-1	383.17	326.52	326.52	12.44	142.49	167.21
SW-2	368.84	308.46	308.46	15.82	127.92	152.96
SW-3	221.78	160.19	160.19	8.04	59.53	82.42
SW-4	182.09	105.65	105.65	7.40	48.51	83.61
SW-5	230.50	148.84	148.84	4.63	72.38	112.08
SW-6	32.87	-55.76	-55.76	0.77	-23.51	13.86
SW-7	69.74	-31.18	-31.18	1.73	-17.16	38.39
SW-8	17.48	-61.67	-61.67	0.72	-29.13	8.26
SW-9	47.37	-50.05	-50.05	1.15	-28.08	26.57
SW-10	333.60	115.77	115.77	8.23	54.80	157.90

Table 5: Relief Aspects Of Sub-Watersheds

- **The Height of the Basin Mouth (H):** serves as the base elevation for each sub-watershed, with values from approximately 17.5 meters (SW-8) to 383.2 meters (SW-1). This elevation establishes the local base level controlling erosion and deposition processes. Sub-watersheds with higher mouth elevations, such as SW-1 and SW-2, possess greater gravitational potential energy, influencing stream gradient and sediment transport capacity from the outset.

- **The Maximum Height of the Basin (Z):** indicates the peak elevation on the watershed divide, showing considerable variation. It is important to note that for several sub-watersheds (SW-6 through SW-9), the calculated maximum height values are lower than the mouth height, resulting in negative relief values. This anomaly requires verification of elevation data, as it impacts the calculation of subsequent relief parameters and the interpretation of the basin's topographic context.

- **Total Basin Relief (R):** the difference between maximum height and mouth height, is the master variable representing potential energy. The data shows positive relief for SW-1 to SW-5 and SW-10, with SW-1 having the highest (326.5 m). Negative values for SW-6 to SW-9 highlight a critical data inconsistency that must be resolved, as accurate relief is fundamental for assessing erosion potential, slope processes, and overall geomorphic activity.

- **Relief Ratio (Rh):** total relief normalized by basin length, indicates overall basin steepness. Valid positive ratios range from 4.63 (SW-5) to 15.82 (SW-2). A high Rh, as in SW-2, signifies a steep landscape conducive to rapid runoff, high stream velocity, and severe erosion. Sub-watersheds with high relief ratios are typically assigned the highest priority for conservation due to their inherent instability and significant sediment yield potential.

- **The Ruggedness Number (Rn):** the product of drainage density and total relief, combines terrain dissection and slope. Valid positive values are observed for SW-1 to SW-5 and SW-10, with SW-1 being the highest (142.49). This index is a direct indicator of erosion susceptibility; high Rn values characterize landscapes prone to landslides and severe soil loss. The negative values for SW-6 to SW-9 are artifacts of the negative relief data and cannot be interpreted meaningfully without correction.

- **The Basin Ruggedness Index (Bri):** provides a similar integrative measure of terrain unevenness. All calculated values are positive, with the highest observed in SW-1 (167.21) and SW-10 (157.90). This index effectively highlights sub-watersheds where steep slopes coincide with dense drainage networks, marking them as areas of extreme geomorphic sensitivity and high priority for land management strategies aimed at mitigating erosion and stabilizing slopes.

The morphometric analysis reveals significant heterogeneity in the hydrological and geomorphic character of the sub-watersheds within Bapatla district, as depicted in the accompanying stream order map. The linear aspects demonstrate a clear hierarchy of drainage network development, with SW-5 exhibiting the highest stream order (122) and a vastly complex network of over 500 streams, indicating a mature and highly integrated system. In contrast, SW-8 presents a simpler, lower-order structure. Key linear metrics like the high bifurcation ratios in SW-5, SW-7, and SW-9 suggest potential structural control over drainage patterns, while variations in the length of overland flow point to differences in runoff concentration times and infiltration opportunities across the landscape. The map visually corroborates these findings, showing dense, intricate channel networks in some sub-watersheds compared to sparser ones in others.

