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Research Article

Geospatial Technology for estimation of Geomorphological Characteristics of an Ungauged Watershed

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Abstract

A geospatial technology is a powerful tool for managing land and water resources to reduce the effect of natural disasters and achieve long-term development. In the present era, synergetic use of remote sensing (RS) data with the geographical information system (GIS) approach has been shown to be an effective tool for developing and managing water resources. In this study, the geospatial methods were used to analyze the geomorphological characteristics of the Mahendratanaya watershed, which lies between 83°59' to 84°22' E longitude and 19°70' to 18°38' N latitude. It is an ungauged watershed with a geographical area of 1192.14 km2. Different geomorphological characteristics such as linear, areal and relief aspects of the watershed were calculated from a 30 m SRTM DEM using ArcGIS software. The morphometric analysis found that the watershed has 99 stream segments, and stream order varies from 1st to 4th order. The bifurcation ratio and form factor of the watershed was found to be 4.25 and 0.16, respectively. The value of the elongation ratio was found to be 0.45, which showed that the watershed is neither fully elongated nor circular. The watershed has a drainage density value of 0.39 km-1, which indicates that the study area is highly porous. This type of study will help model the hydrologic response of the watershed and the planning & management of water harvesting structures.

Keywords: Geospatial, Ungauged Watershed, Geomorphology, Water Harvesting, And Groundwater Recharge.

1. Introduction

Watersheds are the ideal unit for managing resources such as land and water, mitigating the effects of natural disasters, and attaining long-term development. It's a valuable research and management tool that combines the land's ecological, geographical, geological, and cultural features. The size of a watershed can range from a few hectares to thousands of kilometres square [1].

The geomorphology study can better understand the watershed characteristics (Worcester 1948). Geomorphology studies physical features of the Earth's surface and their relationships to its geological structures. The geomorphology study can help us understand how the hydrologic response (discharge) is linked to surface features [2]. Geomorphometry is a type of analysis used to derive landform parameters, and it is essential for a better understanding of watershed characteristics [3]. The morphometric study can measure the watershed linear, areal, and relief parameters [4].

The traditional techniques of measuring morphological characteristics are time-consuming. With geospatial technology, the morphometric analysis of watershed and their drainage networks can be fast and improve the quality of the results. A lot of information is needed to measure the morphometric properties of the watershed, such as slope, stream network, drainage pattern, and drainage location. These data may be extracted with high accuracy digital elevation models (DEMs), digital topographical maps, and satellite pictures (Moore et al.).

The morphometric investigations include the analysis of streams through the measurement of various network properties, which can be done through the evaluation of drainage characteristics of the watershed. Numerous studies have utilized the morphometric properties of watersheds to anticipate and explain geomorphic processes such as flood peaks, sediment yields, and erosion rates (Gardiner). The current research focuses on estimating the geomorphological parameters of Mahendratanaya watershed using RS & GIS to plan and manage water harvesting structures and modeling the watershed hydrologic response.

2. Materials and Methods

2.1. Study Area

The Mahendratanaya river runs through Odisha and Andhra Pradesh states of India. It is a tributary of the Vansadhara River, one of India's medium rivers that flows from the Durgakangar hills of the Eastern Ghats to the Bay of Bengal. The study area is situated between 19° 37' to 18°38' N latitude and 83°59' to 84°22' E longitude. The elevations vary from 22 m to 1497 m above mean sea level. It is a forest-dominated watershed, with forests covering more than 50% of the watershed. The drainage pattern of the Mahendratanaya watershed is dendritic, with a drainage area of 1192.14 km2. The climate of the study area is sub-humid, with an average annual rainfall of 1925.60 mm. The long-term average minimum and maximum temperatures are about 42˚C and 15˚C, respectively. Fig 1 shows the index map of the Mahendraanaya watershed.

