

GIS based morphometric evaluation of Chimmini and Mupily watersheds, parts of Western Ghats, Thrissur District, Kerala, India

N. S. Magesh · K. V. Jitheshlal · N. Chandrasekar ·
K. V. Jini

Received: 28 July 2011 / Accepted: 23 May 2012 / Published online: 29 May 2012
© Springer-Verlag 2012

Abstract GIS and Remote Sensing have proved to be an indispensable tool in morphometric analysis. The identification of morphometric properties based on a geographic information system (GIS) was carried out in two watersheds in the Thrissur district of Kerala, India. These watersheds are parts of Western Ghats, which is an ecologically sensitive area. Quantitative geomorphometric analysis was carried out for the Chimmini and Mupily watersheds independently by estimating their (a) linear aspects like stream number, stream order, stream length, mean stream length, stream length ratio, bifurcation ratio, length of overland flow, drainage pattern (b) aerial aspects like circulatory ratio, elongation ratio, drainage density and (c) relief aspects like basin relief, relief ratio, relative relief and ruggedness number. The drainage areas of Chimmini and Mupily watersheds are 140 and 122 km² respectively and show patterns of dendritic to sub-dendritic drainage. The Chimmini watershed was classified as a sixth order drainage basin, whereas Mupily watershed was classified as a fifth order basin. The

stream order of the basin was predominantly controlled by physiographic and structural conditions. The increase in the stream length ratio from lower to higher order suggests that the study area has reached a mature geomorphic stage. The development of stream segments is affected by rainfall and local lithology of the watersheds. The slope of both watersheds varied from 0° to 50° and 0° to 42° respectively and the slope variation is chiefly controlled by the local geology and erosion cycles. Moreover, these studies are useful for planning rain water harvesting and watershed management.

Keywords Morphometric analysis · GIS · Chimmini and Mupily watersheds · Western Ghats · Watershed management · Kerala

Introduction

In recent years, Remote Sensing and Geographic Information System (GIS) employed in the determination of drainage basin parameters has been shown to be efficient, time saving and an ideal application for the hydrological investigation. Watershed is defined as a geohydrological unit draining to a common point by a system of drainage network. The quantification of river networks was introduced by Horton (1932, 1945) who studied the origin of river networks. Morphometric analysis of a watershed provides a quantitative description of the drainage system which is an important aspect of characterization of watersheds (Strahler 1964). Morphometric features such as basin shape and basin relief influence the nature of hydrographs and hydrological variables. Drainage pattern provides information on the topography and underlying geological structure. Drainage density varies with relative age, differing geology, drainage area etc and enables comparisons of basins and streams.

Communicated by: Hassan A. Babaie

N. S. Magesh (✉) · K. V. Jitheshlal · N. Chandrasekar
Centre for Geotechnology, Manonmaniam Sundaranar University,
Tirunelveli, Tamil Nadu, India 627012
e-mail: mageshissivan@gmail.com

K. V. Jitheshlal
e-mail: kvjitheshlal@gmail.com

N. Chandrasekar
e-mail: profncsekar@gmail.com

K. V. Jini
Department of Geology and Environmental Science,
Christ College,
Irinjalakuda,
Thrissur, Kerala, India 680125
e-mail: kvjini@gmail.com

The emerging trends in the applications of computers especially in mapping, development of information systems made the quantitative approach for surface characterization and the mechanism for the interpretation and manipulation of the quantitative data sets easy. Moreover, the advantages of this digital earth concept over the conventional methods are its ability to create, manipulate, store, and use spatial data much faster and at a rapid rate. The present study employed the same concept on a watershed level and this paper primarily focuses on the description and nature of spatial variations of physical characteristics of the drainage systems of the Chimmini and Mupily watersheds, in order to describe and evaluate the linear, areal and relief characteristics, using data aggregated from Survey of India (SOI) toposheets (1:50000) and corresponding SRTM data (spatial resolution: 90 m).

The morphometric parameters were extracted for the Chimmini and Mupily watersheds of Thrissur district, Kerala. The calculated values were mapped and analyzed using statistical methods and GIS in order to characterize the stream networks and drainage basin systems. The results obtained on the basis of drainage basin analysis provide information for an improved understanding of the hydrological characteristics of the Chimmini-Mupily area.

Study area

The study area, Chimmini and Mupily watersheds are located in the Thrissur district of Kerala, stretching geographically between 76° 21' and 76° 33' E longitudes and 10° 19' and 10° 29' N Latitudes and covers an area of 140 and 122 km² respectively (Fig. 1). The study area has high relief and steep slopes. The Drainage pattern is dendritic to sub-dendritic, which is characterized by irregular branching of tributary system in many directions joining the main channel. The geology of the study area is characterized by archaic crystalline formation (Gneiss, Schist, Charnokite), Tertiary formations sub recent laterite and recent riverine alluvium.

The study area experiences typical tropical climate for the better part of the year and characterized by wet type of climate and four types of seasons are identified. The hot summer season from March to May, the southwest monsoon season from June to September, the northeast monsoon season from October to December, and a general cool and salubrious climate period during January to February. More than 73 % of the total rainfall in the study area occurs during period of June to September (SW monsoon), 16 % during October to December (NE monsoon), 9 % is received during March to May and the remaining 1 % is accounted for January and February months. The average annual rainfall in the study area ranges between 2,180 and 3,484 mm. The temperature of the area varies from 22° to 36 ° C. The most of the study area is covered by tropical wet evergreen and tropical moist deciduous forest.

Methodology

In order to create the appropriate information platform upon which to proceed in a systematic way towards determining the morphometric parameters, the topographic maps were collected and used as the basis for the creation of several GIS thematic layers.

