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ORIGINAL ARTICLE

Morphometrical analysis of two tropical mountain river basins of contrasting environmental settings, the southern Western Ghats, India

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Abstract The morphometric analysis of river basins represents a simple procedure to describe hydrologic and geomorphic processes operating on a basin scale. A morphometric analysis was carried out to evaluate the drainage characteristics of two adjoining, mountain river basins of the southern Western Ghats, India, Muthirapuzha River Basin (MRB) in the western slopes and Pambar River Basin (PRB) in the eastern slopes. The basins, forming a part of the Proterozoic, high-grade, Southern Granulite Terrain of the Peninsular India, are carved out of a terrain dominantly made of granite- and hornblende-biotite gneisses. The Western Ghats, forming the basin divide, significantly influences the regional climate (i.e., humid climate in MRB, while semi-arid in PRB). The Survey of India topographic maps (1:50,000) and Shuttle Radar Topographic Mission digital elevation data were used as the base for delineation and analysis. Both river basins are of 6th order and comparable in basin geometry. The drainage patterns and linear alignment of the drainage networks suggest the influence of structural elements. The Rb of either basins failed to highlight the structural controls on drainage organization, which might be a result of the elongated basin shape. The irregular trends in Rb between various stream orders suggest the influence of geology and relief on drainage branching. The Dd values designate the basins as moderate- to well-drained with lower infiltration rates. The overall increasing trend of Rl between successive stream orders suggests a geomorphic maturity of either basins and confirmed by the characteristic I_{hyp} values. The Re values imply an elongate shape for both MRB and PRB and subsequently lower vulnerability to flash floods and hence, easier flood management. The relatively higher Rr of PRB is an indicative of comparatively steeply sloping terrain and consequently higher intensity of erosion processes. Further, the derivatives of digital elevation data (slope, aspect, topographic wetness index, and stream power index), showing significant differences between MRB and PRB, are useful in soil conservation plans. The study highlighted the variation in morphometric parameters with respect to the dissimilarities in topography and climate.

Keywords Morphometry · DEM · Muthirapuzha · Pambar · Western Ghats · India

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Introduction

Topography, geology, and climate are the three determinants controlling drainage pattern, density and geometry of the fluvial system (Frissel et al. 1986). Among these, the relative influence of each factor may vary from place to place and subsequently displayed in the drainage characteristics. The quantitative analysis of drainage networks and catchment shapes is a subject of interest to both geomorphologists and hydrologists worldwide. Further robust, quantitative descriptions of drainage basins are one of the essential components for the interpretation of basin evolution.

The morphometric parameters represent relatively simple approaches to describe basin processes and to compare basin characteristics and enable an enhanced understanding of the geologic and geomorphic history of a drainage basin (Strahler 1964). The morphometric assessment aids in primary hydrological diagnosis in order to predict approximate basin behavior, when coupled with geomorphology and geology (Esper Angillieri 2008). The hydrological response of a river basin can be interrelated with the physiographic characteristics of the drainage basin, such as size, shape, slope, drainage density and size, and length of the streams (Chorley 1969; Gregory and Walling 1973). In order to understand the influence of sub-basins to flooding on the main channel, morphometric parameters of drainage networks must be considered along with their hydrological characteristics (Youssef et al. 2011). Hence, morphometric analysis of a watershed is an essential first step, toward basic understanding of watershed dynamics.

The application of digital elevation data through geographical information systems (GIS) is a powerful approach in this matter, since the ability to create, manipulate, store, and use spatial data much faster and at a rapid rate, with both operational and quality advantages. Moreover, it made the quantitative approach for surface characterization and the mechanism for the interpretation and manipulation of the quantitative data sets easy. The coupling of Digital Elevation Models (DEMs) and GIS enables the extraction of primary (e.g., slope and aspect) and secondary (e.g., topographic wetness index and stream power index) derivatives of DEM for geomorphometric analysis, which is offered by standard GIS platforms (Wilson and Gallant 2000). As a result, morphometry has evolved into a source of reliable, indirect methods for basin hydrograph computation, soil erosion estimation, landslide susceptibility mapping, predicting the movement of groundwater, analyzing topography and addresses innumerable other problems in the earth sciences and a number of engineering fields (Florinsky 1998; Hodgson 1998; Pike 2000).

In India, a number of papers on drainage basin morphometry especially of the Western Ghats have appeared in the past decades (e.g., Jacob and Narayanaswami 1954; Raghavan and Sridhara Murthy 1990; Chavadi and Hegde 1991). Of late, studies shifted its focus on the application of remote sensing and GIS tools in morphometric analysis for various applications such as watershed characterization (Nag 1998; Vittala et al. 2004; Bali et al. 2011), prioritization of micro-watersheds (Biswas et al. 1999; Nooka Ratnam et al. 2005), soil conservation (Thakkar and Dhiman 2007), natural hazard management (Pankaj and Kumar 2009), groundwater development (Sreedevi et al. 2005, 2009) and agro-meteorological applications (Magesh et al. 2011). In Kerala, examples of such approaches have been applied in basin scale (James and Padmini 1983; Maya 1997; Manu and Anirudhan 2008) as well as in sub-basin scale (Joji and Nair 2002; Vijith and Satheesh 2006; Thomas et al. 2010, 2011). In this context, present paper describes the results of the morphometric analysis of two tropical mountain river basins, Muthirapuzha and Pambar, in the southern Western Ghats, India to understand the basin behavior using remote sensing and GIS tools.

Study area

The study area (Muthirapuzha River Basin, MRB and Pambar River Basin, PRB), forming a part of the Anaimalai-Cardamom Hill Ranges (Idukki district, Kerala State, India) on the southern Western Ghats, is located between 9°59′35″ and 10°21′11″N and 76°59′13″ and 77°15′31″E (Fig. 1). The basins are developed in the Proterozoic high-grade Southern Granulite Terrain (SGT) of the Peninsular India, separated from the Archean low-grade Dharwar craton to north by the orthopyroxene isograd identified by Fermor (1936). The main lithological units in the study area are hornblende-biotite (migmatitic) gneiss (Hbg), granite gneiss (Ggn), intrusive granitic bodies (Gr), calc-granulites (Cg), and quartzite (Qz) patches (Figs. 2, 3). Pegmatites, quartz veins, and basic intrusives traverse the older host rocks (Soman 2002).

The Ggn, dominating both basins, is medium-grained, pinkish and foliated due to parallel planar arrangement of flakes of biotite, prisms of hornblende and lenticular and flattened quartz veins. Mafic layers are relatively thin compared to quartzo-feldspathic layers. Hbg is a composite rock with alternating bands rich in quartzo-feldspathic (thickness = 0.5–3.0 cm) and mafic (thickness = 2.0–5.0 mm) minerals. The occurrence of Hbg within the charnockite terrain is described as the retrograde metamorphism of charnockites under upper amphibolite to granulite facies conditions (Mahadevan 1964; Soman 2002). Cg is medium-grained and the weathered surfaces are puckered, particularly near contacts with Hbg, the projections being formed by veins of quartzo-feldspathic composition (Thampi 1987). The rock generally exhibits faint layering due to the segregation of calc-silicate minerals. In addition, incipient development of metamorphic foliation defined by biotite and pyroxene is also observed.