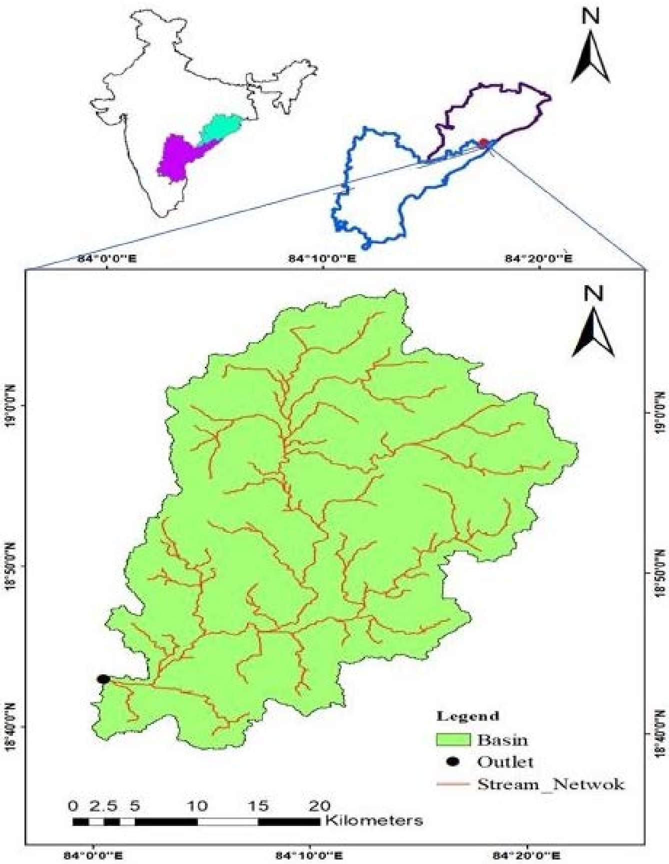

Figure 1: Index Map of Mahendratanya Watershed

2.2. GIS Data

Geographical information system (GIS) is a platform that integrates hardware, software, and data to capture, manage, analyze, and display all forms of geographically referenced data. The collection, storage, analysis, processing, and retrieval of spatial data is called GIS. It's an effective tool for managing and developing water resources locally or nationally. In this present study, for morphometric analysis, the watershed's base map and drainage network map were generated in a GIS environment utilizing Shuttle Radar Topography Mission (SRTM) DEM data.

2.3. Methodology

While deriving geomorphological parameters, computation of the morphological parameters was followed by the usage of mathematical equations to derive geomorphological parameters. For the present study SRTM DEM with 30 m spatial resolution was downloaded from the USGS earth explorer website. Using the Arc Hydro extension tool of ArcGIS, morphological parameters have been calculated from a digital elevation model (DEM) and extracted from attribute tables. The number of streams (Nu) & stream length (Lu) of order u, area (A) & perimeter (P), main channel length (L), elevation, and slope are the basic parameters required to derive the geomorphological parameters. The detailed methodology used to estimate geomorphological parameters has been illustrated in Fig 1.2. first, the geometric correction was done in raw SRTM DEM; then, the DEM was projected in the UTM coordinate system with datum as WGS 1984 (Zone-45N). Then with the help of projected DEM, slope, hillslope, and aspect maps have been prepared. The drainage network has been delineated, followed by filling the sink, flow direction, and flow accumulation steps in the GIS environment. The study area has been extracted through the watershed map using the watershed outlet. Finally, different geomorphological parameters have been estimated using fundamental morphometric analysis.

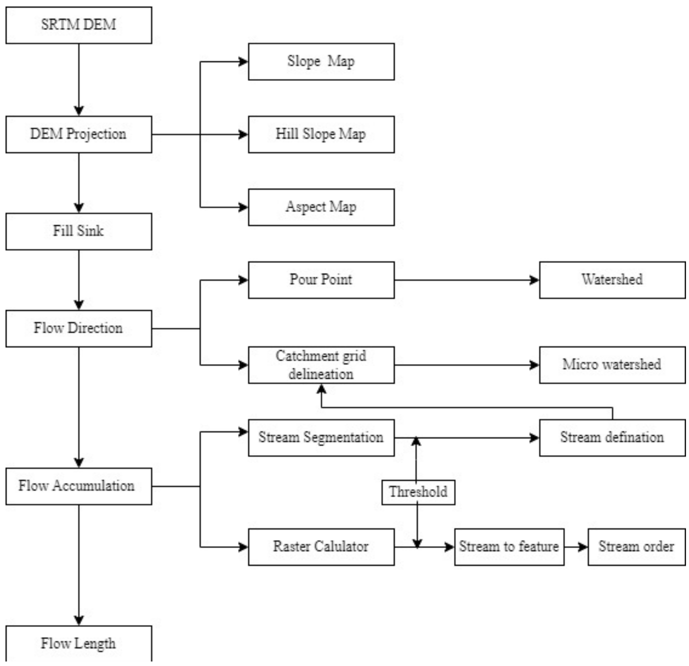

Figure 2: Flow chart for morphometric analysis.