The base maps of the Chimmini and Mupily watersheds were prepared based on Survey of India topographic maps on a 1:50000 scale and also with SRTM data. The drainage networks were traced and digitized from topographic maps. The second principal component derived from the processing of a SRTM data of the study area, with a spatial resolution 90 m. The Consultative Group for International Agriculture Research Consortium for Spatial Information (CGIAR-CSI) Geoportal was able to provide SRTM 90 m Digital Elevation Data for the entire world. Global Mapper[®] software was used for delineating the study area and exporting the information to DEM format. The SRTM DEM data was then imported to ArcGIS[®] 10. As a result, significant geomorphological parameters such as contours, slope gradient and aspect have been quantified.

The Drainage networks of the watersheds were scanned from the Survey of India (SOI) Toposheets No. 58B/7 and 58B/11 (1:50000) and digitized in ArcGIS[®] 10 platform. The ordering of the digitized streams was performed in GIS according to Strahler's system (Strahler 1957, 1964). The Drainage network of the basin is analysed as per the Laws of Horton (1945). In this classification, streams with no tributaries are defined as first order; two first-order streams join to form a second-order stream, etc. In general, two streams of the same order join to form a stream with a stream order increased by one.

The basic watershed characteristics (basin area, perimeter, cumulative length of streams and basin length) were measured in the GIS environment. Morphometric parameters such as stream frequency, drainage density, texture ratio, form factor, bifurcation ratio, length of over land flow, elongation and circulatory ratios were evaluated with mathematical equations (Strahler 1964). The extracted values and the formulae used to calculate them are shown in Table 1.

Result and discussion

Morphometry is the measurement and mathematical analysis of the configuration of the earth's surface, shape and dimensions of its landform (Clarke 1996). The present study emphasizes the use of GIS and remote sensing for morphometric analysis and the results are discussed below.

The SRTM DEM has been obtained with a pixel size of 90 m which covers the two watersheds (Fig. 2). Furthermore, the DEM has been used to calculate slope, contour and aspect

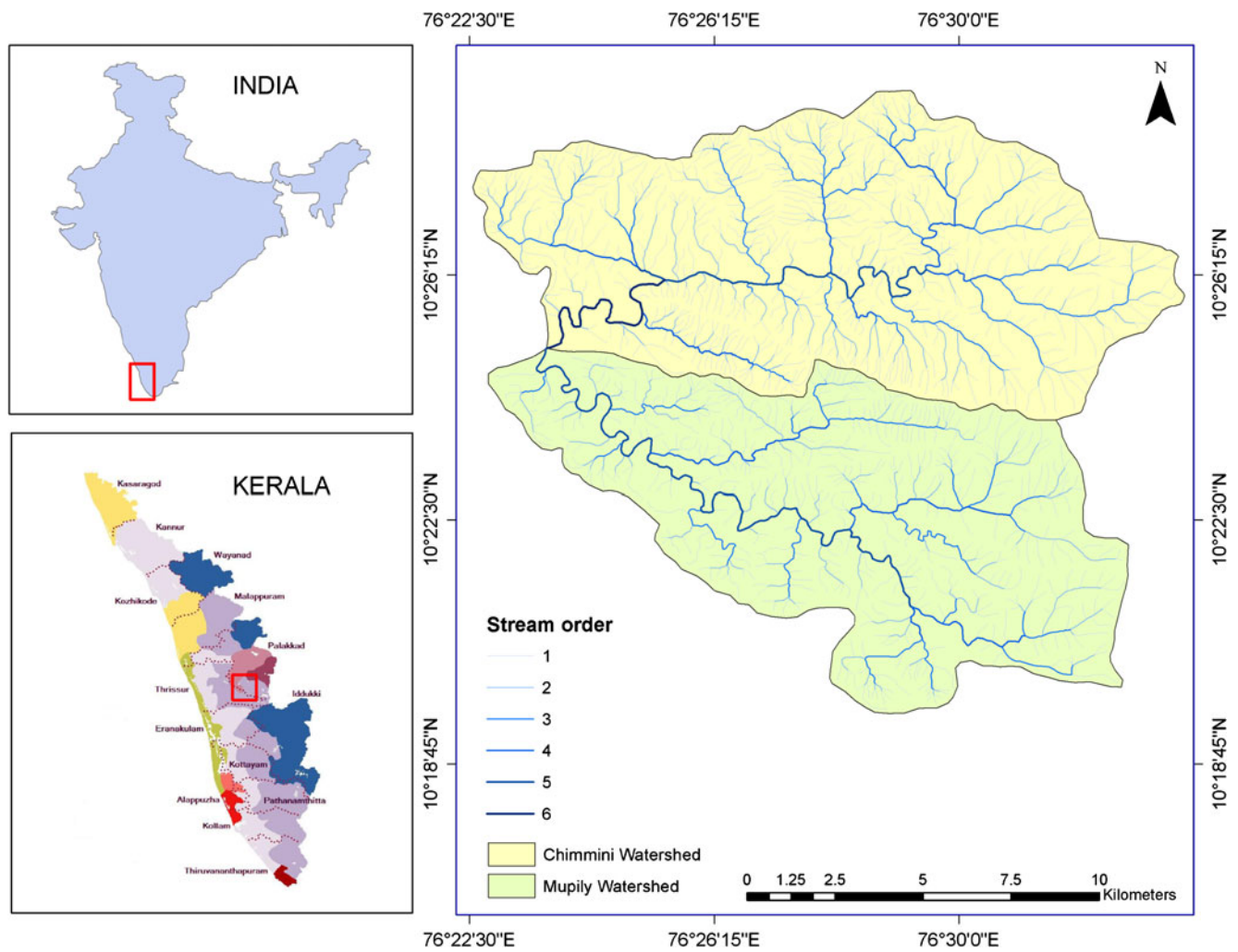
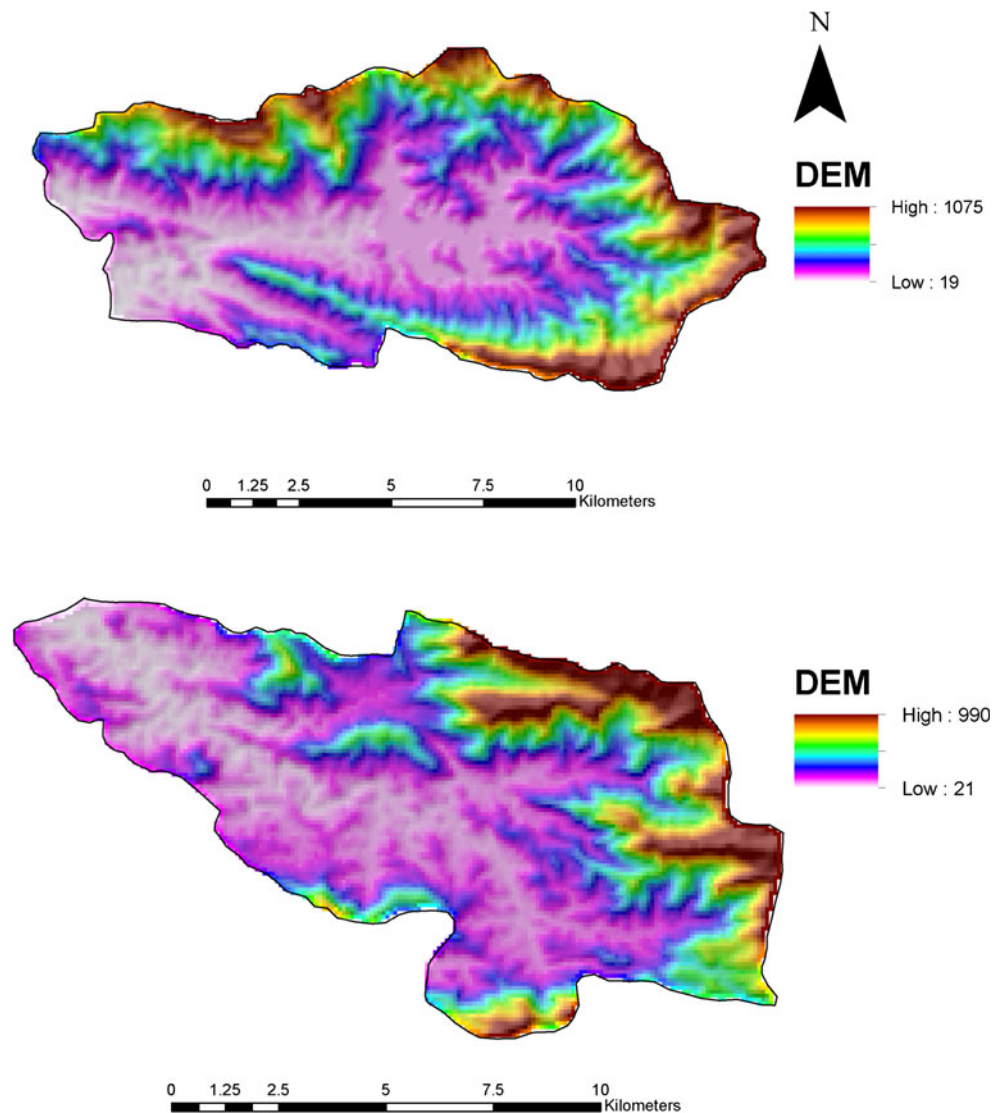


