



Classification of Sub-Watersheds with Respect to Flooding Susceptibility in a Tropical River Basin Using Multi Criteria Approach Based on VIKOR

Ajith G. Nair¹ · K. Sunil Kumar² · Sonu V. Sabu¹

Received: 3 November 2023 / Accepted: 21 May 2024
© The Author(s), under exclusive licence to Springer Nature B.V. 2024

Abstract

Morphometric analysis is important for conservation and management of watersheds including flood control measures, which is in turn related to topographical components. Prioritization of sub-watersheds based on morphometric factors is carried out to understand the vulnerability of different sub-watersheds to hazards like flooding, soil erosion and groundwater storage. It is carried out in the initial phase so as to enhance the efficacy in selection of water and soil management and remedial practices. In the present study, prioritization is attempted using multi criteria approach based on VIKOR on the sub-watersheds of Mahe river basin in southwest India vis-à-vis their susceptibility to flooding. Thirteen morphometric factors pertaining to twelve sub-watersheds of the river basin are used in the present analysis and they are classified (High, Moderate and Low) based on their risk of flooding. Sub-watersheds 3–8, upstream of the Mahe were identified as being the most prone to flooding. Sub-watersheds 1 and 2, offer a moderate risk of flooding, since the advantage of prominent runoff in their upper reaches is inhibited by the laterite dominated terrain downstream. The sub-basins 9–13 in the coastal plains, forming ~60% of total area of Mahe basin, fall in ‘Least’ category. The prioritization of sub-watersheds based on Multi Criteria Decision Analysis of their morphological factors is found to be useful in the discrimination of flooding prone areas. This would help in the selection of suitable management and remedial measures for the sub-watersheds based on their hazard of flooding.

Keywords Morphometric factors · Prioritization · Mahe · Sub-watersheds · VIKOR

✉ Ajith G. Nair
ajithnair@cet.ac.in
K. Sunil Kumar
ksk_sunil@cet.ac.in

¹ Department of Civil Engineering, College of Engineering Trivandrum, Thiruvananthapuram, Kerala State, India 695016

² Department of Mechanical Engineering, College of Engineering Trivandrum, Thiruvananthapuram, Kerala State, India 695016

1 Introduction

The science of morphometry is concerned with the quantitative measurement and generalization of land surface geometry. Since the drainage basin (watershed) is considered as a basic unit of landform analysis, the geometric characters of master channel and its tributary network is important to understand and predict processes like floods, sediment dynamics and erosional patterns (Ritter et al. 1995). Fluvial morphometry embodies these geometric characters that define the linear, areal and relief aspects of the river basin and those of its tributary basins and their interrelationships. They reflect respectively the one-, two- and three-dimensional components of the basin. The hydrological characters and response of a river basin is intimately related to its geometric dimensions. Hence morphometric analysis is important for conservation and management of watersheds including flood control measures, which is in turn related to topographical components like relief, gradient, aspect, soil, vegetation, nature of rocks and tectonic and climatic factors like precipitation (Chorley et al. 1984; Ritter et al. 1995).

The introduction of remote sensing and GIS techniques has led to the rapid and precise estimation of morphometric parameters (Lillesand and Kiefer 1994, Biswas et al. 1999; Nookaratnam et al. 2005). The differentiation of a river basin into its constituent sub-watersheds and subsequent estimation of their morphometric parameters ensures effective and representational coverage of the basin. The influence of topographic and precipitation characters on the morphometric components is thus ensured. This leads to effective planning and development of basin and chalking out strategies for water and soil conservation (Kumar et al., 2011; Ahmed and Rao 2015; Choudhari et al. 2018), flood control (Youssef et al. 2011) and soil conservation (Biswas et al. 1999; Nookaratnam et al. 2005; Gadallah and Siddig 2024) practices.

The success of water or soil management studies of a basin depends on the effective delineation of the degree of susceptibility to hydrological processes in the different parts of the basin. Towards this end, prioritization of sub-basins (sub-watersheds) based on morphometric factors is carried out to understand the vulnerability of different sub-watersheds to hazards like flooding, soil erosion and groundwater storage. The common approach consists of ranking the sub-basins based on the calculation of a compound amount of the ranks given to each morphometric parameter considered for each sub-basin (Biswas et al. 1999; Nookaratnam et al. 2005; Ahmed and Rao 2015; Sengupta et al. 2022, Arulbalaji and Padmalal 2020; Bharath et al. 2021; Shekar and Mathew 2022). However, this method suffer from static deficiencies in that the interdependence between the morphometric values are not considered. Also, the average values do have significance only when the standard deviations of the values of each parameter is low, which seldom happens in natural conditions.

Multi Criteria Decision Analysis (MCDA) is found to be a valuable tool in overcoming these deficits. MCDA techniques have been found to be advantageous in problems which involve uncertainties, conflicting criteria and where the criteria have different units of measurement. Various methods of MCDA have been applied to understand and prioritize in various applications like flood potential, soil erosion and delineation of groundwater potential. Komaragiri et al. (2018) have used entropy method for assigning weights for morphometric criteria and Fuzzy VIKOR is found to be effective for prioritization of sub-watersheds in Mahanadi River for implementation of soil and water conservation measures. Analytical Hierarchical Process (AHP) and a Fuzzy Analytical Hierarchical process (FAHP) technique have been adopted by Meshram et al., (2019)

to rank sub-basins of two rivers for watershed management and FAHP is found to be more useful. Fuzzy based Best Worst Multi-Criteria Decision-Making (F-BWM) and Fuzzy Logic (FL), Interval Rough-Analytical Hierarchy Process (IR-AHP) has also been found to be useful in ranking soil erosion in Gusru river, India (Meshram et al. 2022a, b). Various MCDA methods (AHP, ANP, and ELECTRE I, VIKOR, TOPSIS) coupled with hydrograph concept were utilised by Akay and Koçyigit (2020) to study flood potential and for grading sub-watersheds of ungauged basins. They argue that MCDA methods are superior to traditional methods like hazard degree (HD), compound factor (CF) approaches and a statistical method (SM) adopted by Kocyigit and Akay (2018). Komaragiri et al. (2018) has applied Fuzzy Logic (FL), Interval Rough-Analytical Hierarchy Process (IR-AHP) methods to prioritise erosion susceptibility of Gusru river. Results of Fuzzy AHP and Compound Parameter approaches give similar results for sub-watersheds of the Tenughat (Sengupta et al. 2022), unlike previously mentioned studies. They have used Sediment delivery ratio (SDR) model to explain the variance of soil erosion in the basin. Sridhar and Ganapuram (2021) have operated FAHP and Universal Soil Loss Equation (USLE) to calculate the erosion susceptibility of sub-watersheds of a river, and their outcomes were comparable. Principal Component Analysis (PCA) have been used in the prioritization of sub-basins to select the most significant morphometric parameters to be used. These have been combined with Normalised Difference Vegetation Index (NDVI) to rank Huehuetan river based on soil erosion by López-Pérez and Fernández-Reynoso (2021). They contend that this method suit areas with heavy rainfall and useful to decide on suitable management strategies. Rahman et al. (2022) conducted a similar study using not only PCA, but also PCA adopted weighted sum model (PCA-WSM) to select suitable morphometric variables of Darla basin in Bangladesh. Four most significant variables are identified by both the methods and they yield similar results. Prioritisation of sub-basins of Alaknanda River, India have been attempted using the approaches of Principal Component Analysis (PCA), compounding method (CM), Geomorphological Instantaneous Unit Hydrograph (GIUH), and Revised Universal Soil Loss Equations (RUSLE) by Singh and Kansal (2023). These gave different vulnerability rankings which they attribute to the distinct aspects that influence the basin. The final prioritization was estimated based on weighted average score.

These techniques have been applied in the various facets of hydrological studies. Razavi Toosi and Samani (2017) implemented DEMATEL (fuzzy DEcision-Making Trial and Evaluation Laboratory) model to provide a visual understanding among interdependencies of social, economic, environmental, managerial and technical criteria in five watersheds in Iran and fuzzy VIKOR process for ranking sub-basins. They argue that this model can help to consider weights of policymaking norms by considering intricate relationships among different decision levels and adopting suitable watershed management strategies. Asl-Rousta and Mousavi (2018) have simulated discharge of Sirwan River in Iran by means of SWAT model and have investigated the impacts of the number and location of sites, parameter set, and calibration method on the performance of the model. The twelve calibration settings built are discriminated using TOPSIS approach. Liu et al., (2019) argue that since ecological operation of reservoirs and balancing of traditional benefits like irrigation and flood control involve multi-objective optimization, fuzzy evaluation is a worthy method. Golfam et al., (2019) opine that best scenario to adapting to climate change on agriculture based on data for a thirty-year period on Gharanghu basin, Iran. Eight reservoir efficiency criteria are used as evaluation indices and five scenarios created by reducing water demand amounts. The prioritization studies using AHP and TOPSIS throw out different results regarding the best scenario for agricultural water management.

However, there are only limited efforts in most of these studies, to understand and discuss the topographical, structural and lithological controls that influence the morphometric factors and their interrelationship in individual sub-basins. These, in turn have a bearing on the total river basin that help in the prioritization of their sub-basins vis-à-vis any given hydrological hazards like flooding or soil erosion. It is felt that such an attempt, as in this study, would enhance the efficacy in selection of water and soil management and remedial practices for which prioritization is done in the first place. This is the primary objective of the present work.

In this study, the VIKOR (ViseKriterijumska Optimizacija I Kompromisno Resenje in Serbian) method is the multi criteria analysis used. This method is characterized by its employment of aggregating functions; it focuses on compromising solutions for a prioritization problem with conflicting criteria as is commonly seen in natural systems, which can help decision makers obtain final solutions (Opricovic and Tzeng, 2004). The relative weights for the factors are obtained using SMARTER method. The salient details of how VIKOR was applied in combination with SMARTER method in the present study are discussed in the following section.