The geomorphological characteristics are classified into linear, areal, and relief aspects. Stream number, stream order, stream length, mean stream length, stream length ratio, bifurcation ratio, and length of overland flow are all linear features. Relief elements include watershed relief, relief ratio, relative relief, and roughness number. In contrast, areal aspects include drainage density, stream frequency, form factor, circulatory ratio, elongation ratio, constant of channel maintenance, and shape factor. Fourteen geomorphological parameters were identified and calculated using morphometric analysis in this present study. Table 1 shows the mathematical equations for calculations of geomorphological parameters.

Table 1: Morphometric parameters of watershed.

S. no	Morphometric Parameters	Symbol	Empirical Formula	Notation	Reference
01	Stream number	N_u	-	Number of stream segments	Strahler (1952)
02	Stream order	U	-	Hierarchical rank	Strahler (1964)
03	Stream length (km)	L_u	-	Length of the stream segment	Horton (1945)
04	Mean stream length	L_{sm}	$L_{sm} = L_u / N_u$	Lu = total stream length of order 'u' Nu = total no. of stream segments of order 'u'	Strahler (1964)
05	Stream length ratio	R_L	$R_L = L_u / L_{u-1}$	Lu = total stream length of order 'u' Lu-1 = total stream length of its next lower order	Horton (1932)
06	Bifurcation ratio	R_b	$R_b = N_u/N_{u+1}$	Nu = total no. of stream segments of order 'u' Nu+1 = number of segments of the next higher order	Schumm (1956)
07	Length of overland flow	R_{bm}	-	Average of bifurcation ratios of all orders	Horton (1945)
08	Drainage density (km/km2)	D_d	$D_d = L_u/A$	Lu = total stream length of order, A = area of the watershed (m2)	Horton (1932)
09	Shape Factor	S	$S= L_b^2/A$	Lb = Length of the watershed, A = Area of watershed	Wolfgang and Desmond 2002
10	Stream frequency (km/km2)	F_s	$Fs = N_u/A$	Nu = total no. of streams of all orders, A = Area of watershed	Horton (1932)
11	Form factor	R_f	$R_f = A/L_b^2$	A = area of the watershed(m2) Lb2 = square of watershed length	Horton (1932)
12	Circularity ratio	R_c	$R_c = 4\pi A/P^2$	A = area of the watershed (m2) P = perimeter (m)	Miller (1953)
13	Elongation ratio	R_e	$R_e = (A/L_b^2)$	A = area of the watershed (m2) Lb = basic length (m)	Strahler (1956)
14	Constant of channel maintenance	C	$C= 1/D_d$	Dd = Drainage density	Schumm (1956)
15	Watershed Relief	H	H = A-B	A= Elevation of highest point B= Elevation of lowest point	Avinash et al., 2011
16	Relief ratio	R_h	$R_h = H/L_b$	H = total relief of the watershed (m) Lb = watershed length (m)	Schumm (1956)
17	Relative relief	R_r	$R_r = (H/P)*100$	H = Watershed Relief P = Perimeter	Melton, 1957
18	Ruggedness number	R_n	$R_n = D_d*H$	Dd = Drainage density, H = Watershed Relief	Strahler (1956)

3. Results And Discussion

Morphometric analysis is used to calculate the different physical characteristics, which helps to understand the watershed's hydrologic response. To fulfill the study's objectives, the morphological parameters of the watershed in the study region were evaluated. The morphometric parameters were quantitatively measured. The morphometric data are derived using attribute data. The basin area is 1192.14 km2, the perimeter of a basin is 278 km, and the length of the main channel is about 85.83 km.