Fig. 1 Location of the study area with stream networks

Table 1 Linear relief and areal morphometric parameters

S. No.	Parameters	Formulae	References
1	Stream Order (U)	Hierarchical rank	Strahler (1964)
2	Stream Length (Lu)	Length of the stream	Horton (1945)
3	Mean Stream Length (Lsm)	$Lsm = Lu/Nu$	Strahler (1964)
4	Stream Length Ratio (RL)	$RL = Lu/(Lu-1)$	Horton (1945)
5	Bifurcation Ratio (Rb)	$Rb = Nu/Nu + 1$	Schumm (1956)
6	Mean Bifurcation Ratio (Rbm)	Rbm = average of bifurcation ratios of all order	Strahler (1957)
7	Drainage density (Dd)	$Dd = Lu/A$	Horton (1945)
8	Drainage texture (T)	$T = Dd \times Fs$	Smith (1950)
9	Stream Frequency (Fs)	$Fs = Nu/A$	Horton (1945)
10	Elongation ratio (Re)	$Re = D/L = 1.128\sqrt{A/L}$	Schumm (1956)
11	Circularity ratio (Rc)	$Rc = 4\pi A/P^2$	Strahler 1964
12	Form factor (Ff)	$Ff = A/L^2$	Horton (1945)
13	Length of overland flow (Lg)	$Lg = 1/D \times 2$	Horton (1945)
14	Relief	$R = H-h$	Hadley and Schumm (1961)
15	Relief Ratio	$Rr = R/L$	Schumm (1963)

Fig. 2 DEM map of Chimmini and Mupily watersheds



maps. The development of drainage networks depends on geology, and precipitation apart from exogenic and endogenic influences. The drainage pattern of the basin is dendritic to sub-dendritic. Based on the drainage order, Chimmini and Mupily watersheds are classified as sixth and fifth order basins respectively in order to interpret the morphodynamic parameters listed in Table 1. (Horton 1932, 1945; Smith 1950; Schumm 1956, 1963; Hadley and Schumm 1961; Strahler 1964; Sreedevi et al. 2005; Mesa 2006).