This work is part of our ongoing studies on the accuracy, sensitivity and resolution aspects of digital elevation models derived from different satellite data. Here, the prioritization is attempted on the sub-watersheds of Mahe river basin based on their susceptibility to flooding. The river experiences frequent phases of overflow during the monsoon seasons that last for about seven to eight months of a year. The unusually destructive flooding of 2018 (mortality of >440; economic damage exceeding \$3 billion) and 2019 in northern districts of Kerala (Mishra et al. 2018), gave impetus to the present work. The return periods of the then widely prevalent extreme rainfall events (≥ 204.5 mm), range from 75 to 500 years. Also, the inundated area could increase by about 16, 25, 37 and 40% for 5-, 25-, 50- and 100-year return periods of floods (CWC 2018). It is expected that the present work would help in evolving effective water control and conservation strategies.

2 Study Area

The Mahe river basin (MRB) falls between coordinates N11°35' 16', E75°30' 07'' in the south-west and N11°49' 00'', E75° 50' 07'' in the north-east in the State of Kerala, India (Fig. 1). The state of Kerala is located in the south western margin of the India, with a coastal length of 600 km and width ranging from 35 to 120 km (CWRDM 1995; Soman 2002). The extent of the state roughly resembles a scalene triangle, framed by mountains of Western Ghats (>800 m) along the eastern fringe and the Arabian sea to the west. This unique physiography gives rise to relatively short rivers (<244 km) but with high gradients. These ensure them a youthful nature with disproportionately high erosive power (Soman 2002).

Kerala supports the highest density of population (860/km²) among the states of India (382/km²) as per 2011 census (<https://knowindia.india.gov.in>), most of which are concentrated in the coastal plains in the lower reaches of forty-one rivers of the state. The state enjoys a humid tropical climate with an average annual precipitation of 3266 mm, where about 65% of the rainfall is contributed by the southwest monsoon (Srinivasan et al. 1972).

The Mahe river originates from Wynad Hills at an elevation of about 910 m and flows for 54 km before draining into the Arabian Sea. The area of the basin is about 402 km².

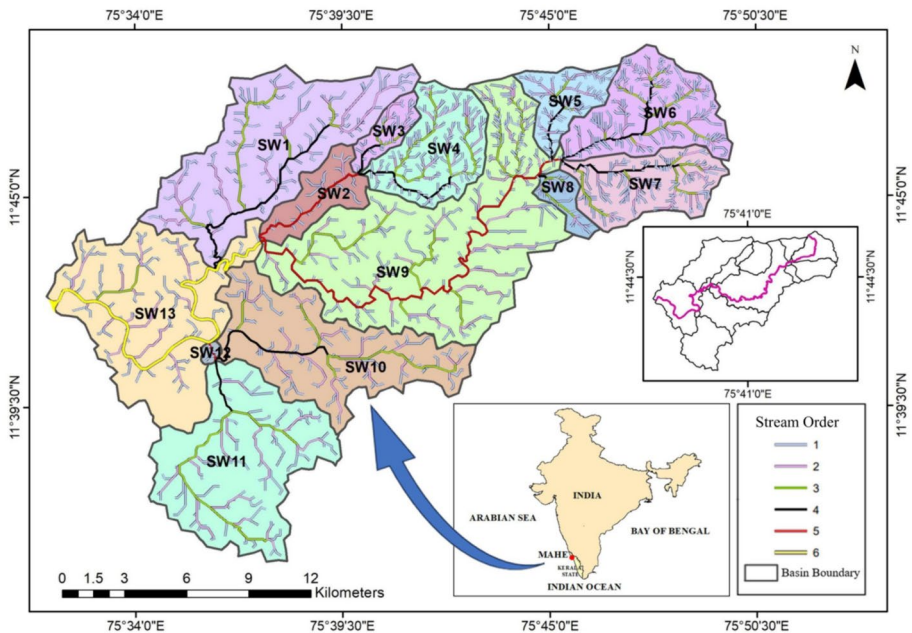


Fig. 1 Sub-watersheds of Mahe River Basin. The main stream is shown in red in the inset at the top

The average annual discharge of the river is about 248 Mm^3 (CWRDM 1995). The average temperature ranges between 25 to 28 °C.

The rock types in this area are dominantly hornblende biotite gneiss, charnockite, quartzo-feldspathic gneiss, pyroxene granulite, banded magnetite quartzite, younger granite, gabbro and mafic intrusives of different generations along with recent sedimentary deposits and laterites. The major set of fault lineaments trend (1) NW–SE to WNW–ESE, (2) NNW–SSE to N– S, and (3) ENE–WSW (Nair 1990). The influence of these is reflected in the rectangular drainage pattern of the Mahe, particularly in the upper courses and the sharp veering of its channels. The major geomorphic components in the area are denudational plateaus, denudational hills and valleys, denudational slopes, flood plain, and valley flat (GSI 2002). The coastal belt with alluvial and beach deposit underlain by laterite, yields abundant yield of water. Open dug wells meet the domestic needs of water. (CGWB 2022).

3 Materials and Methods

The study is based on data derived from Survey of India topographical maps (1:50,000) and Digital Elevation Models of Shuttle Radar Topographic Mission (SRTM) with a pixel size of 90 m. The thematic layers required for the study has been generated using Arc GIS 10 and ERDAS IMAGINE 2011 software. Mahe river basin is divided into thirteen sub-watersheds (Fig. 1), based on analysis from DEM and topographic sheets, and designated as SW 1 to SW 13. Computation of basin parameters required

for morphometric analysis, ordering, lengths, area, etc. are derived in a GIS platform. These are later used to calculate other morphometric parameters using established mathematical equations (Table 1).

Stream order, or classification of streams based on the number and type of tributary junctions, has proven to be a useful indicator of stream size, discharge, and drainage area (Strahler 1957). Essentially it is a method to quantify the hierarchy of linkage in a river network. One of the most accepted is the Strahler method (1964), whereby all the streams of the river network that does not have any tributary is designated as of order one. Two first streams join to form a stream segment of second order, two second order segments join to form a third order segment and so on. Mahe river is of sixth order with two fifth order tributary basins. The details are presented in Fig. 2 and Table 2. The higher number of lower order streams (like first and second), act as feeder channels contributing more water yield to the total basin as a whole.

Thirteen morphometric factors are identified to be significant for MCDA in this work which is further discussed in Table 1. Those are selected based on those parameters which factor in the basic topographic components like relief, slope, basin area, perimeter, length and number of streams etc. the basic morphometric parameters used to calculate each of them. Care has been taken, as far possible to avoid repetition of the same set of factors used as ratios or products. For example, drainage texture (which is product of drainage density and stream frequency) is not considered, since both parameters are separately taken into account. Similarly, form factor, F_f and compactness coefficient, C_c are also left out in the study. They are essentially of ratios of areas between basin lengths and perimeters, respectively. These proportions are represented in elongation ratio and circularity ratios, which are discussed here.

VIKOR method focuses on ranking and selecting from a set of alternatives in the presence of conflicting criteria. VIKOR methodology has been applied to different engineering domains. Fallahpour and Moghassem (2012) have applied for parameter selection problem in rotor spinning. Arif et al. (2020) has addressed the prioritization of the goods sellers in e- market place by integrating VIKOR with the SMARTER method. Mohsen and Fereshteh (2017) have used this method to rank and prioritize the failure modes in a geothermal power plant. Kuo and Liang (2011) have used the method to evaluate service quality of airports. The method offers a variety of advantages:

- The method uses a linear method of normalizing.
- The method uses an aggregating function representing the distance from ideal solution, considering the relative importance of all criteria, and a balance between total and individual satisfaction (Fallahpour and Moghassem 2012).

The general steps involved in the VIKOR method are:

- Step 1: Establish a matrix of criteria and different alternatives.
- Step 2: Determine the weights for each factor.
- Step 3: Determine the best and worst values of all factor functions.
- Step 4: Calculate the utility measure and regret measure for each alternative
- Step 5: Calculate the value of VIKOR index
- Step 6: Rank the preference order

Table 1 Description of morphometric parameters used in prioritisation of sub-watersheds

Parameter	Definition	Formula	Implications	Remarks
Stream length ratio R_L Horton (1945)	The stream length ratio can be defined as the ratio of the total stream length of a given order to the total stream length of next lower order	L_u/L_{u-1}	If the terrain is permeable and/or of low gradient smaller number of streams of longer lengths are formed. Permeability depends on soil/rock type, gradient, vegetation, stage of development and topography	Reflects the hydrological characters of the basin of consecutive orders. Higher values point to less runoff than that for lower values. For subsurface flow the reverse trend is seen Flood (high peak flows with shorter lag) potential of the subbasins in the reverse order of L_{SR} -
Bifurcation Ratio R_b Schumm (1956)	The bifurcation ratio (R_b) is the ratio between stream numbers of a particular order and next higher order	N_u/N_{u+1}	Values between 3-5, when the terrain materials are homogeneous. Higher values indicate marked structural control. Higher R_b lead to surface discharge with high peak flows with low lag time leading to potential flash flooding during storm events	The higher ' R_b ' value for river basins is the result of large differences in number of streams between consecutive orders reflecting their low permeability, high gradient and structural control Flood potential of the subbasins in the increasing order of R_b +
Drainage Density D_d Horton (1945)	Drainage density is defined as the total length of all streams in a basin divided by the area of the basin	L_u/A	D_d is high for terrain with high relief and sparse vegetation. The value is subdued in areas of low relief, gradient, permeable material	Higher values indicate potential for high discharge with high peak flows. D_d classed as Low < 2 km/km ² , Moderate (2-2.5), High (2.5-3) and Very high (> 3) Flood potential of the subbasins in the increasing order of D_d +