The mafic granulites provide evidence of isothermal decompression textures (plagioclase + orthopyroxene symplectites around embayed garnet grains) and P–T trajectory of 880–680°C temperature and 10–7 kb pressures (Ravindrakumar and Chacko 1994). According to Nair and Anilkumar (1989), two periods of granite emplacement have been recorded, in that, thinly foliated, pink, medium-grained gneissic granite (occurs as overturned, doubly

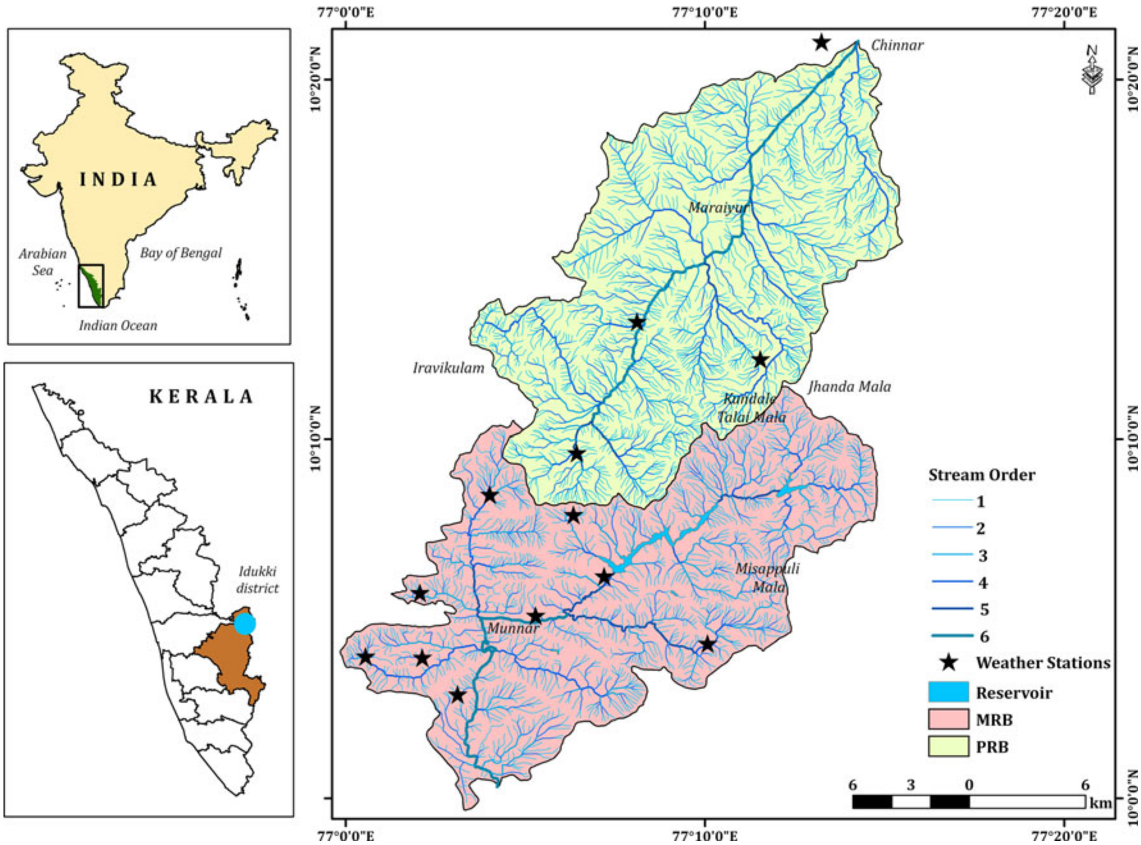
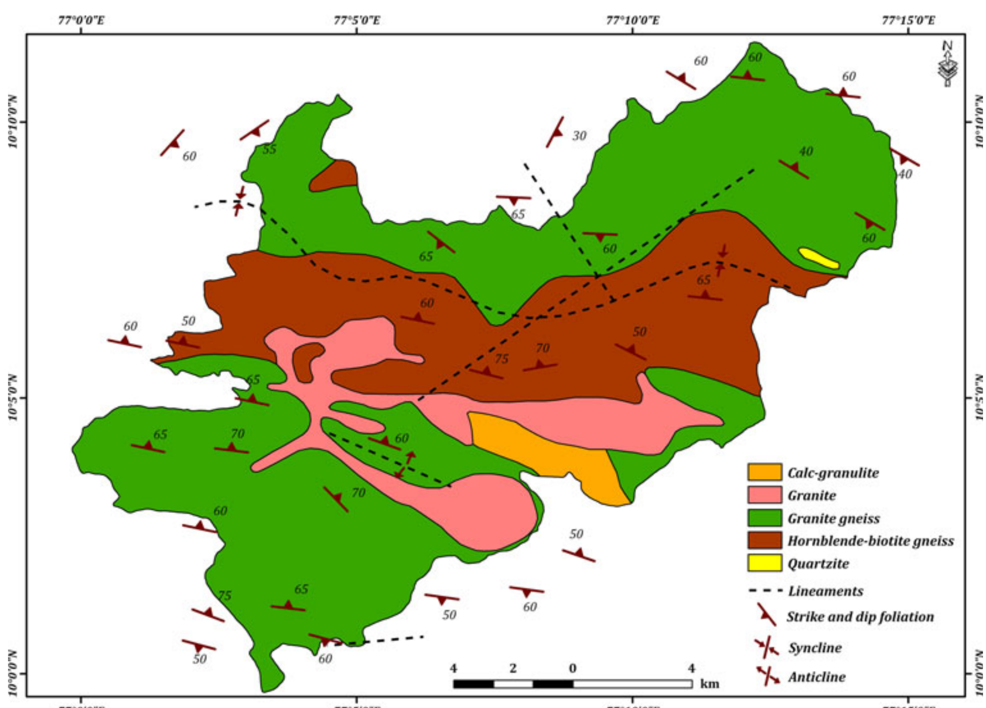


Fig. 1 Location map of study area

Fig. 2 Geology of MRB



plunging cross-folded brachy-structure) containing biotite, magnetite and hornblende as mafic phases represent the first period, while the second period is represented by the massive, medium to coarse grained granite, emplaced pre- to syn-kinematic with the broad, open WNW–ESE to E–W trending folds. In addition, Thampi (1987) reported the

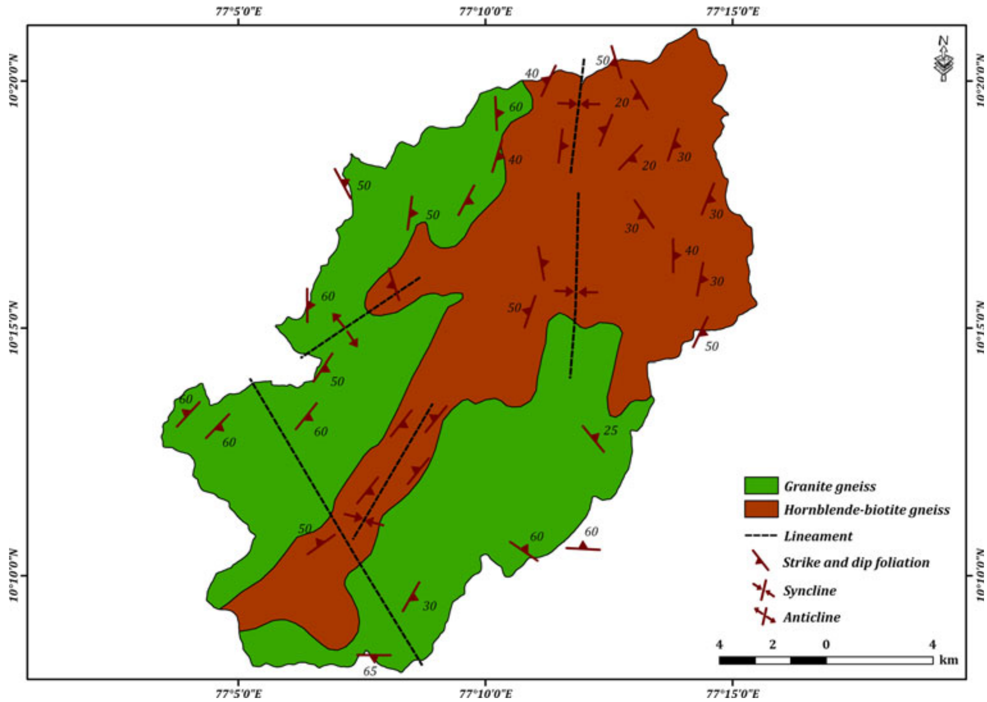


Fig. 3 Geology of PRB

occurrence of a thin layer of laterite (∼15.0 cm) in the high plateau around Iravikulam, 12.0 km to the NNE of Munnar.