Aspect

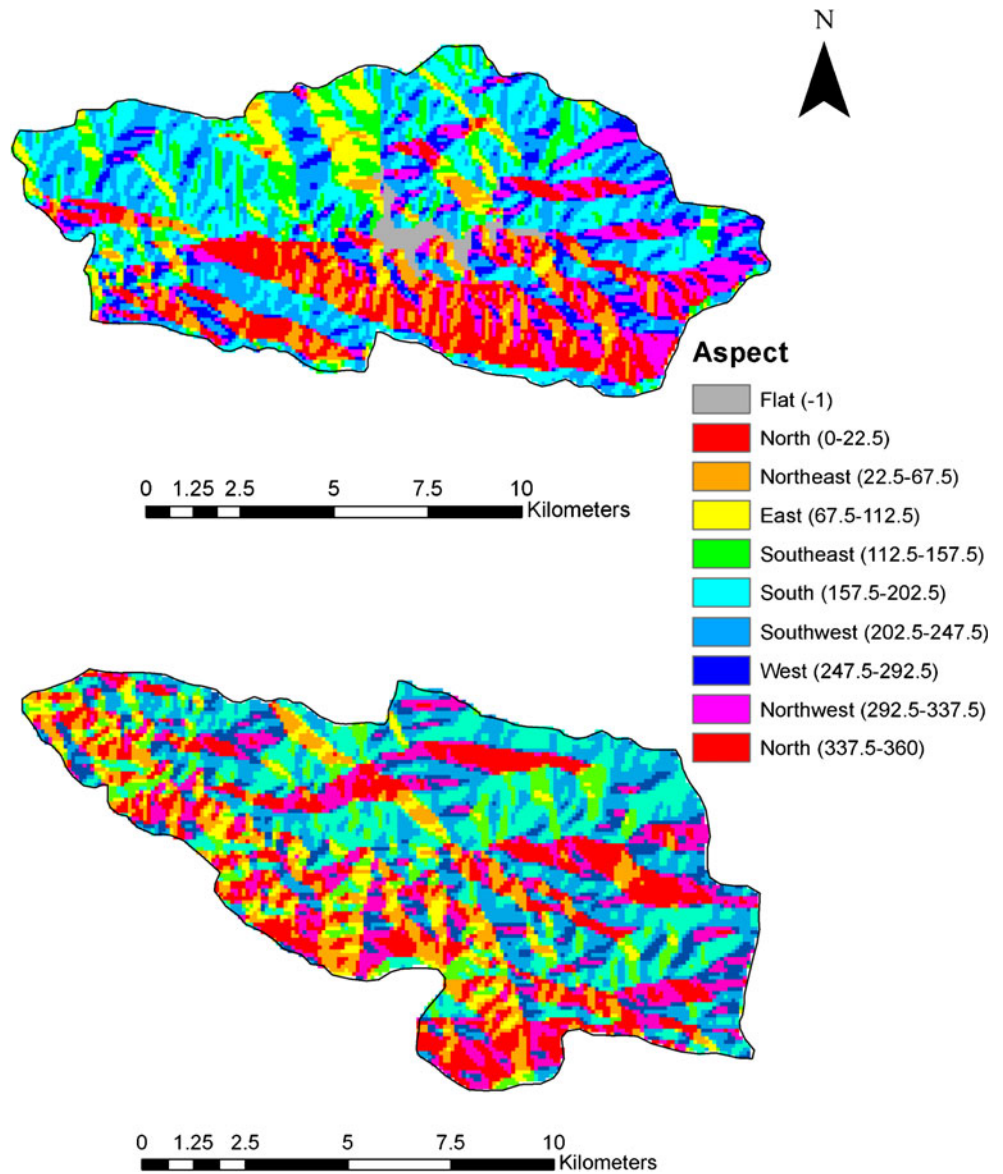
Aspect generally refers to the direction to which a mountain slope faces. The aspect of a slope can make very significant influences on its local climate because the sun's rays are in the west at the hottest time of day in the afternoon, and so in most cases a west-facing slope will be warmer than sheltered east facing slope. This can have major effects on the distribution of

vegetation and bio-diversity in the study area (Magesh et al. 2010). The value of the output raster data set represents the compass direction of the aspect. "0 is true north; a 90 degree aspect is to the east, and so forth. The aspect map of Chimmini and Mupily watersheds are shown in (Fig. 3). From the visual interpretation it is clearly seen that east facing slopes mainly occur in the Mupily watershed. So these slopes have a higher moisture content and lower evaporation rate then for the Chimmini watershed, whose slopes are more commonly west facing. This indicates that the slopes of the Chimmini watersheds are drier, and have a higher evaporation rate. As a result, the vegetation index is higher for the Mupily watershed then for the Chimmini watershed.

Slope

The slope of a physical feature, topographic landform, refers to the amount of inclination of that surface to the horizontal.

Fig. 3 Aspect map of Chimmini and Mupily watersheds



Slope analysis is an important parameter in geomorphic studies. The slope elements, in turn are controlled by the climato-morphogenic processes in areas having rock of varying resistance. Based on SRTM data, the slope map of the study area was prepared using the spatial analysis tool in ArcInfo 10. Slope grid is identified as “the maximum rate of change in value from each cell to its neighbors (Burrough 1986). The slope map of Chimmini and Mupily watersheds are shown in Fig. 4. The degree of slope exhibited by Chimmini watershed varies from 0° to 50° whereas Mupily watershed slope varies from 0° to 42°. Higher degree of slope results in rapid runoff and increased erosion rate with feeble recharge potential.

Stream order (u)