3.1. Linear Aspects

Stream number and Stream order: The first step in drainage basin analysis is the designation of the stream orders based on the hierarchic ranking of the streams. The junction of tributaries determines the stream order, and it is a primary feature of stream networks. This study ranked the drainage watershed's channel segment using Strahler's stream ordering system. The order one tributaries are the smallest/tiniest fingertip tributaries. When two 1st order channels meet, a 2nd order channel segment is generated. When two orders 2nd channels meet, an order 3rd segment is formed, and so on (Strahler). The trunk stream segment is the highest order stream segment through which all the water and debris are discharged [5]. In addition, higher stream order is associated with higher velocity and greater discharge [6]. The highest stream order among the sub-watershed is the fourth-order watershed in the present study. The sub-watershed contains

99 stream segments, including fourth orders of streams, out of which 77 are of 1st order. The 2nd, 3rd & 4th order stream segments are 17, 4 &1, respectively. The higher stream number indicates lesser permeability and infiltration. The first stream order is predominant compared to other hierarchical orders, indicating that the terrain contains steep slopes at various locations and a short flow length in nature. Table 4.1 shows the total number of streams with an order.

Stream length: The stream length has been computed using the method proposed by Horton [7]. The stream length is a direct indicator of drainage density. The stream segment's total length is 475.71 km among them, 1st order occupied the length of 238.28 km, 2nd order about 134.77 km, 3rd order about 52.42 km, and 4th order 50.24 km. Stream lengths of all orders are presented in Table 2. The mean stream length is derived by dividing the total length of the stream order by the number of streams [8]. In the present study, the mean stream length value varies between 3.09 to 50.24 km. Generally, the total length of the stream segment decreases with increasing stream number. The mean stream length segment's summarized value is given order-wise in Table 4.1. The stream length ratio is the ratio of a certain order's mean stream length to the next lower order's mean stream length [7]. The average stream length ratio was observed to be 2.42. The variation in the stream length ratio between stream segments of different order in the study area might be due to the area's changes in topography and slope.

Table 2: Extracted data of stream length with order.

S.no	Stream Order	No of Streams	Stream Length (km)	Mean Stream Length (Km)
1	1	77	238.28	3.09
2	2	17	134.77	7.92
3	3	4	52.42	13.10
4	4	1	50.24	50.24

Bifurcation Ratio (Rb): The bifurcation ratio is determined as the ratio of a particular order's number of streams (Nu) to the next higher order's number of streams (Nu+1) (Schumm, 1956). The mean bifurcation ratio 4.25 in the present study. It is estimated different values for 1st/2nd, 2nd/3rd, and 3rd/4th orders. A higher value of the bifurcation ratio indicates the watershed's low permeability and structural complexity. It is observed that the watershed selected for the present study is neither fully elongated nor circular in shape. A watershed is not circular in shape it may produce delayed peak flow.

Length of Overland Flow: The length of non-channel flow projected to the horizontal from a location on the adjacent stream channel is defined as the length of overland flow [7]. The length of overland flow is the reciprocal of the drainage density [7]. It is primarily influenced by the area's hydrologic and physiographic structures [7]. It indicates the length of time that water flows over the ground before condensing into a definite stream. In the present study, the length of overland flow was 1.25 km, which shows the watershed has fewer structural disturbances with higher overland flow value. The quantitative measurement of linear parameters is given in Table 3.

Table 3: Quantitative measurement of linear parameters.

S. no.	Name of Parameter	Symbol	Quantitative measurement
1	Stream Number	U	99
2	Stream Order	L_u	4
3	Stream Length (in m)	L_{sm}	475.71
4	Mean Stream Length (in m)	R_L	4.81
5	Stream Length Ratio	R_b	2.42
6	Bifurcation Ratio	R_{bm}	4.25
7	Length of Overland Flow	U	1.25

3.2. Areal Aspect

Drainage Density: Drainage density is a significant criterion of the linear characteristic of the watershed. Drainage density denotes the proximity of channel spacing, offering a quantitative estimate of the watershed's average length of the stream channel. The drainage density's low value of less than 5 km/km2 indicates a permeable subsurface. In this study, the drainage density is found as 0.39 km/km2. It shows the terrain is highly permeable with small runoff potential, and it must have dense vegetation with low relief.