From the trend of foliations in MRB, it is inferred that there exists a major synclinal-axial-trace of a high amplitude plan view, confined mostly to Hbg and a minor anticlinal-axial-trace of NW–SE orientation appears with in an enclave of Ggn. The foliation trends of PRB imply the presence of three major synclinal-axial-traces, trending approximately in N–S and NE–SW confined mostly in the Hbg and another major anticlinal-axial-trace of NE–SW trend appearing in both Hbg and Ggn. Three sets of major lineaments are observed to trend roughly along NE–SW, N–S, and NW–SE.

The drainage system of both MRB and PRB is influenced by the Munnar plateau (late Paleocene age), an extensive plantation surface (highest elevated surface in the Kerala region) with a southwesterly slope tending to descend in a stepped manner (Soman 2002). Majority of the drainage network of MRB is developed on the plateau, whereas PRB is developed on the precipitous, northern scarps of the plateau. U-shaped valleys and broad ridges characterize MRB, while PRB is characterized by steep, V-shaped valleys and bedrock channels. Several local planation surfaces (Maraiyur at ∼1,000 m.a.m.s.l. and Chinnar at ∼600 m.a.m.s.l. in PRB; Jhanda Mala at ∼2,200 m.a.m.s.l.-NE boundary of MRB) and terrain with concordant summits (Iravikulam and Kundale Talai Mala at ∼2,200 m.a.m.s.l. in PRB and Misappuli Mala at ∼2,400 m.a.m.s.l. in MRB) are also a characteristic of the basins. The elevation of MRB varies between 2,690 and 760 m.a.m.s.l, while that in PRB ranges from 2,540 to 440 m.a.m.s.l.

As, MRB is located on the western slopes of the southern Western Ghats, a tropical humid climate prevails, whereas PRB is located on the leeward slopes and correspondingly a rain shadow region with tropical semi-arid climate. The mean annual rainfall (P_{ma}) of MRB is 3,700 mm (period = 1989–2009), whereas that of PRB is 1,100 mm (period = 1992–2008). Similarly, the mean annual temperature (T_{ma}) of MRB is 17°C, whereas that of PRB is 26°C. Major soil series in MRB are Anamudi, Pambadumpara, and Venmani series, whereas the Anamudi and Chinnar series cover the PRB and the soil characteristics are given in Table 1 (Anonymous 2007). Again, MRB is covered by several vegetation belts including montane grasslands, southern montane wet temperate forests (shola forests), west coast tropical evergreen forests and southern sub-tropical hill forests. Similarly, dominant vegetation types in PRB include montane grasslands, southern montane wet temperate forests, southern tropical thorn forests, southern dry mixed deciduous forests, and southern moist mixed deciduous forests. Tea and Eucalyptus plantations are common in both the basins.

Methodology

The Survey of India topographic maps on 1:50,000 scale (58 B/16, 58 F/3, 58 F/4, 58 F/7, 58 F/8 and 58 G/1) and

Table 1 Soil characteristics in the study area

Soil series	Anamudi	Pambadumpara	Venmani	Chinnar
Order	Ultisols	Ultisols	Inceptisols	Mollisols
Sub-order	Humults	Humults	Ustepts	Ustolls
Great group	Kandihumults	Kandihumults	Dystrustepts	Haplustolls
Sub-group	Typic Kandihumults	Ustic Kandihumults	Oxic Dystrustepts	Typic Haplustolls
Family	Clayey, mixed, isothermic	Clayey, mixed, isohyperthermic	Fine, mixed, isohyperthermic	Loamy skeletal, mixed, thermic
Pedogenesis	Gneissic parent; on steep to very steep slopes; above 1,200 m amsl	Gneissic parent; on steep to very steep slopes and hill tops; between 600 and 1,200 m amsl	Gneissic parent; on moderate to steep slopes; between 600 and 900 m amsl	Gneissic parent; on gentle slopes of rain shadow region; between 400 and 900 m amsl
Texture	Silt loam to clay loam (A horizon); Silty clay loam to clay (B horizon)	Silty clay to clay (A horizon); Clay (B horizon)	Loam to clay (A horizon); Gravelly sandy clay to gravelly clay (B horizon)	Sandy loam to sandy clay loam (A horizon); Gravelly loamy sand to gravelly sandy loam (C horizon); presence of $CaCO_3$ nodules and mica flakes in the sub-surface soil
Thickness (cm)	>150	>180	>150	75–100
Drainage	Well-drained	Moderately well-drained	Well-drained	Moderately well-drained
Permeability	Moderately rapid	Moderate	Moderately rapid	Moderately rapid
Productivity	High	Medium	Medium	Medium to high
Erodibility	Severe	Severe	Severe	Moderate

Shuttle Radar Topographic Mission (SRTM) digital elevation data (3 arc sec, filled, finished-A, WRS-2, Path-145, Row-053, 2000) from Global Land Cover Facility (GLCF) were used as the base for delineation of MRB and PRB. The data extraction and data analysis were carried out in ERDAS Imagine 9.0, Arc GIS 9.2 and Terrain Analysis System (TAS 2.0). The basin boundary and drainage networks were digitized in Arc GIS 9.2 and analyzed after stream ordering (Strahler 1964). The basic morphometric parameters such as area (*A*), perimeter (*P*), basin length (Lb), stream order (Nu), and mean stream length (Lu) were estimated. Further, bifurcation ratio (Rb), stream length ratio (Rl), drainage density (Dd), length of overland flow (Lg), and elongation ratio (Re) were derived from the basic parameters. The relief ratio (Rr) and hypsometric integral (I_{hyp}) were estimated from the DEM. In addition, derivatives of DEM such as slope, aspect, topographic wetness index (TWI), and stream power index (SPI) were also estimated. "Appendix" summarizes the list of morphometric parameters including their definitions.

Results and discussion

The results of the morphometric analysis of the two mountain river basins is given in Table 2 and discussed in the following sections. Both MRB and PRB, in general, exhibit a dominantly parallel pattern, semi-centripetal, trellis, rectangular and dendritic patterns also co-exist. The straight channel segments and preferred direction of alignment of streams reflect fracture/lineament control on drainage. The asymmetry in the lower order sub-basins may be attributed to the tectonic history of the Munnar plateau (Thomas et al. 2010).

Basic parameters

Basin geometry

The basin area (*A*) of MRB and PRB are 271.75 and 288.53 $km^{2,}$ respectively, (Table 2). Similarly, the perimeter (*P*) of MRB is 109.93 km, whereas that of PRB is 89.92 km and basin length (Lb) of MRB and PRB are 37.81 and 32.34 km accordingly (Table 2). Though MRB has a relatively smaller *A*, comparatively higher *P* is mainly due to the irregularities in the basin divide, which is attributed to the headward erosion of various river basins developed in the plateau scarps.