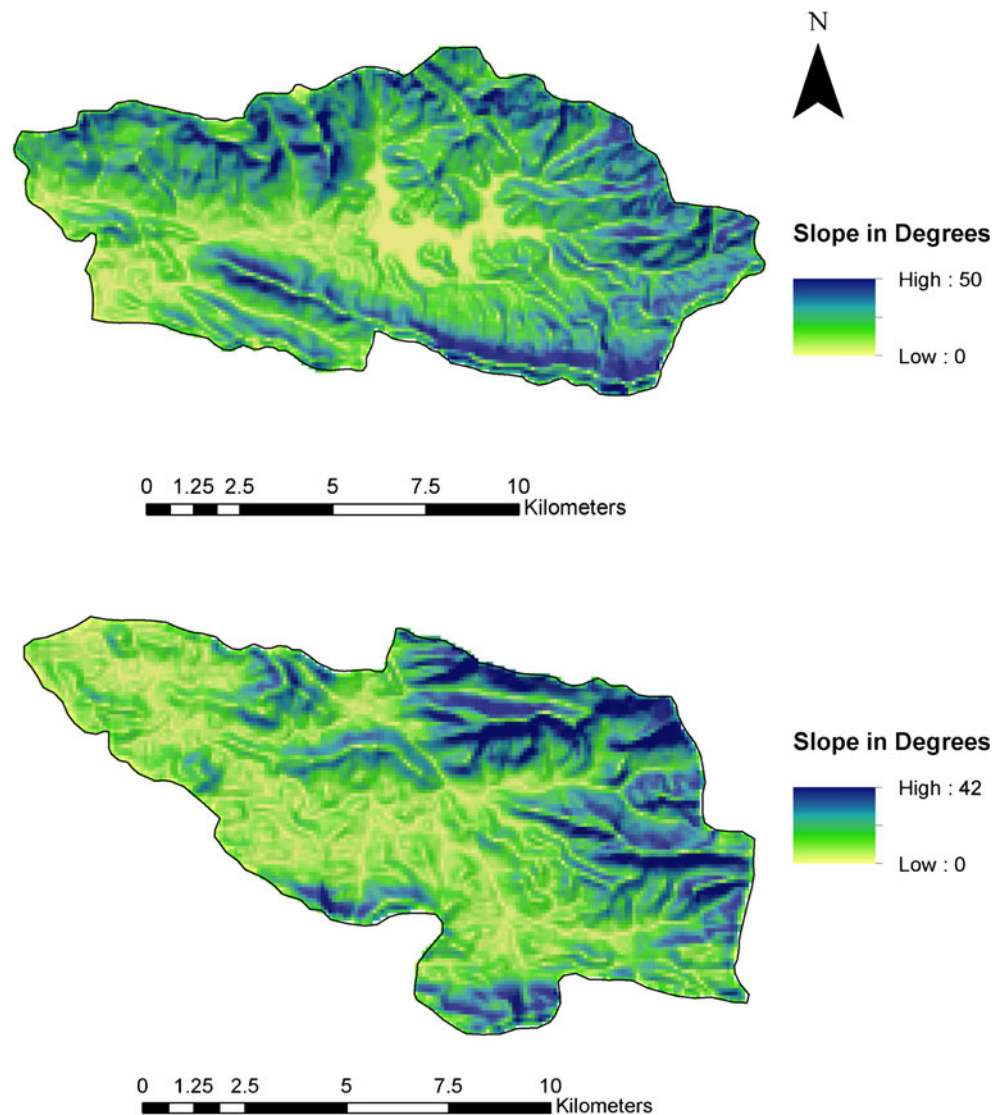
The streams of the study area have been ranked according to Strahler’s classification. In this classification, streams with

no tributaries are defined as first order; two first-order streams join to form a second-order stream, etc. In general, two streams of the same order join to form a stream with a stream order increased by one. The order wise stream length and stream numbers of Chimmini and Mupily watersheds are presented in Table 2. The variation in stream order and the basin area are largely due to physiographic and structural conditions of the region. According to Strahler’s method of ordering, the Chimmini watershed forms the sixth order and hence designated as sixth order watershed, while Mupily Watershed correspond to a fifth order Watershed (Fig. 1).

Stream number (Nu)

The Number of streams of various orders and the total number of streams in the watersheds are counted

Fig. 4 Slope map of Chimmini and Mupily watersheds



independently with the help of GIS software (Table 2). It is obvious that the total number of streams gradually decreases as the stream order increases.

Stream length (L_u)

Stream length is indicative of the contributing area of the basin of a given order. The stream length (L_u) has been computed based on the law proposed by Horton (1945). The stream numbers at various orders in both the watersheds are counted individually on the topographic maps using Arc GIS software and also their lengths from mouth to drainage divide are measured in the same platform. The length of stream segments is maximum for first order streams and decreases as the stream order increases. The regression plot for stream order and logarithmic stream length were computed and it gives a straight line fit (Fig. 5). The straight-line fit

indicates that the ratio between stream length and stream order is constant throughout the successive order of a basin and suggest that the geometrical similarity is preserved in both watersheds of increasing order.

Mean stream length (L_{sm})

The mean stream length (L_{sm}) has been computed by dividing the total stream length of order 'u' by the number of streams of segments in the order (Table 2). It is a characteristic property related to the size of drainage network components and its associated surfaces (Strahler 1964). From the morphometric study it should be noted that the L_{sm} values of the Chimmini vary from 0.52 to 8.18 while in the case of Mupily L_{sm} values varies from 0.52 to 23.7. L_{sm} of any given order is greater than that of the lower order and less than that of its next higher order in both the watersheds.

Table 2 Results of morphometric analysis of Chimmini and Mupily watersheds

S. No.	Parameters	Chimmini watershed						Mupily watershed				
		Stream orders						Stream orders				
		I	II	III	IV	V	VI	I	II	III	IV	V
1	Stream order (Total)	586	141	27	8	2	1	450	91	20	4	1
2	Stream length in km (Lu)	307	88.5	51	22.5	13.3	8.1	236	64.3	38.6	18.6	23.7
3	Mean stream length in km (Lsm)	0.52	0.63	1.89	2.81	6.63	8.1	0.52	0.71	1.93	4.65	23.6
4	Stream length ratio (RL)		II/I	III/II	IV/III	V/IV	VI/V		II/I	III/II	IV/III	V/IV
			1.19	3.01	1.49	2.36	1.23		1.34	2.73	2.41	5.09
5	Bifurcation ratio (Rb)		I/II	II/III	III/IV	IV/V	V/VI		I/II	II/III	III/IV	IV/V
			4.16	5.22	3.38	4.00	2.00		4.95	4.55	5.00	4.00
6	Mean bifurcation ratio (Rbm)			3.75						4.62		
7	Perimeter (P) (km)			57.22						56.68		
8	Basin length (Lb) (km)			20.0						19.8		
9	Basin area (Sq. Km)			140						122		
10	Total relief (R)(Mtrs)			1075						990		
11	Relief ratio (Rh)			53.6						50.0		
12	Elongation ratio (Re)			0.67						0.63		
13	Length of overland flow (Lg)			0.57						0.64		
14	Drainage density (D) (kms/km ²)			3.51						3.12		
15	Stream Frequency (Fs)			5.46						4.64		
16	Texture ratio (Rt)			13.37						9.99		
17	Form factor (Rf)			0.35						0.31		
18	Circulatory ratio (Rc)			0.54						0.48		