Table 1 (continued)

Parameter	Definition	Formula	Implications	Remarks
Stream Frequency F_s Horton (1945)	Stream frequency is the total number of stream segments of all order per unit basin area	Nu/A	Values are a function of high runoff, lithologic characters, vegetation, permeability, gradient and relief	Higher values indicate potential for high discharge with high peak flows Low 0–5 Moderate 5–10 Moderate high 10–15 High 15–20 Very high 20–25 Low 0–5 Moderate 5–10 Moderate high 10–15 High 15–20 Very high 20–25 Low 0–5 Moderate 5–10 Moderate high 10–15 High 15–20 Very high 20–25 Flood potential of the subbasins in the increasing order of $F_s +$
Length of overland flow L_o Horton (1945)	Length of overland flow is the length of water over the ground before it gets concentrated into definite stream channels	$l/2Dd$	High amounts reflect longer flow paths, which in turn point to gentler slopes, low flow rates and higher permeability of the basins	Low values indicate the lengths of shorter paths of sheet flow before concentrating to channelised flow and become part of the fluvial network. Higher values indicate potential for lower discharge with longer time to reach peak flows Flood potential of the subbasins in the reverse order of L_o^-

Table 1 (continued)

Parameter	Definition	Formula	Implications	Remarks
Relief Ratio, R_r Hadley and Schumm (1961)	Basin relief is the ratio between the difference in elevation between the highest and the lowest point of the basin and basin length	$(H-h)/Lb$	Influences the development of landscape, gradient, infiltration, erosion, sediment flux, and surface and subsurface runoff	Enhances the potential of flooding and sediment transport, considering other controls constant High R_r creates high flood potential +
Gradient Ratio G_r Schumm (1956)	Gradient Ratio is ratio between the difference in elevation between the source and mouth of the stream channel and basin length	$(z-Z)/Lb$	Indicator of surface flow rate and erosion processes. High values in mountainous terrain	Directly influences the chances of flash flood with high peak flows of shorter duration Flooding potential directly proportional to G_r values +
Ruggedness Number MR_n Melton (1958)	Ruggedness Number is the ratio between Basin Relief and the square root of the basin area	$D_r/A^{0.5}$	Indicator of efficiency for peak discharge, soil erosion, sediment load, gradient, relief ruggedness and structural complexity	High ratios indicate potential flash floods. Lower ones reflect potential for peak discharge of longer lag times and duration Water Flood (<0.3), Debris Flood (0.3–0.6) Debris Flow (>0.6) Flood potential of the subbasins in the increasing order of R_n +
Texture Ratio T Schumm (1956)	Texture ratio is the total number of first order streams and the basin perimeter	N/P	Useful in comprehending relative spacing of the drainage lines and underlying lithology, infiltration capacity and relief aspect of the watershed	High values indicate rounded basins, revealing high flood potential due to high flow rates and low percolation capacity of terrain. Elongated basins reflect longer duration of flow path, higher infiltration and hence subdued chances of flooding Flood potential of the subbasins in the increasing order of T +

Table 1 (continued)

Parameter	Definition	Formula	Implications	Remarks
Elongation Ratio R_e Schumm (1956)	It is the ratio between the diameter of the circle of the same area as the drainage basin and the maximum length of the basin	$R_e = (2/Lb) * (A/\pi)^{0.5}$	When $R_e = 1$, it is a perfectly circular basin. As the basin approaches a circle, the discharge would be high with decreasing infiltration rates. Influenced by relief and gradient. Reflects hydrological character. The lower values indicate elongated sub-basin representing the youth stage of the river basins that are tectonically controlled, whereas higher values indicate the circular shape of the basin having uniform erosion	Marked relief and slopes would enhance the elongation of basins. R_e values approaching 1 point to gentler slopes High (>0.9), Moderate (0.9-0.7), and Low (<0.7) Flood potential of the subbasins in the decreasing order of R_e -
Circularity Ratio R_c Miller (1953), Strahler (1964)	Circularity ratio is the ratio of the basin area to the area of a circle having the same circumference perimeter as the basin	$R_c = 4\pi A/P^2$	Influenced by stream length, spacing, stage of development of the basin, and structural nature and land cover. When $R_c = 1$, it is a perfectly circular basin	Low R_c values specify that the surface runoff will take a longer time to reach the outlet of the watershed and lower potential of flash floods High (>0.7), Moderate (0.4-0.7), and Low (<0.4) Flood potential of the subbasins in the decreasing order of R_c -
Total Wetness Index TWI Moore (1993)	Total Wetness Index is the natural logarithm of the ratio between basin area and slope gradient in radians	$TWI = \ln (A/\tan \beta)$	Indicator of flow accumulation, soil moisture and thickness and vegetation. Higher TWI indicate zones of saturation in the basin	Low values indicate potential for high peak flows of shorter lag time. As the indices increase, concentration of discharge potentially leads to low peak flows of longer duration Flood potential of the subbasins in the decreasing order of TWI -

Table 1 (continued)

Parameter	Definition	Formula	Implications	Remarks
Stream Power Index SPI Moore (1993)	Stream Power Index is the product between basin area and tan of slope gradient in radians	$SPI = A^* \tan \beta$	Index of erosion potential echoing the slope, channel gradient, discharge, vegetation, texture, sediment load	Higher values indicate higher stream power and enhanced potential for flash floods Flood potential of the subbasins in the increasing order of SPI +

Lu- total stream length of order u, Nu- total no. of stream segments of order u, Lu-1- total stream length of its next lower order, P- perimeter (km), Nu+1- number of segments of the next higher order, H- total relief (relative relief) of the basin in kilometer, A- area of the basin (km²), N1- total no. of first order streams, Z- maximum elevation of the basin, z- lowest elevation, h- elevation at source, H- elevation at mouth, β- slope in radians

+directly proportional to flood potential

- inversely proportional to flood potential

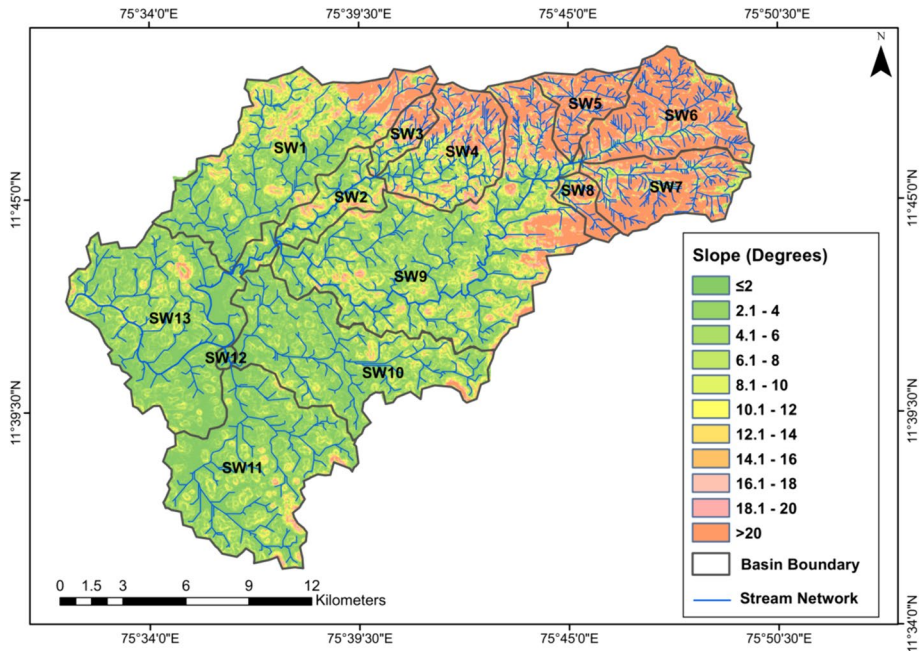


Fig. 2 Slope map of Mahe River Basin

4 Discussion

The relationship between parameters and flood potential is given in Table 1. Higher the values for certain parameters, greater the potential for discharge with high peak flows with shorter lag times for water from upper part of the basin to reach the outlet. These in turn enhance the rate and pace of occurrence of floods. However, the correlation of each of these parameters with the flooding potential is not in the same proportion for each sub-basin (for instance, the highest values of these factors are not exhibited by the same sub-basin). This also holds true for the geometric factors that correlate inversely with discharge and flooding potential. The flooding potential of each basin and its sub-basins are governed by the collective influence of morphometric factors with each other and topographic elements (such as slope, relief, rock and soil characters), tectonics, climatic aspects like temperature and precipitation in a steady state equilibrium (Ritter et al. 1995). This is attested by their conformity to Horton's laws ($r > 0.98$) which contend that the total length and number of streams decrease with increasing order in a geometric series (Horton 1932). On the other hand, the mean stream length shows a positive correlation with stream orders.

SW 12 is the smallest basin (area $< 1 \text{ km}^2$), partially bounded by hillocks and topographic rises, where the river flows over less than 1 km. The small area and perimeter give rise to high drainage density and stream frequency, texture ratio and low TWI and SPI values. Since the first order streams directly join the main fifth order river, its bifurcation and stream length ratios could not be estimated. Its rather peculiar morphometric characters and low spatial extent have induced us to consider it as an 'aberrance' and exclude this sub-basin from further discussions.