Number of streams (N) and order (u)

According to Strahler's (1957) classification, both MRB and PRB are 6th order basins. The number of streams (*N*) in each order (*u*) in MRB and PRB are given in Table 2. The total number of streams (Nt) in MRB and PRB are 1,662 and 1,708, respectively. The 1st order streams account for about 75% of the total number of streams in both MRB and PRB and such a high proportion

Table 2 Results of morphometric analysis

	MRB							PRB						
	I	II	III	IV	V	VI	MRB	I	II	III	IV	V	VI	PRB
A							271.75							288.53
P							109.93							89.92
Lb							37.81							32.34
Nu	1,243	320	81	14	3	1	1,662	1,311	296	78	18	4	1	1,708
Lu	0.51	0.55	1.11	2.39	6.40	17.37	0.58	0.54	0.62	1.30	3.87	2.05	27.36	0.64
LT	635.17	175.79	90.21	33.39	19.20	17.37	971.13	712.56	182.43	101.72	65.74	8.21	27.36	1,098.08
Rb		I/II	II/III	III/IV	IV/V	V/VI			I/II	II/III	III/IV	IV/V	V/VI	
		3.88	3.95	5.79	4.67	3.00	4.26		4.43	3.79	4.33	4.50	4.00	4.21
Rl		II/I	III/II	IV/III	V/IV	VI/V			II/I	III/II	IV/III	V/IV	VI/V	
		1.08	2.02	2.15	2.68	2.71	2.13		1.15	2.10	2.98	0.53	13.35	4.02
Dd							3.57							3.81
Lg							0.14							0.13
Re							0.49							0.59
Rr							0.05							0.06
HI							0.43							0.50

of 1st order streams indicate the structural weakness present in these basins dominantly in the form of lineaments and folding.

Mean stream length (Lu)

The Lu of MRB and PRB are 0.58 and 0.64 km, respectively, (Table 2). The Lu of a given order is higher than that of the next lower order, but lower than the next higher order, indicating that the evolution of these basins follows the laws of erosion acting on homogeneous geologic material with uniform weathering-erosion characteristics. The total stream length (LT) in MRB and PRB are 971.13 and 1,098.08 km, respectively, (Table 2). In both the basins, LT decreases with a corresponding increase in stream order (Table 2). In MRB and PRB, the exponent of the power relation between mainstream length (L) and A (i.e., $L = 1.07 \times A^{0.65}$ in MRB and $L = 1.86 \times A^{0.52}$ in PRB), which is in the range observed by Hack (1957), Mulder and Syvitsky (1996) and Kale and Shejwalkar (2007), indicating that headward erosion as the dominant mode of drainage network development.

Derived parameters

Bifurcation ratio (Rb)

The mean Rb of MRB and PRB are 4.26 and 4.21, respectively, (Table 2), implying a higher degree of drainage integration, suggests the significant influence of structural elements on the drainage organization. In MRB, variability in Rb values between successive orders is comparatively higher than that in PRB, which indicate the influence of relief in stream network development. Further, the obscure trends in Rb values between various stream orders suggest a deviation from Giusti and Schneider's hypothesis (1965), which confirm the substantial influence of geology and relief on drainage branching. Moreover, Fig. 4 shows the distinctive dissimilarity in the Rb variability of various orders between MRB and PRB, which imply the contrasting paleo-environments of drainage development. Although, the theoretical minimum Rb is 2.0, natural drainage systems are generally characterized by Rb between 3.0 and 5.0 (Strahler 1964). Further, several studies suggested that anomalous Rb values (e.g., Rb < 3.0 and Rb > 5.0 in Mekel 1970; Rb ≥ 10 in Chorley et al. 1984) are indirect manifestations of substantial structural controls. However, morphometric analysis of Achankovil

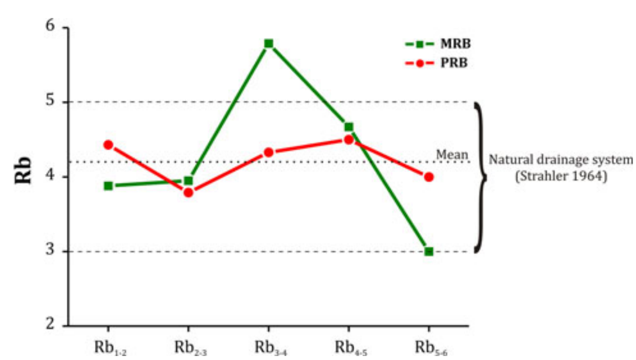


Fig. 4 Variability in Rb in MRB and PRB

River, confined to the Achankovil Shear Zone (AKSZ) in southern India, reported Rb values between 3.46 and 5.50 (Manu and Anirudhan 2008). Earlier, Verstappen (1983) revealed that basin shape significantly influences Rb in that the anomaly in Rb due to structural controls can be thrivingly masked by the elongate shape of the basin.

Stream length ratio (Rl)

The mean Rl of MRB is 2.13, whereas that of PRB is 4.02 (Table 2). Though MRB shows an increasing trend in the Rl between successive stream orders, PRB does not follow any empirical rule or follow any systematic variations. However, such anomalies may also be interpreted as a sign of disequilibrium in the drainage development. According to Scheidegger (1970), the natural range of Rl is 2.10–2.90, while the variations could be a result of the dominance of local geology. Further, an overall increasing trend in Rl between the successive stream orders exists both in MRB and PRB—an indication of geomorphic maturity.

Drainage density (Dd)

The Dd of MRB and PRB are 3.57 and 3.81 km km^{-2}, respectively, (Table 2), indicating highly dissected-steep-terrain with impervious underlying rocks. Further, Dd values of both MRB and PRB reveal that these basins are moderate to well-drained (higher runoff) with relatively lower infiltration. Horton (1932) observed Dd between 0.93 and 1.24 km km^{-2} in humid, steeply sloping terrain underlaid by impervious rocks and nearly zero in permeable basins with very high infiltration rates, while Langbein (1947) suggested a range between km km^{-2} with an average of 1.03 km km^{-2}. However, Schumm (1956) and Smith (1958) recorded Dd values ranging from 313 to 820 mi mi^{-2} in badlands on weak clays at of Perth Amboy, New Jersey and badlands in South Dakota, respectively. Even though Dd is influenced by numerous factors (i.e., topography, lithology, climate, pedology, and vegetation), the relative dominance of each factors vary from place to place. Besides, the scale of the base map also has a significant influence on Dd and works of several researchers (e.g., Giusti and Schneider 1962; Eyles 1966; Selby 1968) disclosed the variations in Dd between various map scales.

Both MRB and PRB exhibit a significantly strong, positive correlation between Dd and mean annual rainfall ($r = 0.857$). However, though PRB receives a significantly lower mean annual rainfall compared to MRB, comparatively higher Dd value in PRB is a clear indication of the dominance of the influence of topography over the climate. Further Table 3 and Fig. 5, showing the spatial variation Dd of MRB and PRB, clearly differentiate the distribution of various Dd zones. According to Morgan (1971), extension of drainage network will be more complex in the early stages of development as individual basins compete for the space available and local instances of stream abstraction and interfluve destruction may cause a spatial variability in Dd.