Shape Factor: The shape factor gives an indication of the watershed's circular properties. In this study the shape factor 6.19 shows that the watershed's area is less circular and more elongated, the shape factor indicating that it has the shortest watershed lag time. If the shape factor is less than one, then the watershed is circular in nature, with a high peak flow in a short period of time.

Stream Frequency: The total stream segments of all orders per unit area indicated a stream frequency of 0.083 km/km^2. Stream frequency mainly depends upon the region's rainfall

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pattern and depends on the temperature of the region. The value of the stream frequency is positively correlated with the drainage density of the basin watershed, such as if there is an increase in the value of the drainage density there is also an increase in the stream population. Lower values imply minimal structural disturbances in the stream, resulting in a high rate of surface runoff and rapid streamflow from higher-order streams.

Form Factor: The form factor is a key parameter that describes the shape of the watershed. It is calculated as the ratio of the sub-watershed area to the square of the main channel length (length of the watershed). The value of the form factor obtained in this study is 0.16. Lower values imply that the sub-watershed has a more extended shape in nature, with flattened peak flow characteristics for a longer period of time. The smaller value of the form factor indicates that there will be an elongated basin shape with a high peak of a shorter duration. The elongated watershed is more vulnerable to flooding than watersheds with a circular form.

Circulatory ratio: The Circulatory ratio is calculated by dividing the watershed area by the area of a circle with a radius equal to the watershed parameter [9]. The value of the circulatory ratio is affected by the geologic structure, the stream length and frequency, land use and land cover, and the slope of the basin. The circulatory ratio was found to be 0.19 in this study. This value implies that the river watershed is long and that the tributaries are in their early stages.

Elongation ratio: The elongation ratio is an essential parameter for determining the geometry of a watershed. It is the ratio of the diameter of a circle the same size as the watershed to the watershed's greatest length. The different watershed slope of the elongation ratio is classified by the slopes of the watershed such as (0.9-1.0) represents a circular watershed, (0.8-0.9) represents an oval watershed, (0.7-0.8) represents a less elongated watershed, (0.5-0.7) represents an elongated watershed and (< 0.5) represents a more elongated watershed. In this study, the elongation ratio is found to be 0.45 which indicates a more elongated shape of the watershed. This shows that the watershed has a large infiltration capacity, stream flow component, high relief, and a steep slope.

Constant of Channel Maintenance: It is defined as the inverse function of drainage density that emphasizes the amount of area in km2 needed to generate a 1km stream. There are serval factors that affect the constant of channel maintenance, such as lithological properties, the permeability & infiltration characteristic of the soil, climatic variables, and land cover of the area [10]. It is expressed in km2 per km. It is found to be 2.506 km2 per km it may be due to the high erodible factor of the study area that means to sustain 1km of channel length 2.506 km2 area is required. The quantitative measurement of areal parameters of the Mahendratanaya watershed are given in Table 4.

Table 4: Quantitative measurement of areal parameters

S. no	Name of Parameter	Symbol	Quantitative measurement
1	Drainage Density	D_d	0.399
2	Shape Factor	S	6.179
3	Stream Frequency	F_s	0.083
4	Form Factor	R_f	0.161
5	Circulatory Ratio	R_c	0.193
6	Elongation Ratio	R_e	0.453
7	Constant of Channel Maintenance	C	2.506

3.3. Relief Aspect

Slope: Watershed slope information is considered an independent variable, and it radically influences the value of time of concentration and directly the runoff generated by the rainfall. In the study the slope of the watershed varies between 0-64.95 percent (Fig. 3.)