Table 2 Morphometric parameters of the sub-watersheds of Mahe basin

Parameters	SW 1	SW 2	SW 3	SW 4	SW 5	SW 6	SW 7	SW 8	SW 9	SW 10	SW 11	SW 12	SW 13	Basin
h	14.00	17.00	23.00	23.00	72.00	77.00	77.00	58.00	17.00	14.00	14.00	13.00	0.00	0.00
H	790.00	145.00	770.00	1026.00	1112.00	1152.00	1348.00	989.00	1036.00	183.00	131.00	20.00	124.00	1348.00
z	15.00	17.00	23.00	23.00	67.00	77.00	77.00	55.00	17.00	14.00	14.00	13.00	0.00	0.00
Z	727.00	23.00	665.00	936.00	903.00	1112.00	757.00	834.00	77.00	49.00	29.00	14.00	17.00	1112.00
Relief, R	776.00	128.00	747.00	1003.00	1040.00	1072.00	1271.00	931.00	1019.00	169.00	117.00	7.00	124.00	1348.00
Melton Ruggedness Ratio MR_n	0.10	0.04	0.31	0.21	0.32	0.20	0.28	0.43	0.11	0.03	0.02	0.01	0.02	0.07
Gradient	712.00	6.00	642.00	913.00	836.00	1035.00	680.00	779.00	60.00	35.00	15.00	1.00	17.00	1112.00
Relief ratio, R_r	0.0563	0.0204	0.1545	0.1475	0.2257	0.1319	0.1553	0.2329	0.0655	0.0136	0.0113	0.0078	0.0117	0.0404
Gradient ratio, G_r	0.0517	0.0010	0.1328	0.1343	0.1815	0.1273	0.0831	0.1948	0.0039	0.0028	0.0015	0.0011	0.0016	0.0333
Slope in radians	0.06	0.02	0.15	0.15	0.22	0.13	0.15	0.23	0.07	0.01	0.01	0.01	0.01	0.04
Slope in degrees	3.22	1.17	8.79	8.39	12.72	7.51	8.83	13.11	3.75	0.78	0.65	0.45	0.67	2.31
Area (A) km^2	54.80	11.29	5.65	22.84	10.89	27.91	21.35	4.60	88.68	45.21	52.07	0.82	56.69	402.79
Perimeter (P) km	41.69	18.48	11.57	21.04	16.90	24.75	21.63	10.82	59.94	43.18	37.19	3.42	43.93	112.59
Basin length (Lb) km	13.78	6.28	4.83	6.80	4.61	8.13	8.18	4.00	15.56	12.40	10.31	0.90	10.64	33.36
Drainage Density (D)	1.69	1.68	3.36	3.43	3.29	3.29	3.42	3.23	1.92	1.65	1.48	2.17	1.41	2.06
Stream Frequency (F_s)	2.21	2.21	7.78	7.75	8.45	7.67	7.63	8.70	3.00	2.12	1.67	4.88	1.53	3.52
Drainage Texture (T)	3.73	3.72	26.19	26.56	27.83	25.25	26.10	28.08	5.75	3.50	2.48	10.58	2.17	7.23
Circularity Ratio (R_c)	0.40	0.42	0.53	0.65	0.48	0.57	0.57	0.49	0.31	0.30	0.47	0.88	0.37	0.40
Elongation Ratio (R_e)	0.61	0.60	0.56	0.79	0.81	0.73	0.64	0.61	0.68	0.61	0.79	1.14	0.80	0.68
Length of Overland Flow (L_o)	0.30	0.30	0.15	0.15	0.15	0.15	0.15	0.15	0.26	0.30	0.34	0.23	0.35	0.24
N/P	2.33	1.19	2.94	6.65	4.38	6.99	6.15	2.77	3.59	1.67	1.83	0.88	1.59	10.05
Total Wetness Index (TWI)	6.88	6.32	3.60	5.04	3.88	5.35	4.92	2.98	7.21	8.11	8.43	4.65	8.49	9.21
Stream Power Index (SPI)	3.09	0.23	0.87	3.37	2.46	3.68	3.32	1.07	5.81	0.62	0.59	0.01	0.66	16.27
Sub-watersheds	SW1	SW2	SW3	SW4	SW5	SW6	SW7	SW8	SW9	SW10	SW11	SW12	SW13	Basin
Total stream length (L_o) of order u in km	1.00	49.32	10.81	9.95	44.63	21.08	57.28	44.68	8.20	85.88	35.66	38.30	0.88	37.70
	2.00	19.46	1.38	4.06	15.28	9.22	16.38	13.16	2.55	35.59	19.08	22.27	17.75	176.18

Table 2 (continued)

Parameters	SW 1	SW 2	SW 3	SW 4	SW 5	SW 6	SW 7	SW 8	SW 9	SW 10	SW 11	SW 12	SW 13	Basin
	3.00	11.95		2.94	12.54	2.04	11.20	8.76	3.59	22.13	12.31	13.92		104.59
	4.00	11.75		2.07	5.84	3.51	7.04	6.41	0.50		7.42	2.74		47.28
	5.00		6.78							26.41			0.90	34.08
	6.00													21.33
$\sum Lu$	92.49	18.97	19.02	78.30	35.85	91.90	73.01	14.84	170.00	74.47	77.23	1.78	80.00	827.85
Stream length ratio (R_L)	2/1	0.39	0.13	0.41	0.34	0.44	0.29	0.31	0.41	0.54	0.58	0.00	0.47	0.40
	3/2	0.61	0.72	0.82	0.22	0.68	0.67	1.41	0.62	0.65	0.62		0.18	0.59
	4/3	0.98	0.70	0.47	1.72	0.63	0.73	0.14	0.00	0.60	0.20		0.00	0.45
	5/4										0.00			0.72
	6/5		0.00									0.00		0.63
Mean	0.66	0.13	0.61	0.54	0.79	0.53	0.56	0.62	0.35	0.59	0.47	0.00	0.22	0.56
Number of streams (Nu) of different stream order (t)	1.00	97.00	22.00	34.00	140.00	74.00	173.00	133.00	30.00	215.00	72.00	68.00	3.00	1131
	2.00	18.00	2.00	7.00	32.00	14.00	32.00	23.00	7.00	44.00	19.00	16.00		229.00
	3.00	5.00		2.00	4.00	3.00	8.00	6.00	2.00	6.00	4.00	2.00		43.00
	4.00	1.00		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00		9.00
	5.00		1.00						1.00			1.00		3.00
	6.00													1.00
$\sum Nu$	121.00	25.00	44.00	177.00	92.00	214.00	163.00	40.00	266.00	96.00	87.00	4.00	87.00	1416
Bifurcation ratio (R_b)	1.00	5.39	11.00	4.86	4.38	5.29	5.41	5.78	4.29	4.89	3.79	4.25		4.67
	2.00	3.60		3.50	8.00	4.67	4.00	3.83	3.50	7.33	4.75	8.00		15.00
	3.00	5.00		2.00	4.00	3.00	8.00	6.00	2.00		4.00	2.00		4.78
	4.00		0.00							0.00		0.00		3.00
	5.00													3.00
Mean	4.66	11.00	3.45	5.46	4.32	5.80	5.21	3.26	6.11	4.18	4.75		0.00	9.83

Minimum Elevation, H-Maximum Elevation, z- Elevation at mouth, Z- Elevation at source

The morphometric parameters of Mahe river (Table 2) reveals it to be a sixth order basin with moderately high runoff as attested by its moderate slope (2.31°), gradient ratio (0.03), bifurcation ratio (4.21), density, stream frequency and consequently lower base flow, percolation rate. The varying nature of slope, relief and other topographic factors, lithological components and tectonic elements account for the fluctuating values of bifurcation ratios (Fig. 1; Table 2). This is in contrast to the theoretical concept that bifurcation ratios decrease with increase of stream orders (Chorley et al. 1984). The relatively high values of length of overland flow (0.24) indicate the appreciable span of flow before it is channelized, reflecting the overall gradient of the basin. The shape parameters of the river identify it to be an elongated basin (low $R_c < 0.4$; $R_e < 0.7$) as per Makrari et al. 2022 with flatter flows with longer lag times. The development of the basin is influenced by topography and terrain than tectonic elements (as R_b is between 3 and 5 (Strahler 1957)). Thus, the Mahe is revealed to possess lower potential for flooding and inundation. This is underscored by the significant wetness index (> 8.3 , Thomas et al. 2012) and lower stream power index highlighting the appreciable groundwater storage and moderate erosion potential (Table 2). This is further underscored by the Melton ruggedness of 0.07, indicating Mahe to be a water flood basin, since $MR_n < 0.3$ (Wilford et al. 2004; Makrari et al. 2022), rather than one where debris flood occurs.

The VIKOR method is implemented for the morphometric factors related to sub-watersheds of Mahe river basin. The steps mentioned above as motivated by Fallahpour and Moghassem (2012) has been applied here and is presented hereunder:

Step 1: The thirteen key morphometric factors (MF) pertaining to thirteen sub-watersheds of Mahe river basin are summarized in Table 3. This is considered for the application of VIKOR methodology.

Step 2: The determination of weights (W) for each factor is obtained by using Simple Multi-Attribute Rating Technique Exploiting Ranks (SMARTER) method. The method is prompted by Arif et al. (2020), wherein it determines the weight of each factor based on Rank Order Centroid (ROC).

Determination of priority factor based on the relative importance of the factor can be written $C_1 \geq C_2 \geq C_3 \geq \dots \geq C_j$, to determine its weight. Weighting with the ROC technique, can be formulated as $W_j = \left(\frac{1}{J}\right) \sum_{i=j}^J \left(\frac{1}{i}\right)$, where J is expressed as the number of factors, j as j -th factor, and I expressed as order of the factor ($i = 1, 2, 3, \dots, j$). Here thirteen factors are rank ordered based on their importance and subsequently factor weights are calculated with the ROC formulation and are given in Table 4.