Table 3 Areal extent of Dd classes, MRB, and PRB

Dd, km km^{-2}	Class	Area, km^2 (%)	
		MRB	PRB
<2.0	Low	24.77 (9.12)	13.99 (4.86)
2.0–4.0	Medium	168.16 (61.88)	164.01 (56.84)
4.0–6.0	High	77.34 (28.46)	108.10 (37.46)
>6.0	Very high	1.48 (0.54)	2.43 (0.84)

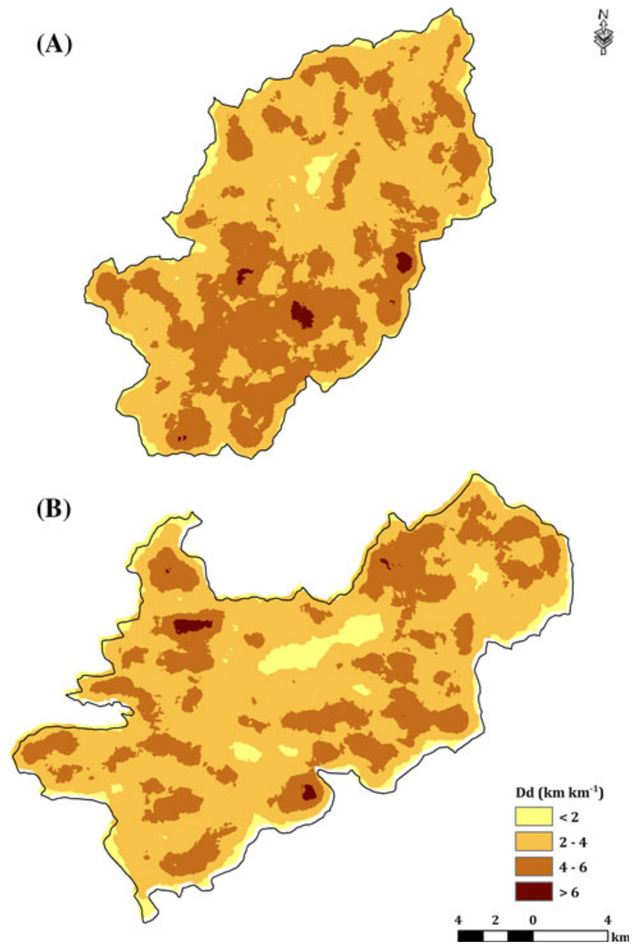


Fig. 5 Spatial variation of Dd in **a** PRB and **b** MRB

Length of overland flow (Lg)

The Lg of MRB and PRB are 0.14 and 0.13 km, respectively, (Table 2). Though there lacks a significant difference in Lg between the basins, relatively lower Lg value of

PRB characterize the steeply sloping terrain and lower length of sheet flow. According to Horton (1945), Lg is significantly influenced by geologic- and pedologic-characteristics, rainfall intensity and vegetation. However, the variability in Lg between MRB and PRB is dominantly determined by rainfall, pedologic characteristics, and vegetation because hardly any significant differences in geology.

Elongation ratio (Re)

The Re of MRB is 0.49, whereas that of PRB is 0.59 (Table 2). Strahler (1964) opined that Re generally varies from 0.60 to 1.00 across a wide range of climate and geologic types. In general, a numerically higher Re is associated with a circular basin, while a lower value is associated with an elongated basin. Re close to 1.00 are typical of regions of very low relief, whereas values in the range 0.60–0.80 are usually associated with high relief with steep round slopes. Further, the classification proposed by Strahler (1964) imply an elongate shape for both MRB and PRB and subsequently the hydrograph of these might be smoother (i.e., crest segment of hydrograph will be flatter and the slope of the rising and recession limbs will be low), which is explained by the greater time lag for the water from upper regions of the catchment to reach the outlet (Verstappen 1983). Further, lower Re values of the basins suggest their lesser vulnerability to flash floods and as a result, easier flood management.

Relief ratio (Rr)

The Rr of MRB and PRB are 0.05 (0.03 in the plateau) and 0.06, respectively, (Table 2), characterizing the mountainous configuration of the terrain. The relatively higher Rr of PRB is an indicative of comparatively steeply sloping terrain and consequently higher basin energy (manifested as intensity of erosion processes operating along the hillslopes) and transport efficiency (sediment load).

Hypsometric Integral (I_{hyp})

The I_{hyp} of MRB and PRB are 0.43 and 0.50, respectively, (Table 2), implying that 43% of the original volume of MRB and 50% of PRB still remains in these basins to erode. The theoretical minimum value of I_{hyp} is 0.0, indicating a completely eroded (peneplained) surface, while the theoretical maximum of 1.0 implies a newly emerged surface ready for erosive forces to begin their work. Based on I_{hyp} values, the cycle of erosion can be divided into three stages viz., monadnock (old) ($I_{hyp} < 0.30$), in which the watershed is fully stabilized; equilibrium or mature ($0.30 \leq I_{hyp} \leq 0.60$); and in equilibrium or young stage ($I_{hyp} > 0.60$), in which the watershed is highly susceptible to erosion (Strahler 1952). According to the former classification, both MRB and PRB are in the mature stage of geomorphic development.

Derivatives of DEM

Slope

The slope of a basin is a morphometrical factor of hydrological relevance (Mesa 2006). The slope distribution in MRB and PRB are shown in the Fig. 6. The slope of MRB and PRB varies from 0° to 85°. The derived slope (in degrees) was classified into seven classes i.e., <5, 5–10, 10–15, 15–20, 20–35, 35–45, and >45 (Table 4). The larger areal extent of steeper slopes (>20°) in PRB than that in MRB clearly indicates the differences in terrain conditions between them. Further, steeper slopes in MRB are mainly associated with the precipitous scarps of the terrain with concordant summits and plateau. On the other hand, steeper slopes in PRB are dominantly distributed along the

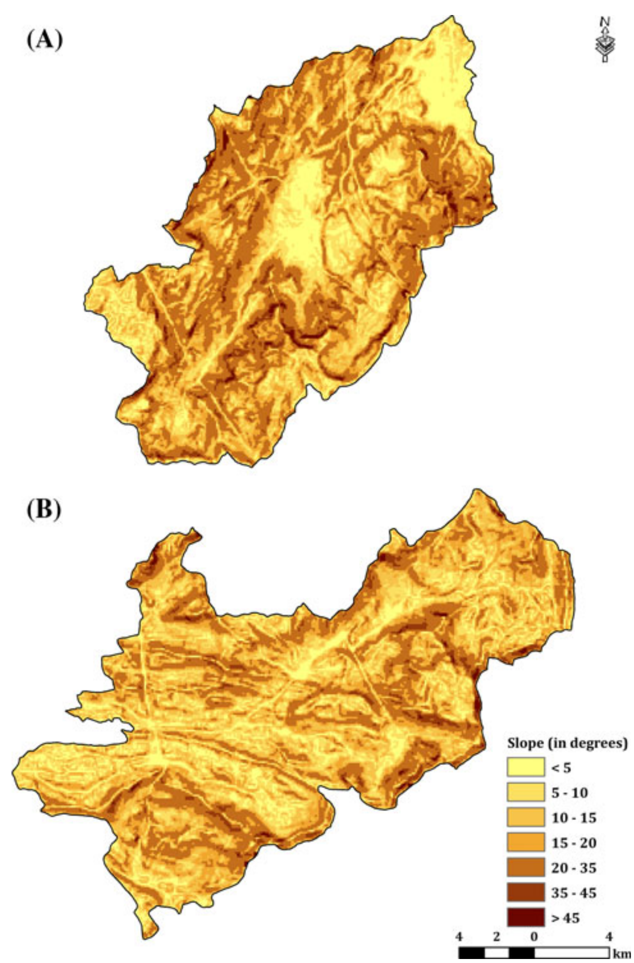


Fig. 6 Slope distribution in **a** PRB and **b** MRB

Table 4 Slope distribution in MRB and PRB

Slope (in degrees)	MRB		PRB	
	Area (km^2)	% of total area	Area (km^2)	% of total area
<5	22.13	8.14	31.21	10.82
5–10	53.10	19.54	44.71	15.50
10–15	65.49	24.10	48.05	16.65
15–20	54.14	19.92	51.39	17.81
20–35	67.64	24.89	97.66	33.85
35–45	7.98	2.94	12.51	4.34
>45	1.27	0.47	3.00	1.04

basin boundary in the form of steep escarpments. The nearly level and very gently sloping areas (<5°) are largely associated with the two planation surfaces in PRB (Fig. 6), whereas it is more or less uniformly distributed in MRB.

Aspect

The aspect maps of MRB and PRB are shown in Fig. 7. A visual comparison of the aspect of MRB and PRB reveal appreciable differences between them, in that NE, SE, and NW slopes are dominant in PRB, whereas S, SW, and NE slopes predominate MRB. The east-facing slopes in both the basins receive feeble amount of insolation, influencing the soil moisture regime, productivity, and micro-climate (since MRB and PRB belong to contrasting climates, only intra-basin comparisons are fruitful).