Stream length ratio (RL)

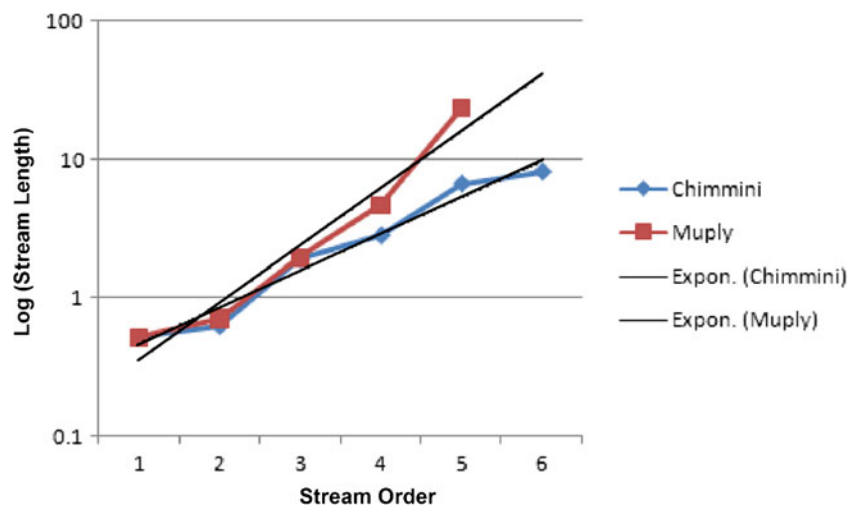
Stream length ratio (RL) may be defined as the ratio of the mean length of the one order to the next lower order of the stream segments (Horton 1945). The RL values are presented in Table 2. The RL between streams of different order in the study area reveals that there is a variation in RL in Chimmini watershed. This variation might be attributed to variation in slope and topography, indicating the late

youth stage. The Mupily watershed exhibits an increasing trend in the length ratio from lower order to higher order indicating their mature geomorphic stage.

Bifurcation ratio (Rb)

Bifurcation ratio (Rb) may be defined as the ratio of the number of stream segments of given order to the number of segments of the next higher order (Schumm 1956) (Table 1).

Fig. 5 Regression of stream length on stream order



Horton (1945) considered the bifurcation ratio as an index of relief and dissections. Strahler (1957) demonstrated that the bifurcation ratio shows a small range of variation for different regions or different environmental conditions except where the geological control dominates. The R_b is also an indicative tool of the shape of the basin. Elongated basins have low R_b value, while circular basins have high R_b values (Morisawa 1985). It is observed from the Table 2; the R_b is not same from one order to its next order. These irregularities depend upon the geological and lithological development of the drainage basin (Strahler 1964). The mean bifurcation ratios of Chimmini and Mupily watersheds are 3.75 and 4.62 respectively, which indicate that these watersheds do not exercise a dominant influence on the drainage pattern.

Relief (R)

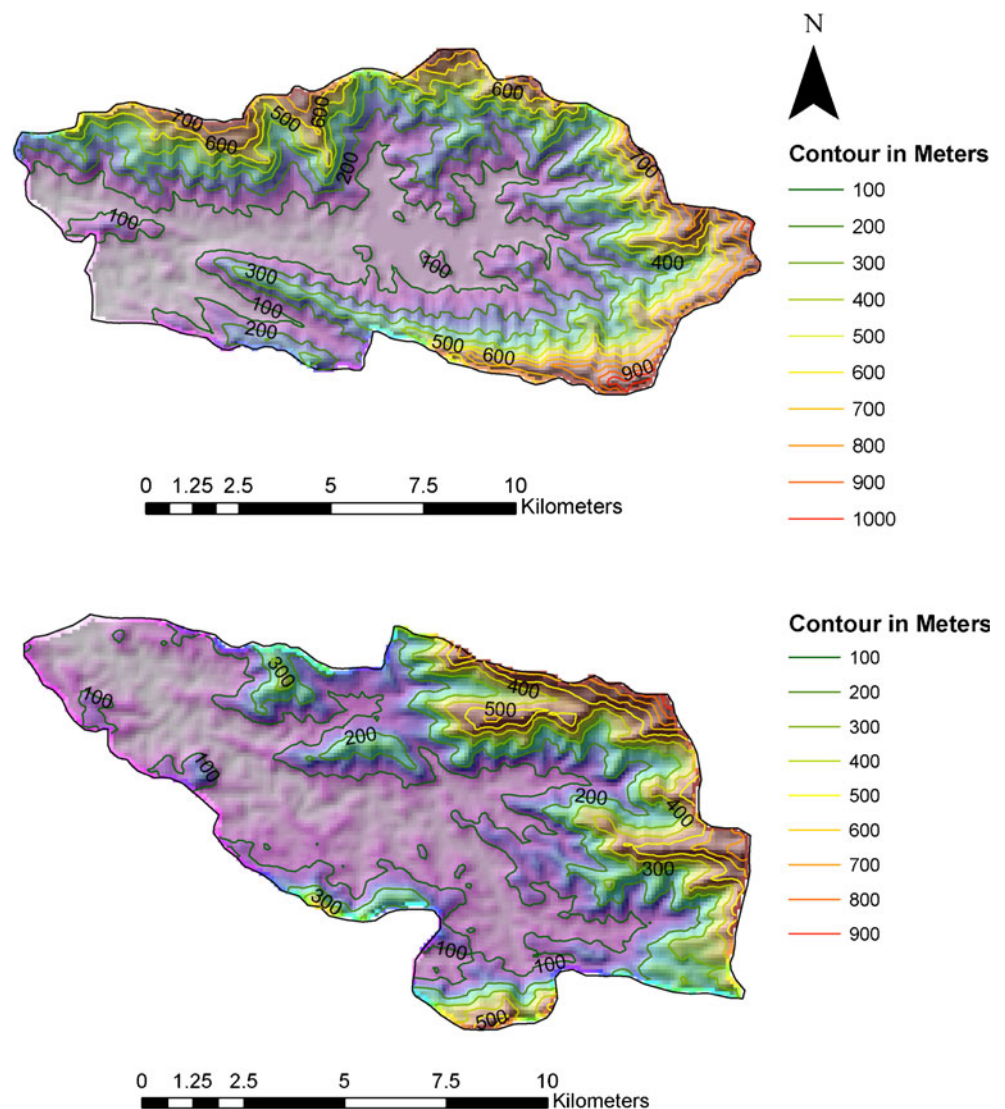
Relief is the maximum vertical difference between the lowest and the highest point of a basin. Basin relief is an

