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Geomorphometric analysis of a hilly watershed in north east India

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ABSTRACT

Morphometric analysis of a hilly watershed was carried out using GIS. The drainage map generated from the Survey of India toposheets was used for morphometric analysis of the watershed in terms of stream order, stream length, bifurcation ratio, relief ratio, drainage density, stream frequency, drainage texture, form factor, circulatory ratio, elongation ratio, infiltration number and ruggedness number. The Um Shipra watershed is a fifth order watershed having dendritic drainage pattern with high drainage density (6.22 km.km^{-2}). The logarithmic plot of the stream length versus stream order showed a linear relationship indicating the watershed has developed over a homogeneous rock material. The mean bifurcation ratio of 1.71 indicated absence of strong structural control on the drainage pattern and that the watershed was structurally less disturbed. The number of streams belonging to the order I, II, III, IV and V were found to be 327, 147, 78, 45 and 46 respectively. Lower values of form factor (0.19), circularity ratio (0.29) and elongation ratio (0.49) suggested that the watershed has elongated shape with lower peak flows for longer duration. The ruggedness number having relatively higher value implied that the area has rugged topography which is prone to soil erosion. Higher values of stream frequency and drainage density indicated that the watershed has high runoff potential despite having lower peak flow creating a good scope for surface water resource development. The results obtained can serve as a useful input for developing soil and water resources conservation and management plan on a watershed basis.

Highlights

- Geomorphometric analysis of a hilly watershed was carried out in a GIS environment.
- Analysis of the morphometric parameters indicated that the watershed has undulated terrain, is prone to erosion and has high runoff potential with lower peak flow offering a good scope for development of surface water resources.

Keywords: Geomorphometric analysis, GIS, hilly watershed, drainage density, stream frequency

A watershed is an ideal unit for management of natural resources such as land and water without causing their further degradation for achieving sustainable development. For effective planning and development of a watershed, quantitative information on its physiography, drainage, geomorphology, soil, land use/land cover, water resources is a pre-requisite. Morphometric analysis provides quantitative description of a basin or watershed which is essential for watershed planning and development (Strahler 1964, Kumar *et al.*, 2012, Panhalkar *et al.*, 2012, Yasmin *et al.*, 2013). Evaluation of the morphometric parameters requires preparation of drainage map, ordering of various streams, measurement of the catchment area and perimeter, channel length, drainage density and a host of other parameters which help in understanding the nature of the drainage basins (Sridhar *et al.*, 2012). Geographical Information System (GIS) techniques provide a powerful environment and tool for analysis, manipulation and extraction of spatial information for better understanding. It has been used to assess various terrain and morphometric parameters of drainage basins and watersheds (Chopra *et al.*, 2005, Kar *et al.*, 2009, Sharma *et al.*, 2010, Sridhar *et al.*, 2012, Wandre and Rank 2013, Aher *et al.*, 2014). Narendra and Nageswara Rao (2006) carried out morphometric analysis of Meghadrigedda watershed, Andhra Pradesh, using GIS and Resourcesat-I data, while, Vincy *et al.*, (2012) characterized the morphometric parameters of two sub-watersheds of Meenachil River in the western ghats of Kerala using GIS tools. In the present study, morphometric analysis of the Um Shipra watershed located in Ri-Bhoi district of Meghalaya state in the north eastern part of India using GIS has been carried out with an objective to study the drainage characteristics of the watershed.

Materials and Methods

Study Area

The Um Shipra watershed lies between 25° 40′ 14″ to 25° 44′ 10″ N latitudes and 91° 54′ 12″ to 92° 0′ 19″ E longitudes in Ri-Bhoi district, Meghalaya (Figure 1) and has a total area of 23.85 km^2. The watershed is characterized by humid, subtropical climate with an annual average rainfall of 2416 mm, 80% of which is received during the months of May to October (Tomar and Satapathy 2000. The mean monthly maximum and minimum temperatures normally range from 20.9 to 27.4°C and 6.7 to 18°C, respectively.

Geologically, the watershed is a part of the Shillong plateau, which tectonically falls in the Central Assam Range. It is an old land surface made up of mostly pre-Cambrian metamorphic and igneous rocks. The main rock formations of the study area are metamorphosed conglomerates, phyllites and quartzites of the Shillong series (Tomar and Satapathy 2000. The watershed being a part of the Khasi hills has an undulating topography comprising of rolling hills with steep slopes interspersed with valleys and plateaus.