Topographic wetness index (TWI)

The TWI of MRB varies between 2.86 and 14.57, whereas that of PRB ranges from 1.85 to 15.26 (Fig. 8). The spatial variability in TWI is a result of the difference in terrain configuration, soil properties and hydrology between and within catchments. Moore et al. (1993b) observed gullies formed when TWI > 6.8 in a semi-arid catchment in Australia and TWI > 8.3 in a humid catchment in Antigua and observed as a good predictor of location of ephemeral gullies. Here, the TWI of both semi-arid PRB and humid MRB were set above this threshold and the TWI values greater than corresponding threshold values have a higher density of gullies than the rest. Further, higher TWI areas in MRB and PRB indicate the zones of saturation and an enhanced knowledge on the spatial distribution of water-saturated areas in the river basins is very essential for predicting water fluxes. In addition, spatial patterns of saturated areas and their relation to geomorphic forms and processes are very relevant for sustainable water resources management, especially in ungauged catchments.

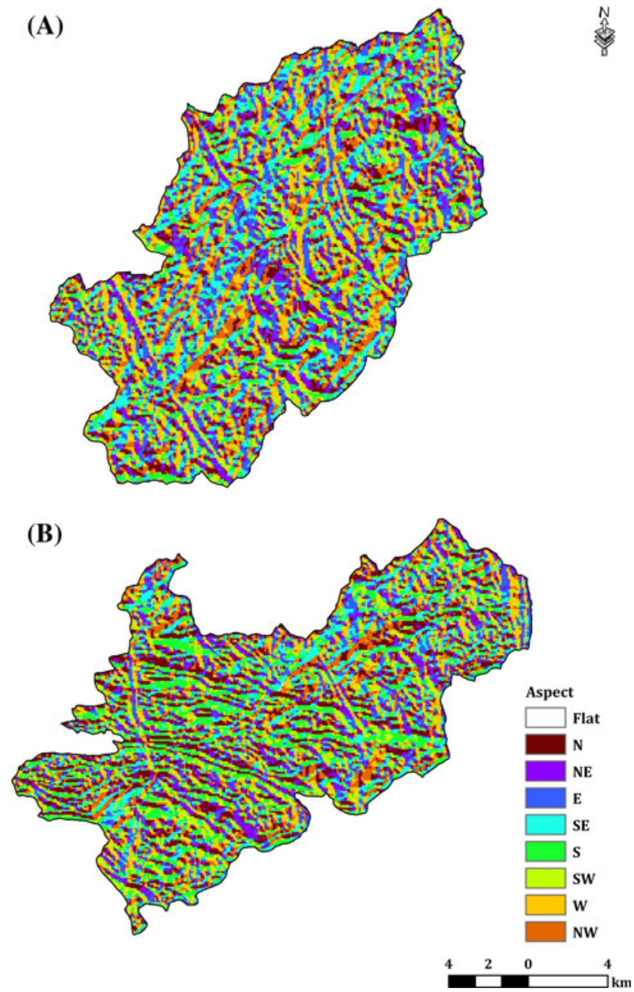


Fig. 7 Aspect map of **a** PRB and **b** MRB

Stream power index (SPI)

The SPI of MRB varies between 0 and 15,687 and that of PRB reaches up to 37,525 (Fig. 9). The higher SPI of PRB is an indication of higher stream power, which is a result of the steeply sloping terrain and relatively highly channel gradient. The higher SPI represents higher erosive capacity and hence deep incision, calling for special river basin management measures.

Similar to TWI, zones of relatively higher SPI also imply significantly higher gully density and hence, soil conservation measures are very essential in such areas. Since, the erosion zones are rather uniformly distributed in both MRB and PRB and therefore, choice of the conservation measures should consider the slope, TWI and SPI of the specific region. The most appropriate measures for areas of gentle slopes and lower TWI- and SPI-indices are gully floor stabilization using vegetation, logs and wire nets, chute spillways and gully reshaping and filling, whereas the steeper slopes with higher TWI and SPI

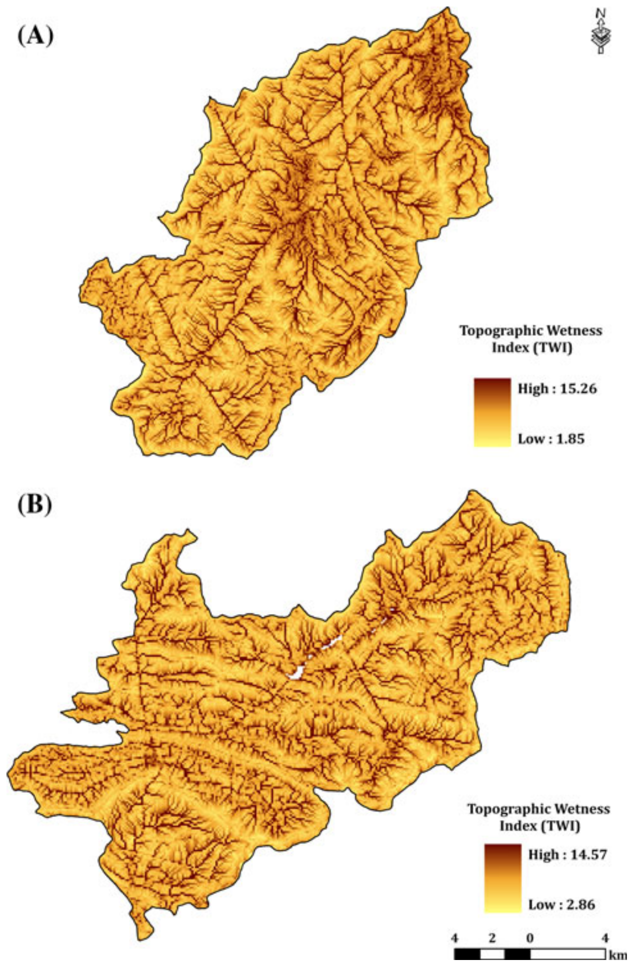


Fig. 8 Spatial variation of TWI in **a** PRB and **b** MRB

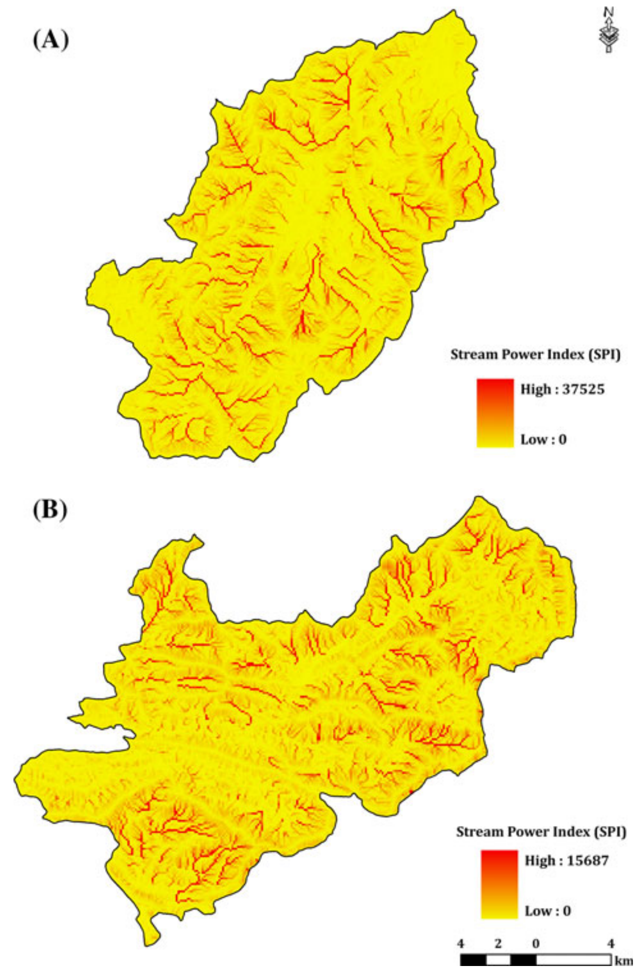


Fig. 9 Spatial variation of SPI in **a** PRB and **b** MRB

require drop- and grade control-structures. Further, lower SPI areas favors sediment deposition leading to the transition from debris flows to less-concentrated flow types (Marchi and Fontana 2005).