Step 3: Determine the best f_j^* and the worst f_j^- values of all factor functions. If the factor contributes lesser to the floods, then use the function $f_j^* = \max_j f_{ij}$ and $f_j^- = \min_j f_{ij}$. If the factor contribute more to the floods, then use the function $f_j^* = \min_j f_{ij}$ and $f_j^- = \max_j f_{ij}$, where I expressed as order of water shed basins ($i = 1, 2, 3, \dots, n$), and j expressed as order of factors ($j = 1, 2, 3, \dots, m$). Accordingly,

the best f_j^* and the worst f_j^- values of all thirteen factor functions are calculated and are presented in Table 5.

Step 4: The utility measure or the value of alternative distance to the positive ideal solution (S_i) and the regret measure or the value of alternative distance to the negative ideal solution (R_i) are calculated for each of the thirteen sub-watersheds using the following formula:

$$S_i = \sum_{j=1}^n W_j \frac{(f_j^* - f_{ij})}{(f_j^* - f_j^-)}$$

$$R_i = \max_j \left[W_j \frac{(f_j^* - f_{ij})}{(f_j^* - f_j^-)} \right]$$

Where W_j is the weight of factor obtained in step 2 using SMARTER method. The calculated values of S_i and R_j for each of the thirteen sub-watersheds are presented in Table 6.

Step 5: VIKOR index (Q_i) is calculated for each of the thirteen sub-watersheds using the following formula:

$$Q_i = v \left[\frac{(S_i - S^*)}{(S^* - S^-)} \right] + (1 - v) \left[\frac{(R_i - R^*)}{(R^* - R^-)} \right]$$

Where $S^* = \min_i S_i$; $S^- = \max_i S_i$; $R^* = \min_i R_i$; $R^- = \max_i R_i$ and v is given as a weight for the strategy of maximum group utility and $(1-v)$ is the weight of the individual regret v can take any value ranging from 0 to 1; normally the value of v is taken as 0.5 (Cristobal

Table 3 Morphometric factors values for thirteen sub-watersheds of Mahe River Basin

Sub-watersheds	Morphometric Factors (MF)												
	MR_n	G_r	R_r	R_b	R_L	D_d	F_s	R_c	R_e	L_o	T	TWI	SPI
SW1	0.1048	0.0517	0.0563	4.66	0.96	1.69	2.21	0.40	0.61	0.30	2.33	6.88	3.09
SW2	0.0381	0.0010	0.0204	11	6.96	3.36	2.21	0.42	0.60	0.15	1.19	6.32	0.23
SW3	0.3142	0.1328	0.1545	2.58	0.85	3.51	7.78	0.53	0.56	0.14	1.30	3.60	0.87
SW4	0.2099	0.1343	0.1475	5.46	0.52	3.55	7.75	0.65	0.79	0.14	6.65	5.04	3.37
SW5	0.3152	0.1815	0.2257	4.22	0.98	3.09	7.72	0.48	0.81	0.16	4.02	3.88	2.46
SW6	0.2029	0.1273	0.1319	5.45	0.50	3.16	7.17	0.57	0.73	0.16	6.50	5.35	3.68
SW7	0.2751	0.0831	0.1553	5.1	0.46	3.43	7.40	0.57	0.64	0.15	6.01	4.92	3.32
SW8	0.4342	0.1948	0.2329	3.31	0.96	1.85	8.92	0.49	0.61	0.15	2.87	2.98	1.07
SW9	0.1082	0.0039	0.0655	5.76	0.53	1.65	2.70	0.31	0.68	0.27	3.17	7.21	5.81
SW10	0.0251	0.0028	0.0136	4.18	0.59	1.48	2.12	0.30	0.61	0.30	1.67	8.11	0.62
SW11	0.0162	0.0015	0.0113	4.75	0.60	2.17	1.67	0.47	0.79	0.34	1.83	8.43	0.59
SW13	0.0165	0.0016	0.0117	9.83	0.33	2.08	1.53	0.37	0.80	0.35	1.59	8.49	0.66

Table 4 Factor weights determined using SMARTER method

<i>MF</i>	<i>MR_n</i>	<i>G_r</i>	<i>R_r</i>	<i>R_b</i>	<i>R_L</i>	<i>D_d</i>	<i>F_s</i>	<i>R_c</i>	<i>R_e</i>	<i>L_o</i>	<i>T</i>	<i>TWI</i>	<i>SPI</i>
<i>Weights</i>	0.036	0.129	0.045	0.084	0.056	0.245	0.168	0.019	0.012	0.069	0.104	0.027	0.006

Table 5 Best f_j^* and the Worst f_j^- values for the morphometric factors

<i>MF</i>	<i>MR_n</i>	<i>G_r</i>	<i>R_r</i>	<i>R_b</i>	<i>R_L</i>	<i>D_d</i>	<i>F_s</i>	<i>R_c</i>	<i>R_e</i>	<i>L_o</i>	<i>T</i>	<i>TWI</i>	<i>SPI</i>
<i>Best, f_j[*]</i>	0.0162	0.0010	0.0113	3.26	0.7900	1.41	1.53	0.65	0.81	0.34	6.99	8.43	0.230
<i>Worst, f_j⁻</i>	0.4342	0.1948	0.2329	11	0.1300	3.43	8.7	0.3	0.56	0.15	1.19	2.98	5.810

2011). The calculated value of VIKOR index for the sub-watersheds are presented in Table 7.

Step 6: Rank the sub-watersheds after sorting by the values of Q_i in decreasing order. In the present study the priority ranks of the sub-watersheds were determined by the Q value so as to compromise the S and R values (Lee et al. 2014). The ranks of the sub-watersheds are presented in Table 6. Higher the rank, more vulnerable the sub-watershed for the floods. Consequently, sub-watersheds SW 3-8 are found to most prone to inundation, while SW 9-13 is found to be least susceptible. These findings are further analysed in terms of topographical, structural and lithological framework.

The spatial analysis of constituent subbasins presents marked contrasting characters from those of Mahe basin, reflecting the difference in terrain, properties of soil, rock and gradient characters within the basin (Ramasamy et al. 2021). VIKOR analysis have recognized SW 3–8 as the sub-watersheds, most vulnerable to flooding. These comprises about 23.2% of the total basin area and are disposed in the crystalline rock terrain of Western Ghats (GSI 2002; Soman 2002). They are characterized by, in general, low areal values, higher relief and gradient ratios $> \sim 0.10$, i.e. 5.71° (Figs. 1 and 2). SW 3–8 are also distinguished by very fine texture (> 26), the highest number of first order streams, slope ($> 7.5^\circ$), Melton ruggedness number (> 0.21) and texture number (> 6). These are indicative of the high gradient and impermeable rocky terrain exposed in parts of these sub basins. The lowest L_o values (0.15) reveal the short flow paths before concentrating into distinct stream channels. In addition, the steep drainage divides (Fig. 2) of sub-basins with their high relief, funnels water from lower orders into the main streams catalyzing narrow high peak flows with shorter flow duration (Avcı 2023). Such tributaries ensure highest discharge per unit area in a basin, though their individual total discharge would be much diminished than the main stream (Ritter et al. 1995). The general circularity and elongation ratios are less than 0.4 and 0.6 indicate their elongated nature, as observed in basins with high gradients (Schumm 1956; Manu and Anirudhan 2008; Kumar et al. 2011). These, thereby reflect their substantial infiltration capacities. These basins are covered by thick tropical ever green forests and attendant thick humus, which is known to encourage water infiltration of the terrain and thus subdues discharge and flooding potential (Chorley et al. 1984; Charlton 2007). However, in SW 3–8, morphometric characters discussed

previously seem to have offset the effects of vegetation and their elongated nature. TWI, a negating parameter of discharge exhibits the lowest values, pointing to the lower base flow and groundwater storage. The Melton ruggedness ratios indicates basins SW 4,6 and 7 belong to the upper grade of water flood category (<0.3), while the rest are capable of debris rich floods (as high as 0.43 in SW 8). The relation between stream number and drainage density ($r=-0.77$) indicates marked influence of headward erosion for these sub-basins. Such trends were noted for the Mahe by Ramasamy et al., (2021) and has also been observed elsewhere (Hack 1957; Mulder and Syvitski 1996; Thomas et al. 2010; Choudhari et al. 2018). On the other hand, in rest of the sub-watersheds this relation is very explicit ($r=0.99$), along expected lines.

The terrain of SW 1 (ranked 5 in MCDM) includes topography of moderate elevation (790 m), relief (776 m.), slope (3.22°), bifurcation ratio (4.66) but with its considerable gradient (712 m.), low D_d (1.68) and elongated nature (Fig. 1; Table 2). These combined with the physiographic unit of laterite uplands (Ramasamy et al. 2021), the porous nature of which encourages infiltration and has a subduing influence on surface runoff. In this sub-basin, the high runoff benefitted from its high relief, gradient and resistant impermeable rocks (Schumm 1956; Ritter et al. 1995) in its upper reaches are to a limit muffled by the lateritic components further downstream. This is further influenced by its considerable areas and elongated nature, resulting in flatter peaks with longer lag times than expected leading to reduced threat of flooding. The medium values of L_o (0.30), underscore the significant base flow and infiltration nature of the terrain. The lower order stream networks coalesce and spreads out in the lower part of the sub-basin where the lower relief, and slope result in flatter topography, relatively unimpeded by restrictions imposed by mountain divides and tectonic lineaments.