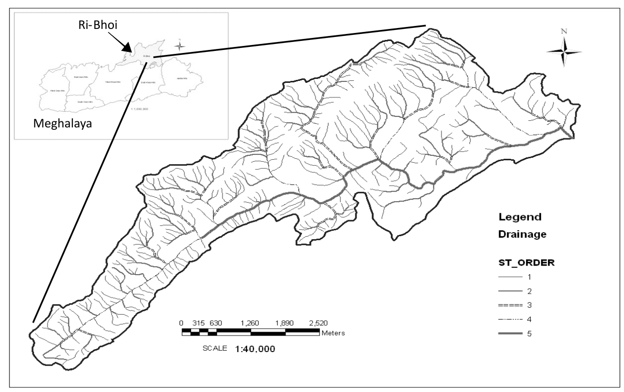


Figure 1. Location and drainage map of Um Shipra watershed showing streams of different orders

Soil erosion is an inherent problem because of steep hill slopes and high intensity of rainfall. The erosion has been further aggravated due to the prevalence of Jhum (Slash and burn agriculture) and Bun cultivation (Raised bed method in which the beds are made along the slopes) on the hill slopes. Though the watershed receives plenty of rainfall during the monsoon season (more than 2000 mm), due to steep slopes much of it is lost as surface runoff and only a meager amount infiltrates into the ground. Streams are the major source of drinking water for the people living in the nearby villages, as well as, for irrigation and livestock uses.

Methodology

The watershed boundary and the associated drainage network from the Survey of India toposheets of 1:25,000 scale was digitized using the ArcGIS software (Ver. 8.3) and the attributes were assigned to create a digital database. Using the hierarchical ranking method (Strahler 1964) the stream orders were assigned and the digital database was updated with stream order as one of the attribute data for the drainage layer. From the digitized boundary and drainage lines, a drainage map (Figure 1) of the watershed was generated at 1:40,000 scale. The information on watershed area, perimeter, basin length, relief, length of streams, stream order was then used to compute the morphometric parameters of the watershed using the standard formulae (Horton 1932, 1945, Miller 1953, Schumm 1956, Strahler 1964, Chopra *et al.*, 2005, Singh 2006) as given in Table 1.

Table 1. Formulae adopted for computation of morphometric parameters

Morphometric Parameters	Formula
Stream Order	Hierarchical rank
Stream Length (L_u)	Length of the stream
Mean Stream Length (Ls_m)	$Lsm = L_u/N_u$ Where, Ls_m = Mean stream length L_u = Total stream length of order 'u' N_u = Total number of stream segments of order 'u'
Stream Length Ratio (R_l)	$R_l = L_u/ L_{u-1}$ Where, L_u = Total stream length of order 'u' L_{u-1} = Total stream length of its next lower order
Bifurcation Ratio (Rb)	$Rb = N_u/ N_{u+1}$ Where, N_u = Total no. of stream segments of order 'u' L_{u-1} = no. of stream segments of the next higher order
Mean Bifurcation Ratio (Rb_m)	Rb_m = Average of bifurcation ratios of all orders
Relief Ratio (R_h)	$Rh = H/L_b$ Where, R_h = Relief ratio H = Total relief of the basin in km L_b = Basin length
Drainage Density (D)	$D = L_u/A$ Where, D = Drainage density L_u = Total stream length of all orders A = Area of the basin (km^2)
Stream Frequency (F_s)	$F_s = N_u/A$ Where, F_s = Stream frequency N_u = Total no. of streams of all orders A = Area of the basin
Drainage texture (R_t)	$R_t = N_u/P$ Where, R_t = Drainage texture N_u = Total no. of streams of all orders P = Perimeter of the basin (km)

Form Factor (R_f)	$R_f = A/(L_b)^2$ Where, R_f = Form factor A = Area of the basin L_b = Basin length
Circularity Ratio (R_c)	$Rc = 4* \pi *A/(P)^2$ Where, R_c = Circularity ratio π = 3.14 A = Area of the basin P = Perimeter of the basin
Elongation Ratio (R_e)	$R_e = (2* \sqrt{(A/3.14)}\ )/L_b$ Where, R_e = Elongation ratio A = Area of the basin L_b = Basin length
Infiltration Number (I_f)	$I_f = D*F_s$ Where, I_f = Infiltration number D = Drainage density F_s = Stream frequency
Ruggedness Number (N_d)	$Nd = H*D$ Where, N_d = Ruggedness number H = Total relief of the basin in km D = Drainage density

Results and Discussion

In the present study, morphometric analysis of the watershed was carried out in terms of the parameters, namely, stream order, stream length, bifurcation ratio, relief ratio, drainage density, stream frequency, drainage texture, form factor, circulatory ratio, elongation ratio, infiltration number and ruggedness number. The results of the analysis have been presented has been presented in Table 2.