Conclusion

The summary of the morphometric analysis of two adjoining, mountain river basins (MRB and PRB) in the southern Western Ghats is as follows:

Proterozoic, high-grade, metamorphic rocks of granulite facies (dominantly granite gneiss and hornblende-biotite gneiss) dominate MRB and PRB. The Munnar plateau has a substantial influence on the drainage system of both MRB and PRB in that majority of the drainage network of MRB is developed on the plateau, while PRB is developed on the precipitous, northern scarps of the plateau. As MRB is on the western slopes of the southern Western Ghats, a tropical humid climate ($P_{ma} = 3{,}700$ mm, $T_{ma} = 17°C$) prevails, whereas PRB is located on the leeward slopes and correspondingly a rain shadow region ($P_{ma} = 1{,}100$ mm, $T_{ma} = 26°C$).

The river basins considered for the study are of 6th order and the drainage network of MRB and PRB is well-developed and systematically organized with a large number of first and second order streams to provide sufficient draining. Even though, both MRB and PRB dominantly exhibit parallel pattern, semi-centripetal, trellis, rectangular, and dendritic patterns also co-exist. Further, the straight channel segments and preferred orientation of streams reflect fracture/lineament control on the drainage alignment. The characteristic relationship between main stream length and basin area suggests headward erosion as the major mode of drainage network development, which is further supported by the irregularities in the boundary of the plateau basin (i.e., MRB). The Rb of either basins failed to highlight the structural controls on drainage organization, which might be a result of the elongated basin shape. The irregular trends in Rb between various stream orders (i.e., disagreement with Giusti and Schneider's hypothesis) not only suggest the substantial influence of geology and relief on drainage branching, but also imply contrasting paleo-environments of drainage development between the basins.

The overall increasing trend of Rl between successive stream orders suggests a geomorphic maturity of either the basins and confirmed by the characteristic I_{hyp} values. Further, Dd of MRB and PRB indicate that these basins are highly dissected and moderate to well-drained with lower infiltration rates. Though, Dd show significant, strong, positive correlation with rainfall in both the basins, comparatively higher Dd in PRB implies a relative dominance of topographic influence over the climate. The variability in Lg between MRB and PRB is dominantly determined by rainfall, pedologic characteristics and vegetation. Further, Re values imply an elongate shape for both MRB and PRB and subsequently smoother hydrograph (i.e., lower vulnerability to flash floods and hence, easier flood management). The relatively higher Rr of PRB is an indicative of comparatively steeply sloping terrain and consequently higher intensity of erosion processes.

Further, the analysis of digital elevation data and the application of GIS provide a spatial dimension to morphometry, which helps to understand the variation of quantitative morphometric parameters within the basins. The spatial distribution of slope form in PRB is significantly different from that in MRB, indicating the variation in terrain configuration between the basins. The aspect of MRB and PRB reveals appreciable differences between them, in that, NE, SE, and NW slopes are dominant in PRB, whereas S, SW, and NE slopes predominate MRB. The east-oriented slopes in both the basins receive feeble amount of insolation and hence influence the soil moisture regime, productivity and micro-climate. The spatial variation of TWI indicate the variability in saturated areas and erosion potential of the terrain, which is very essential for the prediction of water fluxes and significantly relevant for sustainable water resources management, especially in the basins lacking stream flow measurements. In addition, the spatial variability in SPI also indicates the distribution erosion zones and hence, choice of the soil conservation measures is proposed by considering the spatial variation in slope, TWI and SPI.

Hence, it would be concluded from the study that the dissimilarities in topography and climate is distinctively displayed in the morphometric descriptors of the basins. Moreover, analysis of the derivatives of digital elevation data significantly enhances the spatial dimension of the drainage basin morphometry.

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Appendix

See Table 5.

Table 5 Basic and derived morphometric parameters used in the study

Sl. no.	Parameter	Definition	Significance	References
1.	A (km^2)	Area of basin	Determinants of discharge	
2.	P (km)	Perimeter of basin		
3.	Lb (km)	Maximum length of basin measured parallel to main drainage line		
4.	Nu	Hierarchical ordering	Indicator of stream size, discharge and drainage area	Strahler (1957)
5.	Lu (km)	Mean length of streams in each order		Strahler (1964)
6.	Rb	$\text{Rb} = \text{Nu}/N(u+1)$	Measure of the degree of ramification of drainage network (Strahler 1964) and determines the runoff 'peakedness' (Chorley 1969)	Horton (1945)
7.	Rl	$\text{Rl} = \text{Lu}/L(u-1)$	Important in the determination of discharge and erosional stage of the watershed	Horton (1945)
8.	Dd (km km^{-2})	$\text{Dd} = \text{LT}/A$, where LT is total length of streams	A link between form-attributes of a basin and processes operating along the stream course (Strahler 1954; Gregory and Walling 1973); measure of the degree of fluvial dissection and runoff potential (Verstappen 1983)	Horton (1945)

Table 5 continued

Sl. no.	Parameter	Definition	Significance	References
9.	Lg (km)	Lg = 1/2Dd	The length of water to be travelled over the ground before it gets concentrated into definite stream channels; important in determining hydrologic and physiographic development of basins; controlled by geology, pedology, rainfall, vegetation etc	Horton (1945)
10.	Re	$\mathrm{Re} = 1.128\sqrt{A}/\mathrm{Lb}$	Determinant of basin shape	Schumm (1956)
11.	Rr	Rr = $(H - h)$/Lb, where H and h are the maximum and minimum elevations	Measure of basin slope	Schumm (1956)
12.	I_{hyp}	$I_{\mathrm{hyp}} = (\overline{H} - h)/(H - h)$, where $\overline{H}$ is the weighted mean elevation of basin	A measure of the degree of the fluvial landscape erosion; describes elevation distribution across the basin area; powerful tool to differentiate between tectonically active and inactive areas (Keller and Pinter 1996)	Strahler (1952)
13.	Slope (degree)	Rate of change of elevation in the direction of the steepest descent	Controls the flow rates of sediment and water. An understanding of basin slope is essential for planning of engineering structures, morphoconservation practices	ESRI (2005)
14.	Aspect	Direction of the line of the steepest descent	An anisotropic topographic attribute; influence distribution of vegetation and agricultural productivity	ESRI (2005)
15.	TWI	TWI = $\ln(A_s/\tan\beta)$, where A_s is the specific catchment area and β is slope gradient in radians	Indirect measure of flow accumulation, soil moisture, distribution of saturation zones, depth of water table, evapotranspiration (Beven and Kirkby 1979; Quinn and Beven 1993), and soil thickness, organic matter, pH, texture (Moore et al. 1993a), plant cover distribution (Florinsky and Kuryakova 1996) and erosion potential (Burt and Butcher 1985)	Moore et al. (1993a)
16.	SPI	SPI = $A_s\tan\beta$	Indicator of erosion potential of overland flows (Moore et al. 1991), soil thickness, organic matter, pH, texture (Moore et al. 1993a) and plant cover distribution (Florinsky and Kuryakova 1996); used to identify suitable locations for soil conservation measures (Maathuis and Wang 2006)	Moore et al. (1993a)