SW 2, in contrast is of less steepness (1.17°), gradient ratio (0.001), relief (128 m.), compared to SW1 (Fig. 2). However, the similar values are seen in texture and drainage ratios, wetness index, shape factors, mean stream lengths (Table 2). The bifurcation ratios of first order streams indicate the significant structural control and more importantly, the substantial contribution to runoff from these feeder channels for this rather small subbasin ($\sim 11 \text{ km}^2$). Small basins are known to enhance flooding potential (Ritter et al. 1995) with high peak flows and short lag times (Avci 2023). Further, the cumulative discharge from the upstream subbasins forming the fifth order SW 2 supply sizably to the runoff, that is

Table 6 S_i and R_i values for Sub-watersheds

<i>Sub-watersheds (SW_i)</i>	S_i	R_i
SW1	0.2606	0.0850
SW2	0.3445	0.1036
SW3	0.7271	0.2361
SW4	0.6647	0.2446
SW5	0.7405	0.2277
SW6	0.6421	0.2277
SW7	0.6505	0.2434
SW8	0.8035	0.2204
SW9	0.3124	0.0618
SW10	0.2131	0.0950
SW11	0.1590	0.0922
SW13	0.2296	0.0965

Table 7 Q_i and Rank order values for Sub-watersheds

<i>Sub-watersheds (SW_i)</i>	S_i	R_i	Q_j	<i>Rank</i>
SW1	0.2606	0.0850	0.1494	5
SW2	0.3445	0.1036	0.2583	6
SW3	0.7271	0.2361	0.9175	11
SW4	0.6647	0.2446	0.8923	9
SW5	0.7405	0.2277	0.9048	10
SW6	0.6421	0.2277	0.8284	7
SW7	0.6505	0.2434	0.8780	8
SW8	0.8035	0.2204	0.9338	12
SW9	0.3124	0.0618	0.1190	2
SW10	0.2131	0.0950	0.1329	3
SW11	0.1590	0.0922	0.0831	1
SW13	0.2296	0.0965	0.1426	4
S^+, R^+	0.1590	0.0618		
S^-, R^-	0.8035	0.2446		

not reflected in its morphometric values. The permeable laterite that is widespread in the terrain restrains the surface runoff to an extent, a scenario similar to that of SW 1. Thus, SW 1 and 2 constituting about 16.4% of MRB, offer restrained susceptibility (ranked 5 and 6) to flooding, compared to SW3–8.

Such characteristics are more pronounced in SW 10, 11 and 13 that constitute about 38% of the Mahe basin area that virtually comprises the coastal plains (Figs. 1 and 2). These are characterized by lateritic soil and alluvium (and the lateritic highlands in their upstream) that favour percolation of water to the water table where most of agriculture here is concentrated. This is confirmed by highest (mostly > 8) wetness indices, emphasizing the reduced susceptibility to flooding. The slight gradient (0.65–1.2°) likely spawns the low drainage density (< 2) and frequency (and attendant very coarse texture of < 2) and Melton number (0.02–0.04) and very high length of overland flow (0.30–0.35). This is also borne out by low elongation and circularity ratios of the sub-basins of lower relief (i.e., except SW 3–8), which do not display high values as expected in lower relief portions of a river (Schumm 1956). Obviously, the effect of the permeable thick soil and alluvial deposits and the underlying laterite affect the surface runoff (Rai et al. 2014; Aparna et al. 2015) accounting for the low to moderate ratios.

SW 9 with its steep upstream portions (> 20°), expresses a morphometric pattern comparable to SW 1 in many respects (Table 2) but is graded as the one which is second least prone to flooding (Fig. 3). However, the lower gradient ratio (as opposed to slope gradient), reflects the subdued potential energy of the discharge. Its elongated nature, and being the largest sub-watershed, translates to longer length of flow, lag time and consequently lower vulnerability to inundation. In addition, the billowing of its lower reaches and the laterite and lateritic and alluvial soil of landscape checks the energy of the stream, resulting in lower value (vis-à-vis its size) of SPI (5.81), with larger flow accumulation (TWI-7.21) and rate of soil infiltration.

Thus, SW 9–13, that includes the largest sub-watersheds consists of 60.4% of the Mahe basin. As discussed above, the morphometric framework of these sub-basins ensure high infiltration rate of water (and greater base flow) and hence, as the least prone to flooding

in Mahe. The VIKOR analysis too supports this trend. In fact, they form good aquifers as attested by the groundwater yield here (CGWB 2012; 2017). The flood plains and associated wet lands effect a flood controlling system that holds a large amount of water as part of the base flow. This checks the magnitude and height of peak flows that last over a longer duration (Chorley et al. 1984; Ritter et al. 1995). Again, the large swath of the basin encompassing the lower reaches of these sub-watersheds ensure that the flooding effects of the upper sub water sheds are curtailed to an extent, by promoting the broadening out of water.

SW 3–8, nestled at the heights of Western Ghats is benefitted by greater precipitation there (>4000 mm) than the midland and coastal plains in Kerala (Rao and Ramamurti 1968; CWC 2018). Moreover, the orographic effect on precipitation ensures that rainfall increases with height in the Ghats (Tawde and Singh 2014; Halder et al. 2022). Consequently, it is a common observation that even moderate showers in the Ghats sometimes lead to inundation in the higher reaches of rivers (CWC 2018). The short lengths and high gradients of Kerala rivers (11.6° in the mountains to 3.67° at the onset of lowlands, in the case of the Mahe) along with their conducive morphometric factors and flatter topographic nature, ensure that the enhanced collective discharge in sub-basins SW 3–8 during rains, is rapidly emptied to the lower stretches of rivers. The heightened runoff thus produced, leads to broader peaks flows (as discussed earlier) in the coastal plains (i.e. in SW 9–13 in Mahe), that takes a longer time to recede. This is borne out by previous studies (CWC 2018; Das 2020) that reveal that risk of spiked runoff increases in the lower reaches of streams during monsoons, where the population density is highest (<https://ecost.kerala.gov.in/>; Das 2020). Ponding up of water has been observed in many stretches of streams in the midland and coastal areas of Kerala, related to movements along fault zones (Valdiya and Narayana 2007). This probably augments the phases of high discharge during monsoons, adding to the impact of runoff from upstream. Another catalytic feature is the massive deforestation occurring in the Ghats (Padma 2018; Ramachandra and Bharath 2020). However, our ongoing studies reveal that unbridled and rampant constructive practices occurring over the past decades (and thus decreasing the permeability of the sub-basin) likely contributes to the destruction of the natural flood control system, leading to the gradual increase of frequency and extent of floods. This trend is in line with findings of previous studies in the state (George and Chattopadhyay 2001; John et al. 2020) and their effects on surface runoff (Dixit et al. 2022).

From the above discussions, it is seen that sub-watersheds of the Mahe may be categorized into three groups (Fig. 3), based on their flooding potential- Low (SW 9, 10, 11, 13), Moderate (SW 1,2) and High (SW 3, 4,5, 6, 7,8). Suitable control and management strategies could be planned and implemented based on proneness to flooding befitting each sub-watershed. The study highlights the efficacy of MCDA techniques like VIKOR to prioritise sub-basins with respect to any given hazard. However, multi-dimensional studies incorporating discharge and Land Use-Land Cover (LULC) patterns would further enhance the clarity runoff characteristics of a river basin and in consequence, the flooding potential.

Currently, no flood control structures exist in the Mahe. Construction of flood control measures like diversion dams and channelization methods (except resectioning or dredging) may not be feasible when the high population density (as much as $4646/\text{km}^2$ in Mahe district, <https://mahe.gov.in>) and compact built-up patterns extending right to the edge of the river are considered. Implementation of Flood plain zonation based on the flood susceptibility would also be difficult for social and economic reasons. Also, they would involve resettling and rehabilitation of populace and large-scale modification/removal of existing construction structures. Dams in the sparsely populated mountainous terrain of the basin

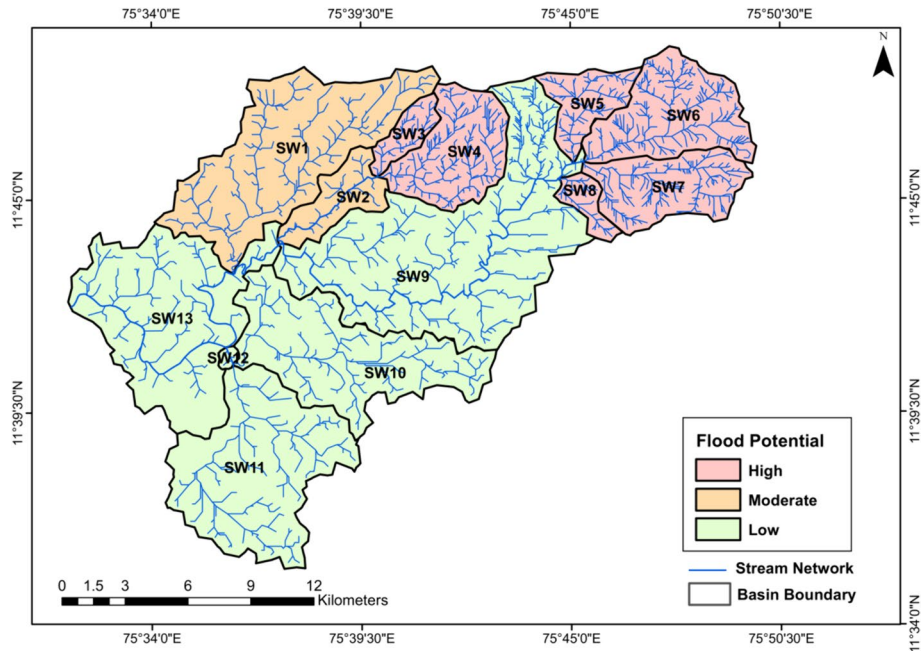


Fig. 3 Classification of sub-watersheds of the Mahe based on their flooding potential

seem to be an effective and viable option considering the performance of these structures in controlling floods in other rivers of the state and elsewhere. The option of closed diversion canals needs to be explored as they have been found to be theoretically operational in similar settings (Indrawati et al. 2018).