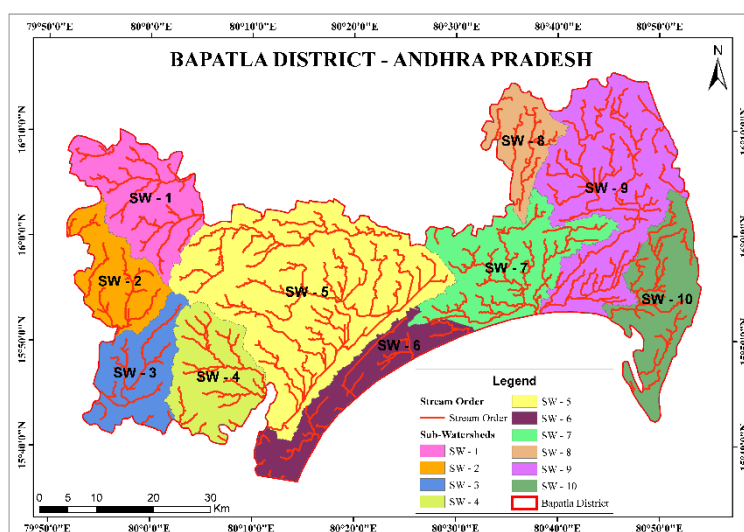


Figure 2: Stream Network of the Study Area

This structural diversity is further explained by the areal and relief parameters. Areally, basins range from the highly elongated form of SW-6 (Form Factor 0.14) to the more compact shape of SW-4, directly influencing flood peak potential. Crucially, integrated indices like drainage density and ruggedness highlight zones of acute geomorphic sensitivity. Sub-watersheds such as SW-1, SW-2, SW-7, SW-9, and SW-10, which combine higher drainage density with substantial relief

(where data is consistent), are characterised by well-dissected terrain on steeper slopes. This confluence of factors signifies a rapid hydrological response, high erosive energy, and a landscape prone to soil loss and flash flooding, underscoring their critical importance for targeted soil and water conservation interventions within the district's overall management strategy.

Land Use and Land Cover

Based on the Land Use and Land Cover (LULC) map for 2024, Bapatla District displays a landscape predominantly characterised by agricultural land, indicating that farming is a primary economic activity. Significant vegetation cover is also present, suggesting healthy natural or cultivated green spaces. Built-up areas appear concentrated, likely representing towns and villages, while distinct zones of waterbodies, sandy areas, rocky land, and salt pans are visible, illustrating the district's diverse coastal and inland features. The distribution shows a clear interplay between human activity and natural landforms.

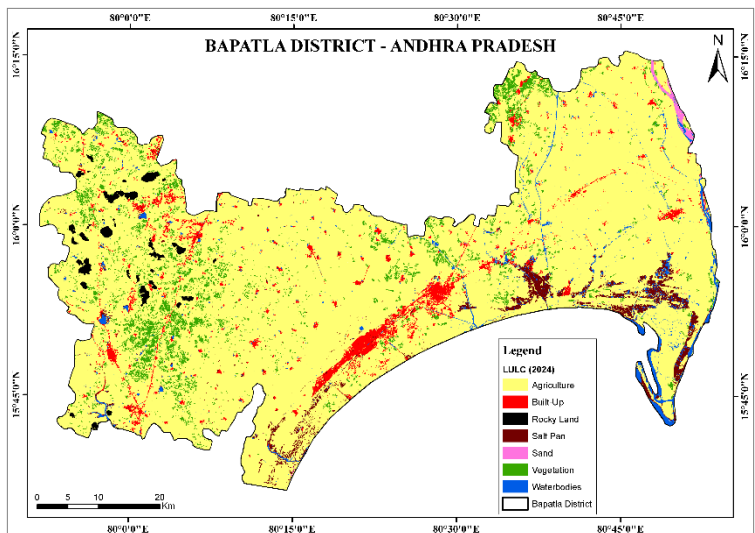


Figure 3: LULC Map of the Study Area

Rainfall

The rainfall map reveals a relatively uniform distribution of precipitation across Bapatla District, with values ranging between 142 mm and 194.72 mm for the measured period. The classification into only two narrow bands suggests minimal spatial variability in rainfall across the region for this specific time frame, indicating that most areas receive a similar amount of precipitation. This homogeneity is significant for agricultural planning, as water availability from rain appears consistent throughout the district.

