Evaluation of geomorphologic similarity between the sub-catchments of Cauvery river basin

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Abstract. Estimation of morphometric indices can be useful in defining similarity relationships between catchments over a wide range of scales and it facilitates the effective understanding of hydrogeologic processes. This study aims at evaluating morphometric parameters to investigate geomorphologic similarity between the sub-catchments of the Cauvery river basin which is a major river basin in Peninsular India. The Digital Elevation Model (DEM) obtained from Shuttle Radar Topographic Mission (SRTM) at 30 m spatial resolution is used for assessing the linear, areal and relief aspects of morphometric analysis. The stream network analysis of sub-catchments reveals that the basin is dominated by streams of lower order and the Cauvery basin can be characterized as a seventh order basin. Linear parameters indicate that the basin is subjected to less structural disturbances. Assessment of areal parameters shows that most of the sub-catchments have elongated shape, low drainage density and course drainage texture. Evaluation of relief parameters suggests that the sub-catchments have mild slopes with moderate ruggedness and resistant soil surface. The sub-catchments are found to be geomorphologically similar in behaviour and this analysis can throw insight on development of scaling relationships as well as hydrological predictions in ungauged areas of the drainage basin.

1. Introduction
Catchments are complex environmental systems and they serve as the fundamental units for hydrological classification. They are self-organizing systems whose form, drainage network, ground and channel slopes, channel hydraulic geometries, soils and vegetation, are all a result of adaptive ecological, geomorphic and land-forming processes [1]. There are different types of catchment classification systems which are based on climate, landcover, catchment responses and storage features. Catchment similarity and classification based on the structural characteristics has been traditionally followed in hydrological analysis. Such characteristics of the basin can be captured in the form of numbers (mostly dimensionless), curves or distributions and conceptual and mathematical models [2]. The geomorphological characteristics of river basins can be evaluated using a set of morphometric parameters which comprises of linear, areal and relief indices [3,4,5].

The measurement and mathematical analysis of the configuration of the earth’s surface, shape and dimension of its landforms is called morphometry. Morphometric analysis of catchments provides a
preliminary understanding of the basin’s evolution with respect to topography, climate and geology. Physiographic characteristics of basins such as shape, relief, drainage density and texture can be correlated with various hydrologic processes [6]. With the advancement of remote sensing and geographical information systems (GIS) based techniques, morphometric analysis has become simple and robust which fostered the implementation of these techniques widely across various river basins around the globe [5,7,8]. The most important applications of quantitative morphometric analysis include flood hazard evaluation, understanding tectonic processes, geomorphic zoning, estimating the implications on soil and water conservation and improving watershed management approaches. The objective of this study is to assess the morphometric parameters for sub-catchments of the Cauvery river basin to understand their similarity features with respect to catchment geomorphology.

2. Study Area
The study is done on Cauvery basin in peninsular India which has a drainage area of about 85,600 sq. kms extending over the states of Tamil Nadu, Karnataka, Kerala and Union Territory of Puducherry. The Cauvery river originates from the Western Ghats at an elevation of about 1341 m and meets the Bay of Bengal with a flow length of about 800 kms. The basin falls in a sub-tropical climatic zone and the most dominant type of land cover is agricultural land followed by forest area. The predominant soil types include black soils, red soils and alluvial soils and a variety of combinations of them are found across the basin. The mean monthly temperature varies from 22.98°C to 28.43°C and the annual average rainfall varies from 800 mm to 3800 mm which indicate the amount of regional variability in the catchment meteorology. The basin is characterized by extensive regional variability in surface and ground water availability and large-scale shift in land use patterns. The Cauvery basin is divided into sub-catchments (figure 1) based on the Central Water Commission (CWC) gauge locations and morphometric analysis is carried out for each of the sub-catchments as well as for the entire basin.

Figure 1. Cauvery river basin with delineated sub-catchments, gauge points, stream network and elevation in metres.
3. Materials & Methods
The Digital Elevation Model (DEM) is downloaded from Global Land Cover Facility (GLCF) website which is obtained through the Shuttle Radar Topographic Mission (SRTM). The SRTM DEM is available at 30m spatial resolution. The Cauvery basin is sub-divided into contributing sub-catchments based on the Central Water Commission (CWC) specified gauge locations. Morphometric parameters related to linear, areal and relief aspects of 27 sub-catchments and the Cauvery basin are quantified. The sub-watersheds are numbered from ‘C1’ to ‘C28’ based on the increasing order of catchment area as shown in table 1. Morphometric analysis is performed after watershed delineation using ArcGIS 10.4 software. Drainage network analysis is done based on Horton’s method and extraction of river networks is based on [9].