5 Conclusion

The disaggregation of river basins into their constituent sub-watersheds affords workable representative component units. This study has revealed the efficiency of MCDM techniques through SMARTER and VIKOR methods in prioritizing sub-basins based on their inclination to flooding considering conflicting factors. This would help in chalking out relevant protection and regulatory mechanisms based on the probability of inundation for each sub-basin.

The morphometric measurements of the Mahe river reveal it to be a sixth-order basin with moderately high runoff, consequently appreciable percolation rate, base flow and groundwater potential, particularly in its lower reaches. SW 3–8 in the upstream of the Mahe, situated in the crystalline rock terrain, was identified to be the sub-basins most prone to flooding. This is reflected in their highest values of relief, gradient, fine texture and texture ratios. These, along with their small areal extents, counteract the effects of dense foliage and elongated nature in regulating runoff, leading to high peak flows of shorter duration. They form 23% of the total river basin. SW 1 and 2, offers a moderate risk of flooding, since the advantage of prominent runoff in their upper reaches is inhibited by the laterite

components of the downstream terrain. The sub-basins SW 10–13 virtually covers the coastal plains of the Mahe. The low measures of gradient and slope, coarse texture, along with thick soil and alluvium of their lateritic terrain regulate their discharge rendering them least vulnerable to flooding. The low gradient ratio, elongated nature and permeable terrain ensures the low susceptibility of the largest sub-basin SW 9 to inundation, though its morphometry mostly echoes that of ‘Moderate’ SW 1. Hence, SW 9–13, forming 60% of the Mahe basin fall in the ‘Low’ grade of flooding potential. However, the enhanced cumulative discharge from the higher reaches during monsoons leads to heightened runoff in these sub-basins, that diminishes only over a longer period of time. Construction of dams may be a feasible flood control measure in the Mahe.

Acknowledgements Authors thank the Head of the Institution and Heads of the Departments of Civil and Mechanical Engineering for their support and encouragement in carrying out the current study.

Author Contributions All authors contributed to the study, conception and design. Material preparation, data collection and analysis were performed by Ajith G Nair, K Sunil Kumar and Sonu V Sabu. The first draft of the manuscript was written by Ajith G Nair and all authors commented on the previous versions of the manuscript. All authors read and approved the final manuscript.

Funding The authors declare that no funds, grants or other support were received during the preparation of this manuscript.

Declarations

Competing Interests The authors have no relevant financial or non-financial interests to disclose.

References

- Ahmed F, Rao KS (2015) Prioritization of sub-watersheds based on morphometric analysis using remote sensing and geographic information system techniques. *Int J Remote Sens GIS* 4:51–65
- Akay H, Koçyiğit MB (2020) Flash flood potential prioritization of sub-basins in an ungauged basin in Turkey using traditional multi-criteria decision-making methods. *Soft Comput* 24:14251–14263. <https://doi.org/10.1007/s00500-020-04792-0>
- Aparna P, Nigee K, Shimna P, Drissia TK (2015) Quantitative analysis of geomorphology and flow pattern analysis of Muvattupuzha River Basin using Geographic information system. *Aquatic Procedia* 4:609–616
- Arif M, Suseno JE, Isnanto RR (2020) Multi-criteria decision making with the VIKOR and SMARTER methods for optimal seller selection from several e-marketplaces. *E3S Web of Conf* 202:14002
- Arulbalaji P, Padmalal D (2020) Sub-watershed prioritization based on drainage morphometric analysis: a case study of Cauvery River Basin in South India. *Jour Geo Soc Ind* 95:25–35. <https://doi.org/10.1007/s12594-020-1383-6>
- Asl-Rousta B, Mousavi SJ (2018) A TOPSIS-based multicriteria approach to the calibration of a basin-scale SWAT hydrological model. *Water Resour Manag* 33:439–452. <https://doi.org/10.1007/s11269-018-2111-5>
- Avci V (2023) Relationship between basin morphometry and flood-overflow: case of Tabakhane stream (Ünye-Ordu, Türkiye). *Gümüşhane Üniv Sosyal Bilimler Derg* 14(1):1–21
- Bharath A, Kiran Kumar K, Maddamsetty R, Manjunatha M, Tangadagi RB, Preethi S (2021) Drainage morphometry-based sub-watershed prioritization of Kalinadi basin using geospatial technology. *Environ Chall* 5(21):100277. <https://doi.org/10.1016/j.envc.2021.100277>
- Biswas S, Sudhakar S, Desai VR (1999) Prioritization of sub-watershed based on morphometric analysis of drainage basin: a remote sensing and GIS approach. *Jf Indian Soc Remote Sens* 27(3):155–166
- CGWB (2022) Ground water resources of Kerala. CGWB/KR/TR Series/2022-18. Report by Ground Water Department, Government of Kerala and Central Ground Water Board, Government of India, pp 1–40
- CGWB (2012) Report on aquifer systems of India. Report by Central Ground Water Board, Ministry of Water Resources, Government of India, pp 1–103

- CGWB (2017) Dynamic ground water resources of India. Report by Central Ground Water Board, Ministry of Water Resources, River Development & Ganga Rejuvenation, Government of India, pp 1–52
- Charlton R (2007) Fundamentals of Fluvial Geomorphology, 1st edn. Routledge, London, p 234
- Chorley RJ, Schumm SA, Sugden DE (1984) Geomorphology. Methuen & Co., Ltd, pp 316–319
- Choudhari PP, Nigam GK, Singh SK, Thakur S (2018) Morphometric based prioritization of watershed for groundwater potential of Mula river basin, Maharashtra, India. *Geol Ecol Landsc* 2(4):256–267
- Cristobal JRS (2011) Multicriteria decision-making in the selection of a renewable energy project in Spain: The Vikor method. *Renew Energy* 36:498–502
- CWC (2018) Report on Kerala flood and solutions. Published by Central Water Commission, Ministry of Water Resources, Government of India, pp 1–60
- CWRDM (1995) Water atlas of Kerala. Published by Centre for Water Resource Development and Management. Government of Kerala, pp 1–80
- Das S (2020) Flood susceptibility mapping of the Western Ghat coastal belt using multi-source geospatial data and analytical hierarchy process (AHP). *Remote Sens Appl: Soc Environ* 20:100379
- Dixit A, Sahany S, Rajagopalan B, Choubey S (2022) Role of changing land use and land cover (LULC) on the 2018 megafloods over Kerala, India. *Clim Res* 89:1–14. <https://doi.org/10.3354/cr10701>
- Fallahpour AR, Moghassem AR (2012) Evaluating applicability of Vikor method of multi-criteria decision making for parameters selection problem in rotor spinning. *Fibers Polym* 13(6):802–808
- Gadallah NAH, Siddig AAH (2024) Space and Ground-based earth observations for hazards valuation and disaster risk management in the era of climate change. Revolutionizing earth observation-new technologies and insights [Working Title]. IntechOpen. <https://doi.org/10.5772/intechopen.1004395>
- George PS, Chattopadhyay S (2001) Population and land use in Kerala. In: *Growing Populations, Changing Landscapes: Studies from India, China and the United States*. National Academy of Sciences, The National Academies Press, pp 79–106
- Golfam P, Ashofteh PS, Rajaei T, Chu X (2019) Prioritization of water allocation for adaptation to climate change using multi-criteria decision making (MCDM). *Water Resour Manag* 33:3401–3416. <https://doi.org/10.1007/s11269-019-02307-7>
- GSI (2002) Geomorphological map of India. Published by Geological Survey of India, Government of India
- Hack JT (1957) Studies of longitudinal stream-profiles in Virginia and Maryland. *US Geol Surv Prof Pap* 294(B):45–97
- Hadley R, Schumm S (1961) Sediment sources and drainage basin characteristics in upper Cheyenne River basin. *US Geological Survey Water-Supply Paper* 1531-B, Washington DC, 198
- Halder S, Parekh A, Chowdary JS, Gnanaseelan C (2022) Dynamical and moist thermodynamical processes associated with Western Ghats rainfall decadal variability. *npj Clim Atmos Sci* 5:8. <https://doi.org/10.1038/s41612-022-00232-y>
- Horton RE (1932) Drainage basin characteristics. *Am Geophys Union* 13:350–361
- Horton RE (1945) Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology. *Geol Soc Am Bull* 56:275–370
- Indrawati D, Hadihardaja IK, Adityawan MB, Pahrizal SF, Taufik F (2018) Diversion canal to decrease flooding (case Study: Kebon Jati-Kalibata segment, Ciliwung River Basin). *MATEC Web Conf* 147:03006. <https://doi.org/10.1051/mateconf/201814703006>
- John J, Bindu G, Srimuruganandam B, Wadhwa A, Rajan P (2020) Land use/land cover and land surface temperature analysis in Wayanad district India, using satellite imagery. *Ann GIS* 26(4):343–360
- Kocyiğit MB, Akay H (2018) Estimation of potential flash flood risk in a basin using morphometric parameters: a case study of Akçay Basin. *J Fac Eng Archit Gazi Univ* 33(4):1321–1332
- Komaragiri SR, Kumar DN, Jalali A (2018) Prioritization of sub-catchments of a river basin using DEM and Fuzzy VIKOR. *H2Open J* 1:1–11. <https://doi.org/10.2166/h2oj.2017.001>
- Kumar A, Jayappa KS, Deepika B (2011) Prioritization of sub-basins based on geomorphology and morphometric analysis using remote sensing and geographic information system (GIS) techniques. *Geocarto Int* 26(7):569–592
- Kuo MS, Liang GS (2011) Combining VIKOR with GRA techniques to evaluate service quality of airports under fuzzy environment. *Expert Syst Appl* 38(3):1304–1312
- Lee G, Jun KS, Cung ES (2014) Groupdecision-making approach for flood vulnerability identification using the fuzzy VIKOR method. *Nat Hazards Earth Syst Sci Discuss* 2:6141–6171
- Lillesand TM, Kiefer RW (1994) *Remote Sensing and Image Interpretation*, 3rd edn. John Wiley & Sons, New York, p 752