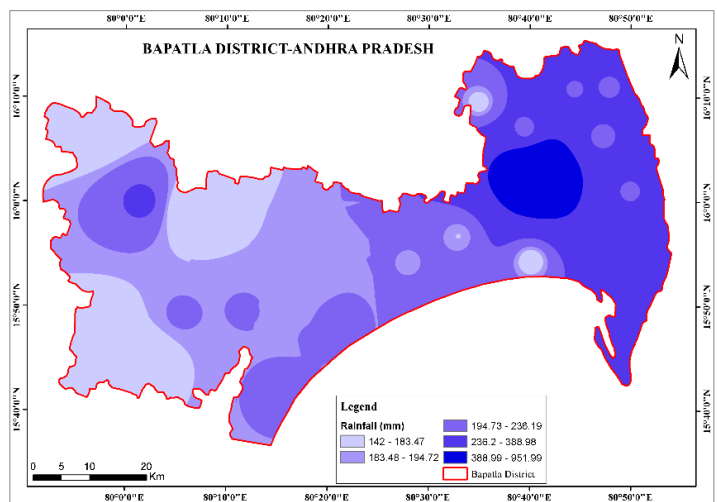


Figure 4: Rainfall Map of the Study Area

Slope

The slope map indicates that the topography of Bapatla District is overwhelmingly characterised by very gentle to gentle slopes. The prevalence of these flat to mildly inclined areas suggests a landscape highly suitable for widespread agriculture, irrigation, and construction. The absence of significant areas with moderate, steep, or very steep slopes implies a low risk of erosion from terrain and generally favourable conditions for infrastructure development and farming activities across most of the district.

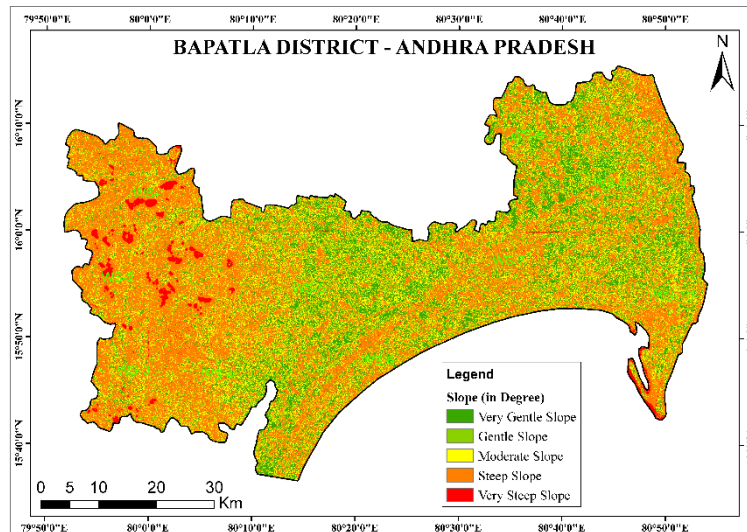


Figure 5: Slope Map of the Study Area

Soil

The soil map highlights considerable pedological diversity within the Bapatla District. A variety of soil types are present, including Black Soil, Clay Red Soil, Deep Black Clay Soil, and Loamy Soil, which are typically fertile and suitable for agriculture.

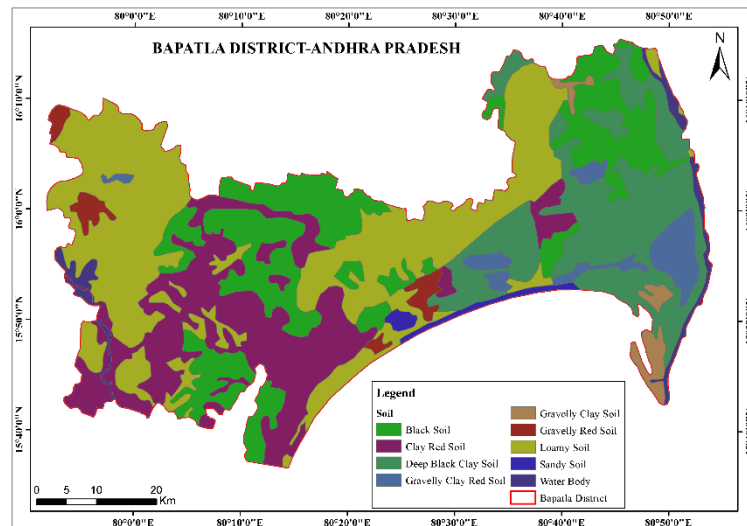


Figure 6: Soil Map of the Study Area

The presence of Gravelly Clay, Gravelly Red Soil, and Sandy Soil indicates areas with potentially lower water retention or different agricultural suitability. This mosaic of soil types directly influences local land use capabilities and crop patterns across the region.