important factor in understanding the denudational characteristics of the basin. It plays a significant role in landforms development, drainage development, surface and sub surface water flow, permeability and erosional properties of the terrain. The total reliefs of the Chimmini and Mupily watersheds are 1,075 and 990 m respectively. The high relief value indicates the gravity of water flow, low infiltration and high runoff conditions. Figure 6 present the relief maps for both watersheds.

Relief ratio

Relief ratio (R_h) is defined as the horizontal distance along the longest dimension of the basin parallel to the principal drainage line (Schumm 1956). R_h indicates the overall steepness of a drainage basin and is an indicator of intensity of erosion processes operating on the slopes of the basin. In the present study, it should be noted that the relief ratios of

Fig. 6 Relief map of Chimmini and Mupily watersheds



Chimmini and Mupily watersheds are 53.6 and 50.0 respectively, corresponding to steep slopes and medium relief.

Drainage density (Dd)

Drainage density indicates the closeness of spacing of channels (Horton 1932). Drainage density is defined as the total length of streams of all order per drainage area. According to Strahler (1964), low drainage density values occur where basin relief is low while high Dd is favoured where basin relief is high. The Density factor is related to climate, type of rocks, relief, infiltration capacity, vegetation cover and runoff intensity index. Slope gradient and relative relief are the main morphological factors controlling drainage density. The Dd values for Chimmini and Mupily watersheds are 3.51 and 3.12 km/km² respectively. The Dd of these two watersheds reveals that the nature of subsurface strata is permeable, which is a characteristic feature of coarse drainage as the density values are less than 5.0. The measurement of drainage density provides a numerical measurement of landscape dissection and runoff potential.

Stream frequency (Fs)

Horton (1932) introduced stream frequency (Fs) or channel frequency which is the ratio of the total number of stream segments of all the orders in the basin to the total area of the basin. The stream frequency values for the Chimmini and Mupily watersheds are 5.46 and 4.64 km/km² respectively (Table 2). Stream frequency dependant more or less on the rainfall, temperature and lithology of the basin and reflect the texture of the drainage network. It is noted that the Fs values of both watersheds exhibits positive correlation. This indicates that the increase in stream population is connected to that of drainage density.

Drainage texture (T)

The drainage texture depends upon a number of natural factors such as climate, rainfall, vegetation, rock and soil type, infiltration capacity, relief and stage of development (Smith 1950). Drainage texture is the total number of stream segments of all orders per perimeter of that area (Horton 1945). Smith (1950) classified the drainage texture, which is shown in Table 3. According to Smith's classification, it is noted that the Chimmini watershed has a fine drainage texture as the value is less than 15, while the Mupily watershed having T value between 4 and 10 hence exhibits intermediate drainage texture.

Table 3 Drainage texture (T) classification based on Smith (1950)

Range	Texture
For 4.0 and below	Course
From 4.0 to 10.0	Intermediate
Above 10.0	Fine
Above 15.0	Ultra fine (bad land topography)

Form factor (Ff)

Form factor (Ff) is defined as the ratio of the basin area to the square of the basin length. This factor indicates the flow intensity of a basin of a defined area (Horton 1945). The form factor value should always be less than 0.7854 (the value corresponding to a perfectly circular basin). The Smaller the value of the form factor, the basin will be more elongated with lower peak flows of longer duration. Circular basins have intermediate form factors, which are close to one. Basins with high form factors experience larger peak flows of shorter duration, whereas elongated watersheds with low form factors experience lower peak flows of longer duration. The index of Ff shows the inverse relationship with the square of the axial length and a direct relationship with peak discharge. The Ff values for Chimmini and Mupily are 0.35 and 0.31 respectively, indicating both watersheds comprise elongated basin with lower peak flows of longer duration than the average.

Circularity ratio (Rc)

Circularity ratio of a basin is mainly concerned with the length and frequency of streams, geological structures, land use/land cover, climate, relief and slope of the basin. Circularity ratio (Rc) is the ratio of the area of a basin to the area of a circle having the same circumference as the perimeter of the basin (Miller 1953). The Mupily watershed has value of Rc less than 0.5 indicating that it is elongated, whereas the Chimmini watershed have greater value than 0.5 suggesting that it is more or less circular in shape and are characterized by the high to moderate relief and the drainage system is were structurally controlled. Rc is a significant ratio that indicates the dendritic stage of a watershed. Low, medium and high values of Rc indicate the young, mature, and old stages of the life cycle of the tributary watershed. The Rc values of Chimmini and Mupily watersheds are 0.54 and 0.48 respectively which indicates both watersheds reached the topographical maturity.