- Liu B, Zhang F, Wan W, Luo X (2019) Multi-objective decision-making for the ecological operation of built reservoirs based on the improved comprehensive fuzzy evaluation method. *Water Resour Manag* 33:3949–3964. <https://doi.org/10.1007/s11269-019-02349-x>
- López-Pérez A, Fernández-Reynoso DS (2021) Watershed prioritization using morphometric analysis and vegetation index: a case study of Huehuetan river sub-basin, Mexico. *Arab J Geosci* 14:1852. <https://doi.org/10.1007/s12517-021-08212-x>
- Makrari S, Sharma G, Taloor AK, Singh MS, Sarma KK, Aggarwal SP (2022) Assessment of the geomorphic indices in relation to tectonics along selected sectors of Borpani River Basin, Assam using Cartosat DEM data. *Geosyst Geoenviron* 1(3):10006: 1–12
- Manu MS, Anirudhan S (2008) Drainage characteristics of Achankovil River basin, Kerala. *J Geol Soc India* 71:841–850
- Melton MA (1958) Correlation structure of morphometric properties of drainage systems and their controlling agents. *J Geol* 66:442–460
- Meshram SG, Alvandi E, Singh VP, Meshram C (2019) Comparison of AHP and fuzzy AHP models for prioritization of watersheds. *Soft Comput* 23(24):13615–13625
- Meshram SG, Hasan MA, Meshram C et al (2022a) Assessing vulnerability to soil erosion based on fuzzy best worst multi-criteria decision-making method. *Appl Water Sci* 12:219. <https://doi.org/10.1007/s13201-022-01714-3>
- Meshram S, Singh V, Kahya E, Sepehr, M, Meshram C, Abul Hasan M, Islam S, Duc P (2022b) Assessing erosion prone areas in a watershed using interval rough-analytical hierarchy process (IR-AHP) and fuzzy logic (FL). *Stoch Environ Res Risk Assess* 36: 297–312
- Miller V (1953) A quantitative geomorphic study of drainage basin characteristics in the Clinch Mountain area, Virginia and Tennessee. Project NR 389-402, Technical Report 3, Columbia University, Department of Geology, ONR, New York
- Mishra V, Aadhar S, Shah H, Kumar R, Pattanaik D, Tiwari A (2018) The Kerala flood of 2018: combined impact of extreme rainfall and reservoir storage. *Hydrol Earth Syst Sci Discuss* 1–13
- Mohsen O, Fereshteh N (2017) An extended VIKOR method based on entropy measure for the failure modes risk assessment – A case study of the geothermal power plant (GPP). *Saf Sci* 92:160–172
- Moore I, Gessler P, Nielsen G, Peerson G (1993) Soil attribute prediction using terrain analysis. *Soil Sci Soc Am J* 57(2):443–452
- Mulder T, Syvitski J (1996) Climatic and morphologic relationships of rivers: implications of sea-level fluctuations on river loads. *J Geol - J GEOL* 104:509–523. <https://doi.org/10.1086/629849>
- Nair MM (1990) Structural trend line patterns and lineaments of the Western Ghats, south of 13° latitude. *J Geol Soc India* 35:99–105
- Nookaratnam K, Srivastava YK, Venkateswara RV, Amminendu E, Murthy KSR (2005) Check Dam positioning by prioritization of micro watersheds using SYI model and morphometric analysis—remote sensing and GIS perspective. *J Indian Soc Remote Sens* 33:25–38
- Opricovic S, Tzeng GH (2004) Compromise solution by MCDM methods: a comparative analysis of VIKOR and TOPSIS. *Eur J Oper Res* 156(2):445–455
- Padma TV (2018) Mining and dams exacerbated devastating Kerala floods. *Nature* 561(7721):3–14
- Rahman MM, Zaman MN, Biswas PK (2022) Optimization of significant morphometric parameters and sub-watershed prioritization using PCA and PCA-WSM for soil conservation: a case study in Dharla River watershed, Bangladesh. *Model Earth Syst Environ* 8:2661–2674. <https://doi.org/10.1007/s40808-021-01255-9>
- Rai PK, Mohan K, Mishra S, Ahmad A, Mishra VN (2014) A GIS-based approach in drainage morphometric analysis of Kanhar River Basin, India. *Appl Water Sci* 7:217–232
- Rai PK, Chandell RS, Mishra VN, Singh P (2018) Hydrological inferences through morphometric analysis of lower Kosi River basin of India for water resource management based on remote sensing data. *Appl Water Sci* 8:15. <https://doi.org/10.1007/s13201-018-0660-7>
- Ramachandra TV, Bharath S (2020) Carbon sequestration potential of the forest ecosystems in the Western Ghats, a global biodiversity hotspot. *Nat Resour Res* 29:2753–2771. <https://doi.org/10.1007/s11053-019-09588-0>
- Ramasamy SM, Gunasekaran, Sh, Saravanel J, Joshua Melwyn, Rajaperumal R, Raju Kathiravan, Kathiresan Palanivel, Meyyappan Muthukumar M (2021) Geomorphology and landslide Proneness of Kerala, India. A geospatial study. *Landslides* 18. <https://doi.org/10.1007/s10346-020-01562-9>
- Rao YP, Ramamurti KS (1968) Forecasting manual part I climatology of India and neighbourhood 2: climate of India. India Meteorological Department, Government of India, pp 1–40
- Razavi Toosi SL, Samani JMV (2017) Prioritizing watersheds using a novel hybrid decision model based on fuzzy DEMATEL, Fuzzy ANP and Fuzzy VIKOR. *Water Resour Manage* 31:2853–2867. <https://doi.org/10.1007/s11269-017-1667-9>

- Ritter DF, Kochel RC, Miller JR (1995) Process geomorphology, 3rd edn. Brown Publishers, Dubuque, p 539
- Schumm SA (1956) Evaluation of drainage system and slopes in badlands at Perth Amboy, New Jersey. *Bull Geol Soc Am* 17:595–646
- Sengupta S, Mohinuddin SK, Arif M (2022) Sub-watershed prioritization for soil erosion potentiality estimation in Tenughat catchment, India. *Geocarto Int* 37(25):9160–9189. <https://doi.org/10.1080/10106049.2021.2017008>
- Shekar PR, Mathew A (2022) Morphometric analysis for prioritizing sub-watersheds of Murredu River basin, Telangana State, India, using a geographical information system. *J Eng Appl Sci* 69:44. <https://doi.org/10.1186/s44147-022-00094-4>
- Singh S, Kansal ML (2023) A comparative study of morphometric, hydrologic, and semi-empirical methods for the prioritization of sub-watersheds against flash flood-induced landslides in a part of the Indian Himalayan Region. *Environ Sci Pollut Res*. <https://doi.org/10.1007/s11356-023-30613-6>
- Soman K (2002) Geology of Kerala. Geological Society of India, Bangalore, p 335
- Sridhar P, Ganapuram S (2021) Morphometric analysis using fuzzy analytical hierarchy process (FAHP) and geographic information systems (GIS) for the prioritization of watersheds. *Arab J Geosci* 14:236. <https://doi.org/10.1007/s12517-021-06539-z>
- Srinivasan V, Mukherji S, Ramamurthy K (1972) Forecasting manual part III discussion of typical synoptic weather situations 3.8: southwest monsoon - typical situations over Kerala and Arabian Sea Islands. The Deputy Director General of Observatories (Forecasting), pp 1–41
- Strahler AN (1957) Dynamic basics of geomorphology. *Bull Geol Soc Am* 6:923–928
- Strahler AN (1964) Quantitative geomorphology of drainage basins and channel networks. In: Chow VT (ed) *Handbook of Applied hydrology*. McGraw - Hill, New York, pp 439–476
- Tawde S, Singh C (2014) Investigation of orographic features influencing spatial distribution of rainfall over the Western Ghats of India using satellite data. *Int J Climatol* 35:2280–2293
- Thomas J, Joseph S, Thirivikramaji KP (2010) Morphometric aspects of a small tropical mountain river system, the southern Western Ghats, India. *Int J Digit Earth* 3(2):135–156. <https://doi.org/10.1080/17538940903464370>
- Thomas J, Joseph S, Thirivikramaji KP, George A, Kannan N (2012) Morphometrical analysis of two tropical mountain river basins of contrasting environmental settings, the southern Western Ghats, India. *Environ Earth Sci* 66:2353–2366. <https://doi.org/10.1007/s12665-011-1457-2>
- Valdiya KS, Narayana AC (2007) River response to neotectonic activity: Example from Kerala, India. *J Geol Soc India* 70:427–443
- Waikar M, Nilawar AP (2014) Morphometric analysis of a drainage basin using geographical information system: a case study. *Int J Multidiscip Curr Res* 2:179–184
- Wilford DJ, Sakals ME, Innes JL, Sidle RC, Bergerud WA (2004) Recognition of debris flow, debris flood and flood hazard through watershed morphometrics. *Landslides* 1:61–66. <https://doi.org/10.1007/s10346-003-0002-0>
- Youssef AM, Pradhan B, Hassan AM (2011) Flash flood risk estimation along the St. Katherine Road, Southern Sinai, Egypt using GIS based morphometry and satellite imagery. *Environ Earth Sci* 62:611–623

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.