### Table 1: Features of sub-catchments of Cauvery basin and evaluated morphometric parameters.

| Catchment Number | Name of the sub-catchments (gauge locations) | Area (km²) | Perimeter (km) | Basin Length (km) | Elevation Min (m) | Elevation Max (m) | Mean slope angle (degrees) | Longest flow path (km) |
|------------------|---------------------------------------------|------------|----------------|-------------------|-----------------|-------------------|--------------------------|------------------------|
| C1               | Thoppur                                     | 329.41     | 140.10         | 35.18             | 316             | 1645              | 11.22                    | 49.23                  |
| C2               | Sevanur                                     | 378.66     | 154.36         | 35.13             | 157             | 1562              | 10.59                    | 42.77                  |
| C3               | Sakleshpur                                  | 586.75     | 222.07         | 44.00             | 845             | 1410              | 8.66                     | 50.37                  |
| C4               | Kodur                                       | 719.30     | 157.72         | 34.97             | 436             | 2291              | 13.70                    | 51.07                  |
| C5               | K.M.Vadi                                    | 742.07     | 218.31         | 34.40             | 735             | 1307              | 4.68                     | 60.68                  |
| C6               | Thimmanahalli                               | 965.34     | 279.01         | 60.37             | 877             | 1832              | 5.93                     | 80.21                  |
| C7               | Kadige                                      | 990.00     | 263.42         | 36.53             | 790             | 1622              | 9.14                     | 49.70                  |
| C8               | Muthankera                                  | 1167.21    | 303.89         | 43.15             | 662             | 2043              | 9.97                     | 62.89                  |
| C9               | Thuvur                                      | 1194.02    | 249.19         | 69.93             | 154             | 1645              | 5.98                     | 97.01                  |
| C10              | Thengumarahada                              | 1352.43    | 243.55         | 56.33             | 315             | 2633              | 13.29                    | 97.55                  |
| C11              | Nellithurai                                 | 1465.72    | 265.62         | 57.33             | 292             | 2633              | 16.68                    | 86.01                  |
| C12              | Hogenakkal                                  | 1546.54    | 307.86         | 85.39             | 242             | 1377              | 9.18                     | 127.63                 |
| C13              | Bendrahalli                                 | 1860.93    | 289.84         | 71.49             | 600             | 1805              | 7.41                     | 106.25                 |
| C14              | Chunchunkatte                               | 2087.16    | 428.45         | 79.61             | 748             | 1622              | 6.81                     | 106.96                 |
| C15              | M.H.Halli                                   | 3026.66    | 565.35         | 90.11             | 813             | 1832              | 6.60                     | 120.16                 |
| C16              | T.Bekuppe                                   | 3300.81    | 455.94         | 115.38            | 580             | 1452              | 5.68                     | 146.85                 |
| C17              | E-mangalam                                  | 3459.54    | 479.71         | 151.73            | 120             | 1962              | 4.72                     | 184.35                 |
| C18              | Akkihebbal                                  | 5105.00    | 775.45         | 133.77            | 718             | 1832              | 5.76                     | 206.44                 |
| C19              | Savandapur                                  | 5585.34    | 612.81         | 141.79            | 162             | 2633              | 12.42                    | 195.16                 |
| C20              | T.Narasipur                                 | 6974.10    | 771.11         | 138.54            | 598             | 2043              | 6.45                     | 204.16                 |
| C21              | T.K.Halli                                   | 8056.84    | 686.39         | 157.47            | 558             | 1306              | 4.41                     | 226.20                 |
| C22              | Nalammaranapatti                            | 8631.50    | 657.30         | 126.88            | 108             | 2536              | 6.91                     | 214.84                 |
| C23              | Kollegal                                    | 20128.20   | 1293.05        | 296.92            | 559             | 2043              | 5.98                     | 333.37                 |
| C24              | Biligundulu                                 | 35823.30   | 1719.41        | 304.07            | 239             | 2043              | 5.93                     | 435.77                 |
| C25              | Urachikottai                                | 48817.70   | 2096.13        | 362.20            | 132             | 2633              | 7.29                     | 544.11                 |
| C26              | Kodumudi                                    | 51010.80   | 2126.25        | 429.46            | 80              | 2633              | 7.15                     | 603.66                 |
| C27              | Musiri                                      | 67819.50   | 2534.70        | 483.36            | 50              | 2633              | 6.86                     | 680.76                 |
| C28              | Cauvery                                     | 85714.40   | 3235.24        | 680.49            | 0               | 2633              | 6.25                     | 914.43                 |