Elongation ratio (Re)

Elongation ratio (Re) is the ratio between the diameter of a circle of the same area as the drainage basin and the

maximum basin length (Schumm 1956). Values of R_e generally vary from 0.6 to 1.0 over a wide variety of climatic and geologic types. R_e values close to unity correspond typically to regions of low relief, whereas values in the range 0.6 to 0.8 are usually associated with high relief and steep ground slope (Strahler 1964). These values can be grouped into four categories namely—Circular—(>0.9), Oval—(0.9 to 0.8), Less elongated—(<0.7). In the case of Chimmini and Mupily watersheds the elongation ratio is less than 0.7 indicating that both the watersheds are less elongated and having high relief and steep slopes.

Length of overland flow (L_g)

The length of the overland flow is defined as the length of the longest drainage path that water takes before it gets concentrated (Horton 1945) (Table 1). The length of overland flow (L_g) approximately equals half the reciprocal of the drainage density (Horton 1945). This factor relates inversely to the average slope of the channel and is quite synonymous with the length of sheet flow. The computed L_g values of the Chimmini and Mupily watersheds are 0.57 and 0.63 respectively.

The present study is valuable for rainwater harvesting, watershed and ecosystem management. The first and second order streams are not useful for constructing check dams; hence, rainwater harvesting cannot be applied in these areas because of high gradient and rapid runoff. Moreover, ecological management should be executed carefully for the well being of nature-human interaction.

Conclusion

The conventional methods of morphometric analysis are time consuming, tiresome and error prone, while employment of present techniques of GIS and Remote Sensing provides more reliable and accurate estimation and proves to be an ideal application for the hydrological investigation of similar parameters of a watershed. The drainage basin is a fundamental landform unit in fluvial terrain and is of particular relevance to morphometric analysis. Landscape morphology is a function of drainage, climate, and structure of a given basin. The present paper has described morphometric analysis of the Chimmini and Mupily watersheds based on several drainage parameters, by which the watersheds have been classified as sixth and fifth order basins respectively. Each basin is mainly dominated by lower order streams. The drainage areas of Chimmini and Mupily watersheds are 140 and 122 km² respectively and show patterns of dendritic to sub-dendritic drainage. The variation in the stream length ratio may be due to changes in slope and topography. The drainage network of the watershed is effective to provide a

sufficient superficial draining with a high number of streams of low order that flow directly in the principal collector or in upper order streams. In the case of Chimmini watershed, the stream length ratio fluctuates according to local changes in slope and topography. But for the Mupily watershed, the stream length ratio exhibits an upward trend from lower to higher order, due to the geomorphic stage being more mature. The drainage density values of the Chimmini and Mupily watersheds have values below 5 revealing that the sub-surface strata is permeable, a characteristic feature of coarse drainage. The bifurcation ratio indicates that the watershed areas do not exercise a dominant influence on drainage patterns. The study areas experience intermediate to fine drainage textures. Rainfall may affect the development of stream segments in the watersheds. The aspect of Mupily watershed is dominated by east facing slopes indicative of high moisture content, whereas the Chimmini watershed is dominated by west facing slopes and correspondingly lower moisture content. This is because the sun's radiation intensity is greater on west facing slopes, causing increased evaporation. The elongation ratio indicates that both watersheds have high relief, steep slopes and are less elongated (than average)—the latter, mainly due to the guiding effect of thrusting and forcing. The relief ratio indicates that the discharge capability of these watersheds is very high and the potential groundwater resource is meager.

Usually, morphometric analysis of drainage system is prerequisite to any hydrological study. Thus, determination of stream networks' behavior and their interrelation with each other is of great importance in many water resources studies. The used approaches in this study include a comprehensive morphometric analysis that can be applied for any drainage system elsewhere to understand the drainage characteristics with respect to the fluvial ecosystem.

References

- Burrough PA (1986) Principles of geographical information systems for land resources assessment. Oxford University Press, New York, p 50
- Clarke JI (1996) Morphometry from maps. Essays in geomorphology. Elsevier Publ. Co., New York, pp 235–274
- Hadley RF, Schumm SA (1961) Sediment sources and drainage basin characteristics in upper Cheyenne River Basin. U.S. Geological Survey Water-Supply Paper 1531-B, pp 198
- Horton RE (1932) Drainage basin characteristics. Trans Am Geophys Union 13:350–361
- Horton RE (1945) Erosional development of streams and their drainage basins; Hydrophysical approach to quantitative morphology. Bull Geo Soc Am 56:275–370
- Magesh NS, Chandrasekar N, Soundranayagam JP (2010) Morphometric evaluation of Papanasam and Manimuthar watersheds, parts of Western Ghats, Tirunelveli district, Tamil Nadu, India: a GIS approach. Environ Earth Sci. doi:10.1007/s12665-010-0860-4
- Mesa LM (2006) Morphometric analysis of a subtropical Andean basin (Tucumán, Argentina). J Environ Geol 50(8):1235–1242

- Miller VC (1953) A quantitative geomorphologic study of drainage basin characteristics in the Clinch Mountain area, Virginia and Tennessee, Project NR 389042, Tech Rept 3 Columbia University Department of Geology, ONR Geography Branch New York
- Morisawa M (1985) Geomorphology texts books: rivers, forms and process, Chapter 5, “Structural and lithological control”
- Schumm SA (1956) Evolution of drainage systems and slopes in bad lands at Perth Amboy. New Jersey, Bull Geol Soc Am 67:597–646
- Schumm SA (1963) Sinuosity of alluvial rivers on the great plains. Geol Soc Am Bull 74:1089–1100
- Smith KG (1950) Standards for grading texture of erosional topography. Am J Sci 248:655–668
- Sreedevi PD, Subrahmanyam K, Shakeel A (2005) The significance of morphometric analysis for obtaining groundwater potential zones in a structurally controlled terrain. J Environ Geol 47 (3):412–420
- Strahler AN (1957) Quantitative analysis of watershed geomorphology. Trans Am Geophys Union 38:913–920
- Strahler AN (1964) Quantitative geomorphology of drainage basins and channel networks. In: Chow VT (ed) Hand book of applied hydrology. McGraw Hill Book Company, New York