Prioritisation of Sub-Watershed

The prioritisation of sub-watersheds (WS-1 to WS-10) in Bapatla District is conducted using an integrated multi-criteria approach that synthesises morphometric, physiographic, and climatic factors. The methodology involves analysing quantitative morphometric parameters from the dataset, including drainage density, stream frequency, bifurcation ratio, relief, ruggedness index, and shape factors to assess inherent erosion and runoff potential. This geomorphic analysis is then contextualised with qualitative thematic layers: Land Use/Land Cover (LULC) to evaluate anthropogenic pressure and surface permeability; Slope to understand terrain steepness and runoff velocity; Soil type to consider erodibility and infiltration capacity; and Rainfall distribution to account for precipitation input. The Stream Order map provides a spatial validation of the drainage network structure. Each watershed is ranked by interpreting the convergence of high-risk morphometric traits with adverse conditions on other thematic maps, such as steep slopes, erodible soils, intense rainfall zones, and agricultural/barren land covers, to identify areas most vulnerable to soil erosion, flash floods, and land degradation.

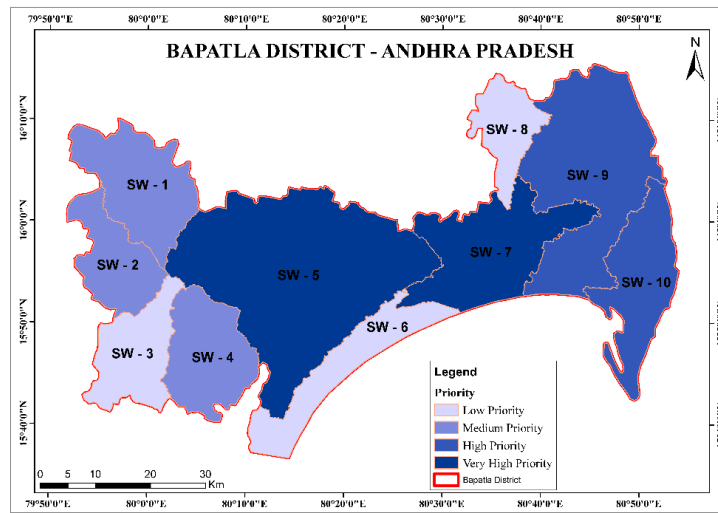


Figure 7: Prioritisation of Sub-Watershed

Priority Rank	Sub-Watershed	Primary Reasons for Ranking
Very High	WS-7	The highest drainage density (0.550) and the highest ruggedness index (38.39) indicate severe erosion susceptibility. Likely coincides with moderate-steep slopes, erodible soils (e.g., Clay Red), and high rainfall, amplifying runoff and sediment yield.
Very High	WS-5	Largest stream network (122 streams) and high stream frequency. Very large area likely containing significant agriculture on variable slopes and soils, leading to high sediment generation and hydrological responsiveness.
High	WS-10	Very high relief (333.6 m) and high ruggedness index (157.9). Expected association with steeper slopes and higher rainfall, making it prone to rapid runoff and erosion, especially if covered with less protective land use.
High	WS-9	High stream frequency (86) and elevated drainage density (0.561). Large area likely under agriculture on mixed slopes, with soils like deep black clay that may be prone to erosion, contributing to significant sediment load.
Medium	WS-1	High absolute relief and dissection index. However, a more elongated shape may attenuate peak flow. Priority is medium as land use and soil type may moderate risk compared to steeper, denser basins.
Medium	WS-4	A high elongation ratio suggests less flashy runoff. Moderate morphometric values. Likely contains mixed land use on gentle to moderate slopes, presenting a balanced, moderate erosion concern.
Medium	WS-2	Moderate values across most morphometric parameters. Expected to have gentle slopes and mixed land use/soil, leading to a medium but notable erosion and runoff risk.