4. Results & Discussion
The estimated morphometric parameters are classified into three sections as linear, areal and relief parameters. The basin characteristics for all the sub-catchments such as area, perimeter, basin length, minimum and maximum elevation, mean slope angle and longest flow path are tabulated in table 1.
4.1. Linear parameters

Linear parameters include the one-dimensional features associated with the catchment morphology. The linear aspects of the sub-catchments accounted in this study include stream order, stream length ratio, basin length, bifurcation ratio and Rho coefficient. Evaluation of linear parameters aids in analysing the evolution of river networks with respect to lithologic and physiographic conditions.

4.1.1. Stream order. Classification of streams in a basin based on the number of tributaries joining at a junction is known as stream ordering and it is an important indicator of the catchment size and drainage properties [4]. In this work, Strahler method of stream ordering is adopted in which the order of 1 is assignment to those stream links without any tributaries. As tributaries of same order intersect, the stream order increases. In this study, it is found that Cauvery is designated as a seventh order basin. The streams of sub-catchments C1 to C6 follow fourth order, C7 to C21 follow fifth order and C22 to C27 follow sixth order. The total number of stream segments found in each stream order is termed as the stream number ($N_u$) where $N$ is the stream number of order ‘$u$’. The stream numbers obtained follows Horton’s first law of drainage decomposition [3] which states that the number of streams of different orders in a given drainage basin tend closely to approximate an inverse geometric series. Figure 2 shows the stream ordering of selected sub-catchments and it is observed that they closely follow Horton’s law. It is also noted that, in the sub-catchments, the streams of first order are highest in number and as the order increases, the stream number decreases.

4.1.2. Stream length ratio. Stream length ($L_u$) is defined as the total length of stream segments present in the stream order ‘$u$’. The total stream length decreases with increase in the stream order. The stream lengths obtained for the sub-catchments confirm Horton’s second law [3] which states that the average length of streams of consecutive stream orders tend to follow a geometric progression. Stream length ratio is a derived morphometric parameter and is defined as the ratio of mean stream length of a given drainage basin tend closely to approximate an inverse geometric series. Figure 2 shows the stream ordering of selected sub-catchments and it is observed that they closely follow Horton’s law. It is also noted that, in the sub-catchments, the streams of first order are highest in number and as the order increases, the stream number decreases.

Figure 2. Sub-catchments follow Horton’s first law of stream ordering.

\[
\log(N_u) \text{ vs. Stream Order}
\]

- C2
- C5
- C15
- C17
- C24
- C25
- C26
- C27
- C28

0 0.5 1 1.5 2 2.5 3 3.5 4 4.5

0 1 2 3 4 5 6 7

Stream Order
4.1.3. Bifurcation ratio. The ratio of number of stream segments of a given order \((N_u)\) to that of the higher order \((N_{u+1})\) is termed as bifurcation ratio \((R_b)\). It is an indicator of the lithologic development and geologic conditions of the basin. In this study, the \(R_b\) values ranges from 2.5 to 6.7 for the sub-catchments. \(R_b\) values between 3 and 5 indicate that the geologic structure does not have a dominant influence on the drainage patterns of the basin [4]. The bifurcation ratio of Cauvery basin is 2.19. Lower values of \(R_b\) indicate flat basin characteristics and less structural disturbances whereas higher values suggest strong influence of structural controls on drainage patterns [4].

4.1.4. Rho coefficient. The ‘Rho’ coefficient \((\rho)\) is a parameter which relates drainage density to physiographic growth of the basin which facilitate assessment of storage ability of stream network. Rho coefficient is affected by climatic, geological, biological, geomorphological and human induced factors. It is defined as the ratio between the stream length ratio and bifurcation ratio [3]. Values greater than 0.60 indicates higher hydric storage during flood periods. The mean value for the sub-catchments is 0.28 and the variation across the basin is found to be negligible. For Cauvery basin, the rho value is 0.26 suggesting the similarity of catchments.

4.2. Areal parameters
Areal parameters are those morphometric parameters which are calculated based on the basin’s geometrical features. Drainage density, stream frequency and drainage texture are those areal aspects which helps in evaluating the drainage features and its texture. Elongation ratio, circularity ratio and form factor are classified as shape parameters and it serves as a quantitative measure of the basin shape which also governs the runoff behaviour at the outlet. Figure 4 shows the shape parameters evaluated for the sub-catchments of Cauvery basin.