The ranking of streams into different orders is the first step in drainage basin analysis and was carried out based on the hierarchical method proposed by Strahler (1964). A perusal of Table 2 indicates that there are 643 stream segments of different orders and the Um Shipra watershed can be designated as a fifth order watershed having dendritic drainage pattern. The order of streams is closely governed by the slope conditions. The higher order streams are associated with flat topography, while, streams of lowest orders are found in steeper slopes. According to Singh (2006), lower the stream order, higher is the number of streams. In the present study, a similar relationship between the stream order and number of streams was observed (Table 2). A logarithmic plot of the number of streams of a given order against the order (Figure 2a) showed a linear relationship with small deviation of the plotted points from the straight line which is in accordance to the law of stream numbers proposed by Horton (1945). Similar relationship has also been observed by Subba Rao (2009) and Thakuriah *et al.*, (2012).

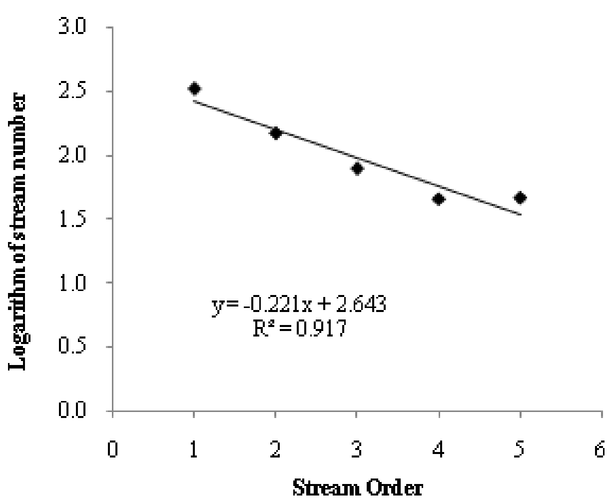
Table 2. Morphometric parameters of Um Shipra Watershed

Stream order	Area (A) (km^2)	Stream Order (N_u)					Stream Length (L_u) (km)					Perimeter (P) (km)	Basin Length (L_b) (km)
		I	II	III	IV	V	I	II	III	IV	V		
V	23.85	327	147	78	45	46	89.00	29.14	12.63	8.77	8.68	32.15	11.32

Mean Stream Length (Ls_m) (km)					Stream Length Ratio (R_l)				Total relief (H)	Relief Ratio (R_h)	Elongation Ratio (R_e)	Drainage Texture (R_t)
I	II	III	IV	V	II/I	III/II	IV/III	V/IV				
0.27	0.20	0.16	0.19	0.19	0.33	0.43	0.69	0.99	0.50	0.04	0.49	20.00

Bifurcation Ratio (R_b)				Mean Bifurcation Ratio (Rb_m)	Drainage Density (D) (km. km^{-2})	Stream Frequency (F_s)	Form Factor (R_f)	Circularity ratio (R_c)	Infiltration Number (I_f)	Ruggedness Number (N_d)
I/II	II/III	III/IV	IV/V							
2.22	1.88	1.73	0.98	1.71	6.22	26.97	0.19	0.29	167.61	3.11

The stream length (L_u) is the total length of streams in a particular order. Generally, the total length of stream segments in the first order is highest and decreases as the stream order increases. The logarithmic plot of stream length of a given order versus stream order (Figure 2b) showed a linear pattern indicating the watershed so developed over a homogeneous rock material and subjected to weathering and erosion (Narendra and Rao 2006). Similar relationships have also been reported by Vandana (2013) and Yasmin *et al.*, (2013). The mean stream length of a channel is a dimensional property and reveals the characteristic size of drainage network components and its contributing basin surfaces (Strahler 1964). Table 2 indicates that the mean stream length for the watershed ranged from 0.16 to 0.27. The mean stream length of any given order is greater than that of lower order. However in the present study, there was a deviation from the trend which may be due to variation in slope and topography prevalent in a hilly watershed system.



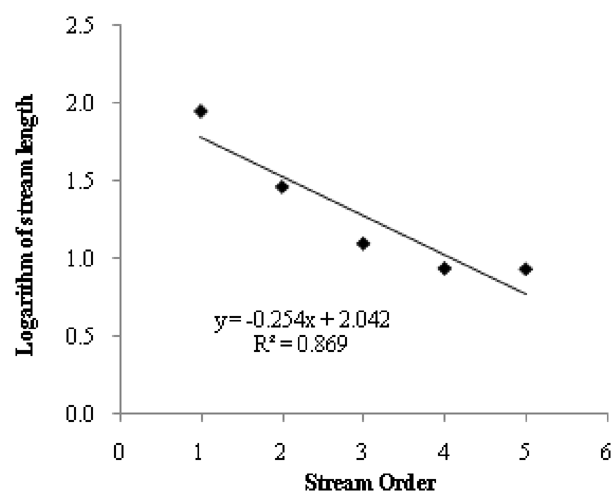


Figure 2. Logarithmic plot of (a) stream numbers vs. stream order (b) stream length vs. stream order for Um Shipra watershed.