Low	WS-3	Lower drainage density and relief. Likely associated with gentler slopes, stable soils (e.g., loamy), and less intensive land use, indicating lower geomorphic activity.
Low	WS-6	Very low relief and negative dissection index. Likely dominated by very gentle slopes, sandy/stable soils, and land covers like salt pan or sand, resulting in minimal erosion and runoff risk.
Low	WS-8	Lowest stream frequency and very low relief. Small, subdued basin expected on gentle terrain with stable soils and low rainfall impact, presenting minimal vulnerability.

Table 5: Prioritisation Ranking and Reasons for Ranking

The integrated analysis reveals that the highest priority sub-watersheds, WS-7 and WS-5, are critical due to a dangerous convergence of factors. WS-7's exceptionally high drainage density and ruggedness index signify a landscape intensely dissected by channels and highly susceptible to erosion. When this inherent geomorphic vulnerability is combined with the likelihood of steeper slopes, erodible clay-based soils, and areas of higher rainfall as suggested by the thematic maps, the potential for severe soil loss, gully formation, and flash flooding becomes paramount. Similarly, WS-5, with the most extensive stream network, acts as a major sediment conveyor; its vast area, presumed to be dominantly agricultural, represents a significant source area for runoff and pollutants, especially if cultivation practices on sloping land are not managed conservatively.

Sub-watersheds ranked as High and Medium priority, such as WS-10, WS-9, WS-1, WS-2, and WS-4, represent a gradient of risk where certain mitigating factors moderate the threat. WS-10's very high relief makes it energetically prone to erosion, but its actual impact depends on the protective quality of its land cover. WS-9's high stream frequency indicates efficient runoff collection, but its risk is modulated by soil type and slope. The medium-priority basins often benefit from more elongated shapes, which lengthen flow paths and reduce peak discharges, or from gentler terrain that slows overland flow, thereby reducing their immediacy for intervention compared to the very high-priority ones.

Conversely, the low-priority watersheds (WS-3, WS-6, and WS-8) are characterised by physical attributes that inherently suppress erosive processes. Their very low relief, gentle slopes, and likely stable soil types (e.g., sandy or loamy) result in minimal gravitational energy for erosion and better infiltration. Land covers in these areas, such as salt pans, sand, or vegetation, further stabilise the surface. The negative dissection index in WS-6 explicitly indicates a landscape with minimal vertical erosion, affirming its low vulnerability. This triage of watersheds underscores that effective resource allocation for soil and water conservation must focus on areas where aggressive geomorphic processes are activated and amplified by human land use and climatic drivers, rather than on landscapes where natural stability prevails.

Conclusion

This study successfully prioritised the ten sub-watersheds of Bapatla District through an integrated analysis that synthesised quantitative morphometric data with qualitative thematic layers on land use, slope, soil, and rainfall. The comprehensive morphometric assessment, encompassing linear, areal, and relief parameters, provided a foundational understanding of each watershed's inherent hydrological behaviour and erosion susceptibility. The methodology revealed a clear spectrum of geomorphic vulnerability, where specific watersheds emerged as critically sensitive due to the convergence of high-risk traits. Specifically, watersheds like WS-7 and WS-5 were identified as having the highest priority due to their extreme drainage density, extensive channel networks, and high ruggedness, factors which indicate a landscape primed for rapid runoff generation and severe soil erosion.

The final prioritisation underscores the critical importance of a holistic, multi-criteria approach for effective watershed management. The rankings move beyond a simple analysis of size or stream count to interpret how basin shape, terrain steepness, and network structure interact with surface conditions like soil erodibility and land cover. Consequently, the very high and high-priority watersheds represent zones where aggressive geomorphic processes are likely amplified by anthropogenic pressure, necessitating immediate and targeted conservation interventions to mitigate soil loss and flood risk. Conversely, the low-priority watersheds exhibit natural stability through gentle relief and stable soils, allowing for the strategic allocation of limited resources towards areas where intervention will yield the greatest impact on landscape degradation and downstream water quality.

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