4.2.1. Basin geometry. Geometrical analysis is the primary procedure in the determination of watershed characteristics. The area, perimeter and relief values give information about the discharge and peak flows from the basin. Basin length is defined as the longest length of the watershed from the mouth of the stream to the point of confluence measured parallel to the main drainage line [6]. Basin area, perimeter, basin length and longest flow path are estimated using GIS techniques and the values obtained from the study are tabulated in table 1. The relation between the sub-catchment area and the basin length (figure 3) is found to be positively correlated indicating the homogenous geomorphological evolution of the basin [6].

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y = 0.0069x + 64.602
R² = 0.96
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![Figure 3. Positive correlation between basin area (km²) and basin length (km).](image)

4.2.2. Drainage density. Drainage density \((D_d)\) is a measure of the length of the stream segment per unit area [3]. It helps in identifying the permeability and porosity characteristics of the watershed. It is
also a measure of the degree of fluvial dissection and is dependent on geomorphologic factors like topography, pedology, lithology, vegetation and climate [10,11]. Slope gradient and relative relief are the major controlling factors of drainage density [4]. A positive relationship for drainage density is found for semi-arid catchments and the combined role of relative relief and climate on drainage density has been investigated in many studies [5,12]. Low drainage density indicates course drainage texture and implies that the area has permeable sub-soil and it is highly resistant to erosion. There are five classes defined for drainage density values (km/km²) which are: very coarse (<2), coarse (2-4), moderate (4-6), fine (6-8) and very fine (>8) [13]. The drainage density for the sub-catchments considered in this study ranges from 0.40 to 0.49 and for Cauvery basin the Dd value is 0.45. The low values indicate very course drainage structure and the presence of resistant soil sub-surface with dense vegetative cover.

4.2.3. Stream frequency. Stream frequency (Fs) is an estimate of the total number of stream segments of all orders per unit area. It is positively correlated with the drainage density and it is also an indicator of the texture of drainage network [3]. In this study, stream frequency for the sub-catchments are found to be approximately equal and the mean value is 0.17 indicating course drainage network.

4.2.4. Drainage texture/texture ratio. Drainage texture (T) is an important indicator of the relative spacing of drainage lines in a basin [3]. It is defined as the ratio of total number of stream segments of all orders to the perimeter of the basin. It is dependent upon several factors such as climate, vegetation, rainfall, infiltration capacity of the soil, relief and stage development of the basin [13]. Similar to the drainage density classification, higher values of texture ratio indicate very fine drainage structure and implies that the basin has more risk of erosion. Based on the values of T, the texture is classified as coarse (T < 4), intermediate (4<T<10), fine (10<T<15) and ultra-fine (T>15) [13]. In the present study, Cauvery basin is found to have a texture ratio of 4.54 and the mean value for the sub-catchments is 1.64 which indicates coarse drainage texture. Also, the texture ratio is found to increase with increase in the catchment size.

4.2.5. Elongation ratio. Elongation ratio (Re) is defined as the ratio of the diameter of the circle of the same area as that of the basin to the basin length. Values close to 1 implies that the regions are of very low relief and Re values between 0.6 and 0.8 are associated with high relief and steep ground slope [14]. Based on elongation ratio, the catchments can be classified as circular (Re > 0.9), oval (0.8 < Re <0.9) and less elongated (0.7 < Re < 0.8) and elongated (Re < 0.7). In this study, most of the sub-catchments have elongation ratio between 0.5 and 0.8 which implies that they are mostly elongated. The Cauvery basin has an elongation ratio of 0.49 implying that the catchment is elongated in shape.

4.2.6. Circularity ratio. It is the ratio of the area of the basin to the area of a circle having the same circumference as the perimeter of the basin [4]. It is affected by the lithological features of the basin. The circularity ratio (Re) is influenced by length of the stream, slope conditions and drainage patterns. It also indicates the dendritic stage of the basin. Re values greater than 0.5 indicates circular shape of the catchment. The Cauvery basin has a Re value of 0.10 and the sub-catchments have Re values ranging between 0.1 and 0.3 which confirms that they are not circular in shape.