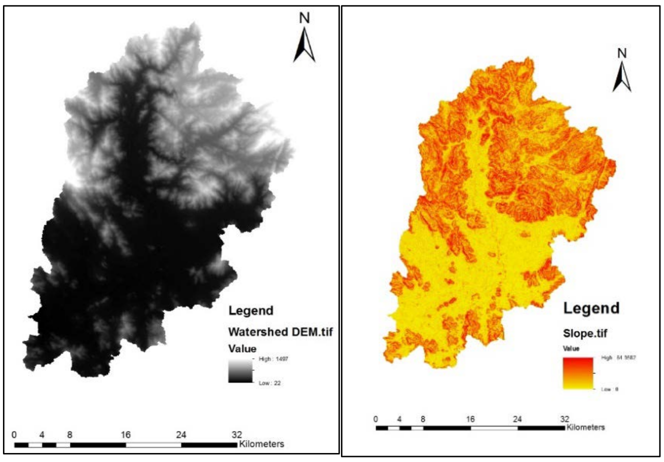

Figure 3: Digital Elevation Model and slope map of Mahendratanaya watershed

Aspect Map: The horizontal direction in which the slope of the surface faces is referred to as its aspect. Surface features can have a considerable impact on the local climate. The compass direction of aspect on the output raster map runs from 0˚ to 360˚, with 0˚ representing true north and 90˚representing east, 180˚ representing south, and so on. The aspect map's visual interpretation is shown in Fig. 4.

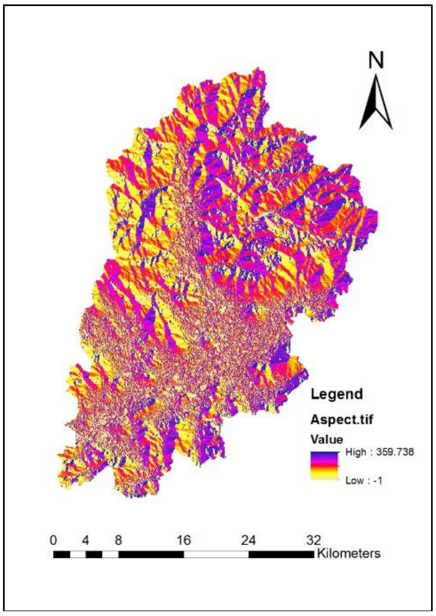

Figure 4: Aspect Map of Mahenndratanaya watershed

Maximum Relief: It is the vertical distance between the watershed's highest and lowest point., which indicates the time required for flow accumulation. In this study watershed relief is found as 1475 km, indicating that there is less time for flow accumulation results more runoff.

Relief Ratio: The overall stiffness of the river watershed is described by the relief ratio, which is the primary measure of the intensity of erosion in the watershed. A higher number implies that the area is in a hilly area, while the lower value suggests that the watershed is in a valley area. The relief ratio computed from the study area is 17.18, and this lower value indicates moderate relief and a gentle slope in the watershed.

Relative Relief: Relative relief is the ratio of relief to the perimeter of the watershed. In this study, the relative relief is found to be 5.30. Due to irregular terrain, the watershed length is significantly less than the length of the main channel, and there is a wide range of steepness along with the point of origin of stream segments [11-18].

Ruggedness Number: It is the function of drainage density and watershed relief (Strahler). It represents the terrain's structural complexity with relief and drainage density. The ruggedness number value is 588.58, indicating moderate stream velocity because the relief parameters have higher values. The quantitative measurement of relief parameters of the Mahendratanaya watershed are given in Table 3

Table 5: Quantitative measurement of relief parameters.

S. no.	Name of Parameter	Symbol	Quantitative measurement
1	Maximum Relief (km)	H	1475
2	Relief Ratio	R_h	17.185
3	Relative Relief	R_r	5.305
4	Ruggedness Number	R_n	588.58

4. Summary and Conclusions

The present study used geospatial technology in the Mahendratanaya watershed delineation and morphometric analysis. basic morphometric parameters were calculated with the different processes such as flow direction, flow accumulation, and flow length watershed delineation using Arc Hydro tool of ArcGIS software. The morphometric results show that the watershed's area, perimeter, and length are 1192.14 km2, 278 km, and 87.11 km, respectively. The total number of streams is 99. The highest order of the stream is 4th order. The bifurcation ratio value reveals that the watershed is neither fully elongated nor circular in nature. The drainage density value is found to be 0.39, which indicates the high permeability of terrain with small runoff potential. The watershed's form factor and the circulatory ratio is 0.16 and 0.19, respectively. The elongation ratio of watershed is 0.45 and the length of overland flow is 1.25. The watershed's maximum relief, relative relief, and relief ratio is 1475 km, 5.30 and 17.18, respectively. The study will be helpful in modelling the hydrologic response of the watershed and the planning & management of water harvesting structures.

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