The bifurcation ratio (R_b) is an index of relief and dissections (Horton 1945) and lower values are characteristics of structurally less disturbed watersheds without any distortion in drainage pattern (Nag 1998). According to Strahler (1964), R_b values of 3-5 indicated that the geological structures do not have a dominant control over the drainage pattern of the watershed. In the present study, the mean bifurcation ratio of 1.71 indicated the absence of strong structural control on the drainage pattern and that the watershed was structurally less disturbed. Similar finding has also been reported by Subba Rao (2009). Higher values of R_b between the first and the second order streams (Table 2) indicated that the steeper slopes of the watershed is more prone to soil erosion. Kumar *et al.*, (2012) observed that higher values of bifurcation ratios for the first and second order streams indicated more chances of erosion in the upper reaches of a mountainous watershed in Uttarakhand, India. In our study also, we observed higher bifurcation ratios for the first and second order (I/II =2.22 and II/III = 1.88) streams, which highlighted susceptibility of the upper reaches in the watershed to erosion.

Relief ratio (R_h) is the ratio of the maximum relief to the horizontal distance along the longest dimension of the basin parallel to the principal drainage line (Schumm 1956). It is a measure of the overall steepness of a drainage basin and is an indicator of the intensity of the erosion processes operating on the slopes of the basin. Its value normally increases with decreasing drainage area and size of a given drainage basin. For Um Shipra watershed the value of R_h was found to be 0.04.

The drainage density (D) expresses the closeness of spacing of channels and is affected by factors which control the characteristic length of streams like resistance to weathering, permeability of rock formation, climate, vegetation, etc. It also provides a numerical measurement of land dissection and runoff potential. In general, low value of D is observed in regions underlain by highly resistant permeable material with vegetative cover and low relief. High drainage density is observed in regions of weak and impermeable subsurface material with sparse vegetation and mountainous relief (Chopra *et al.*, 2005). Smith (1950) had classified drainage density into three classes i.e. low (D<1.5 km.km^{-2}), medium (1.5-2.5 km.km^{-2}) and high (>2.5 km.km^{-2}). A high drainage density of 6.22 km.km^{-2} suggested that the region was composed of weak and impermeable subsurface materials, sparse vegetation and mountainous relief with high runoff potential.

A perusal of Table 2 reveals that lower values of form factor and elongation ratio, as well as, circularity ratio indicated the watershed to be elongated in shape having flatter peak flow of longer duration. Flood flows of such basins can easily be managed than those of a circular basin (Sharma *et al.*, 2012, Wandre and Rank 2013). Ruggedness number (R_n) of 3.11 indicated that the area has very rugged topography. It also implied that the area is prone to soil erosion. The stream frequency (F_s) is closely related to the permeability, infiltration capacity and relief. The value of F_s for the watershed was found to be 26.97, which indicated high relief and low infiltration of the bed rock and consequent high runoff. As a result, despite of having flatter peak flow, the runoff potential of the watershed is high, which is further supported by the fact that it has a high drainage density (6.22 km.km^{-2}). High value of infiltration number (167.61) suggested that there is adequate scope for surface and ground water development (Singh 2006).

Conclusion

The watershed exhibited a dendritic drainage pattern with high drainage density indicating that the area is composed of weak and impermeable subsurface materials with sparse vegetation and mountainous relief having high runoff potential. Relatively lower value of bifurcation ratio indicated the absence of strong structural control on the drainage. A plot of the logarithms of the stream length of a given order against the order showed a linear relationship indicating the watershed has developed over a homogeneous rock material. Lower values of form factor, circularity ratio and elongation ratio suggested that the watershed is elongated in shape and has lower peak flows for longer duration. The ruggedness number having relatively higher value implied that the area has rugged topography and is prone to soil erosion. Higher values of stream frequency and drainage density indicated that the watershed has high runoff potential despite having lower peak flow creating good scope for surface water resource development. The ground water prospects are limited in the watershed except in few areas like valley fills, river terraces and flood plains. The quantitative analysis of the morphometric parameters thus provides an understanding of the useful hydrologic characteristics of the watershed like infiltration capacity, surface runoff, peak flow, etc. The results obtained can therefore, serve as useful input for developing a comprehensive soil and water resources conservation and management plan on a watershed basis.

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