4.2.7. Form factor. The ratio of the basin area to the square of basin length is termed as form factor (Ff) and it was proposed to predict the flow intensity of a basin [3]. Form factor shows a direct relationship with the peak discharges and has an inverse relationship with the square of axial length of the basin. Ff values for elongated basins range between 0.1 and 0.8 [4] and in the study all the sub-catchments are found to have values in the range 0.15< Ff < 0.74 which indicate that the sub-catchments have narrow and elongated form. Figure 4 shows the results of evaluation of shape factors for the Cauvery basin and it can be inferred that most of the sub-catchments have elongated and narrow shape indicating geomorphic similarity with respect to shape.
4.2.8. Constant channel maintenance. Constant channel maintenance (Cc) is the inverse of drainage density and it indicates the relative size of landform units in a drainage basin [14]. The values for Cc in this study are found to be almost uniform across the sub-catchments and the mean value obtained is 2.26 units.

4.2.9. Infiltration number. The infiltration number (In) is a characteristic of the basin which signifies its infiltration capacity [15]. It is defined as the product of drainage density and stream frequency and a higher value implies lower infiltration rates in the basin. The mean value of infiltration number for the sub-catchments in the analysis is 0.076 units.

4.3. Relief parameters
Relief parameters such as basin relief, relief ratio, slope and gradient ratio are important factors in understanding the denudational characteristics of the basin which are formed as the result of weathering and erosion by geomorphic agents such as water, glaciers and wind. Understanding the slope features of a basin is important for planning settlements, designing engineering structures and implementing morpho conservation practices [5]. The elevation map of Cauvery basin is shown in figure 1. The minimum and maximum elevations for Cauvery basin and the sub-catchments are tabulated in table 1.

4.3.1. Basin relief. The vertical distance between the lowest and the highest points of the basin is termed as basin relief. It affects the stream gradient and thereby influences the flood patterns and sediment transport in the basin [14]. The maximum basin relief obtained in the analysis is 2.63 kms which corresponds to Cauvery basin and among the sub-catchments, Sakleshpur has the least basin relief (0.56 kms) and Musiri has the highest value (2.58 kms).

4.3.2. Relief ratio. The relief ratio is a dimensionless height-length ratio which equals to the tangent of the angle formed by two planes intersecting at the mouth of the basin, one representing the horizontal, the other passing through the highest point of the basin [14]. It is calculated as the ratio between basin relief and basin length. Relief Ratio (Rh) = (H-h/L) where H = highest elevation in the basin, h = lowest elevation in the basin and L = longest axis of the basin. It is a quantitative measure of the overall steepness of the basin and is also an indicator of the basin’s susceptibility to surface erosion. Sub-catchments with more area are found to have lesser relief ratio and the mean value of Rh
is found to be 0.02. The Cauvery basin has a relief ratio of 0.003 which signifies low degree of slopes and resistance of basement rocks against erosion [14].

4.3.3. Slope angle. The slope of the basin is controlled by morphogenic processes and the climatic conditions. Steep slope angle signifies high surface runoff and low infiltration rates. Sediment transport is also governed by the slope of the basin. Cauvery basin has a slope angle of 6.25 degrees and that of the sub-catchments vary between 4.4 degrees and 16.5 degrees. The least slope angle is obtained for T.K.Halli and the highest value is for Nellithurai sub-catchment which is located in the Western Ghats. The slope angles for all the sub-catchments are tabulated in table 1.

4.3.4. Ruggedness number. Ruggedness number (Rn) is used to measure the flash flood potential of the streams [16]. It is determined by the product of basin relief and drainage density (Dd). The average ruggedness number of the sub-catchments considered in the analysis is 0.70 which suggest moderate rugged terrain characteristics of the basin.

5. Conclusions

Drainage network analysis and evaluation of morphometric indices are important in deriving hydrological inferences for catchment classification and similarity analysis. Remotely sensed data such as SRTM DEM and the application of GIS-based techniques are useful in performing systematic morphometric analysis of drainage basins. Quantitative analysis of morphometric parameters is successfully carried out for Cauvery basin and it is observed that the river network follows seventh order with streams of first order dominating across the basin. Low bifurcation ratios can be attributed to flat and structurally stable basin characteristics. Very coarse drainage density is observed for most of the sub-catchments and it indicates the presence of resistant soil surface with dense vegetative cover and low relief. Analysis of relief aspects signifies higher slope features in the sub-catchments near Western Ghats. The values of relief ratio and ruggedness number for the basin suggests moderate rugged terrain and resistance of basement rocks against erosion. Most of the parameters analyzed are found to have less variation from the mean values across the sub-catchments and this implies that they are geomorphologically similar in behavior with respect to the parameters considered in this study. With the efficient usage of high resolution satellite datasets and GIS techniques, morphometric analysis can provide fundamental insights on catchment geomorphology and can be further used in deriving hydrologic similarity of catchment responses.

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