References

Anonymous (2007) Benchmark soils of Kerala. Soil Survey Organization. Department of Agriculture, Government of Kerala, Kerala

Bali R, Agarwal KK, Nawaz Ali S, Rastogi SK, Krishna K (2011) Drainage morphometry of Himalayan Glacio-fluvial basin, India: hydrologic and neotectonic implications. Environ Earth Sci. doi: 10.1007/s12665-011-1324-1

Beven KJ, Kirkby MJ (1979) A physically based, variable contributing area model of basin hydrology. Hydrol Sci Bull 24(1):43–70

Biswas S, Sudhakar S, Desai VR (1999) Prioritization of subwatersheds based on morphometric analysis of drainage basin: a remote sensing and GIS approach. J Indian Soc Remote Sens 27(3):155–166

Burt TP, Butcher DP (1985) Topographic controls of soil moisture distribution. J Soil Sci 36:469–486

Chavadi VC, Hegde VS (1991) Some aspects of drainage network analysis of Gangavali River and its tributaries in northern Karnataka. In: Proceedings Conference on the Quaternary landscape of Indian Subcontinent, Department of Geology, MSU, Baroda, 26–32

Chorley RJ (1969) Introduction to fluvial processes. Methuen, UK, pp 30–52

Chorley RJ, Schumm SA, Sugden DE (1984) Geomorphology. Methuen, London, p 318

ES RI(2005) Arc GIS 9.1. Redlands, CA

Esper Angillieri MY (2008) Morphometric analysis of Colanguil river basin and flash flood hazard, San Juan, Argentina. Environ Geol 55:107–111

Eyles RJ (1966) Stream representation on Malayan maps. J Trop Geogr 22:1–9

Fermor LL (1936) An attempt at the correlation of the ancient schistose formations of Peninsular India. Mem Geol Surv India 70:1–52

Florinsky IV (1998) Combined analysis of digital terrain models and remotely sensed data in landscape investigations. Prog Phys Geogr 22:33–60

Florinsky IV, Kuryakova GA (1996) Influence of topography on some vegetation cover properties. Catena 27:123–141

Frissel CA, Liss WJ, Warren CE, Hurley MD (1986) A hierarchical framework for stream habitat classification-viewing streams in a watershed context. Environ Manage 10:199–214

Giusti EV, Schneider WJ (1962) Comparison of drainage on topographic maps of the Piedmont province. USGS Prof Paper 450 E

Giusti EV, Schneider WJ (1965) The distribution of branches in river networks. USGS Prof Paper 422 G

Gregory KJ, Walling DE (1973) Drainage basin form and process: a geomorphological approach. Edward Arnold, London, pp 37–92

Hack JT (1957) Studies of longitudinal stream profiles in Virginia and Maryland. USGS Prof Paper 294 B

Hodgson ME (1998) Comparison of angles from surface slope and aspect algorithms. Cartogr Geogr Inf Sys 25:173–185
Horton RE (1932) Drainage basin characteristics. Trans Am Geophys Union 13:350–361
Horton RE (1945) Erosional development of streams and their drainage basins: hydrophysical approach to quantitative morphology. Geol Soc Am Bull 56(3):275–370
Jacob K, Narayanaswami S (1954) The structural and drainage pattern of the Western Ghats in the vicinity of the Palaghat gap. In: Proceedings of the National Institute of Science, India 20:101–118
James EJ, Padmini V (1983) Quantitative geomorphologic studies of the Kuttiyadi River Basin on the Malabar Coast. J Inst Eng 63:266–271
Joji VS, Nair ASK (2002) Significance of fourth order sub basins of Vamanapuram River Basin, southern Kerala, India. In: Proceedings of the XII Swadeshi Science Congress 352–358
Kale VS, Shejwalkar N (2007) Western Ghats escarpment evolution in the Deccan Basalt Province: geomorphic observations based on DEM analysis. J Geol Soc India 70:459–473
Keller EA, Pinter N (1996) Active tectonic earthquakes: uplift and landscape. Prentice Hall, New Jersey, p 337
Langbein WB (1947) Topographic characteristics of drainage basins. USGS Water Supply Pap 968C:125–157
Maathuis BHP, Wang L (2006) Digital elevation model based hydro-processing. Geocarto Int 21(1):21–26
Magesh NS, Chandrasekar N, Soundranayagam JP (2011) Morphometric evaluation of Papanasam and Manimuthar watersheds, parts of Western Ghats, Tirunelveli district, Tamil Nadu, India: a GIS approach. Environ Earth Sci 64:373–381
Mahadevan TM (1964) The origin of the charnockite suite of rocks forming part of the Western Ghats, Kerala, India. In: Proceedings of International Geological Congress, 22nd session 13:87–96
Manu MS, Anirudhan S (2008) Drainage characteristics of Achankovil River Basin, Kerala. J Geol Soc India 71:841–850
Marchi L, Fontana GD (2005) GIS morphometric indicators for the analysis of sediment dynamics in mountain basins. Environ Geol 48:218–228
Maya K (1997) Morphometric and geomorphic aspects of Chalakkudy River Basin. Technical Report PRT 97-1, Centre for Earth Science Studies, Thiruvananthapuram, Kerala, India
Mekel JFM (1970) The use of aerial photographs in geological mapping. ITC text book of Photo-interpretations, vol 8, pp 1–169
Mesa LM (2006) Morphometric analysis of a subtropical Andean basin (Tucuman, Argentina). Environ Geol 50:1235–1242
Moore ID, Grayson RB, Ladson AR (1991) Digital terrain modeling: a review of hydrological, geomorphological, and biological applications. Hydrol Process 5:3–30
Moore ID, Gesseler PE, Nielsen GA, Peterson GA (1993a) Soil attribute prediction using terrain analysis. Soil Sci Soc Am J 57:443–452
Moore ID, Grayson RB, Landson AR (1993b) Digital terrain modeling: a review of hydrological, geomorphological and biological application. In: Beven KJ, Moore ID (eds) Terrain analysis and distributed modeling in hydrology: advances in hydrological processes. Wiley, New York, pp 7–34
Morgan RPC (1971) A morphometric study of some valley systems on the English Chalklands. Trans Inst Br Geogr 54:33–44
Mulder T, Syvitsky JPM (1996) Climatic and morphologic relationships of rivers: implications of sea-level fluctuations on river loads. J Geol 104:509–523
Nag SK (1998) Morphometric analysis using remote sensing techniques in the Chaka sub-basin, Purulia district, West Bengal. J Indian Soc Remote Sens 26(1&2):69–76
Nair MM, Anilkumar PS (1989) Detailed studies of the acid intrusive of Kerala. Rec Geol Surv India 122:203–206
Nooka Ratnam K, Srivastava YK, Venkateswara Rao V, Amminedu 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(1):25–38
Pankaj A, Kumar P (2009) GIS-based morphometric analysis of five major sub-watersheds of Song River, Dehradun District, Uttarakhand with special reference to landslide incidences. J Indian Soc Remote Sens 37(1):157–166
Pike RJ (2000) Geomorphometry: diversity in quantitative surface analysis. Prog Phys Geog 24:1–20
Quinn PF, Beven KJ (1993) Spatial and temporal prediction of soil moisture dynamics, runoff, variable source areas and evapotranspiration for Plynlimon, mid-Wales. Hydrol Process 7:425–448
Raghavan BR, Sridhara Murthy TR (1990) Stream frequency and density in Sita-Swarna basin, Karnataka, India. Indian Geog J 65:141–148
Ravindrakumar GR, Chacko T (1994) Geothermobarometry of mafic granulites of Manantoddy, North Kerala. J Geol Soc India 33(2):132–139
Scheidegger AE (1970) Theoretical geomorphology. George Allen and Unwin, London, pp 243–248
Schumm SA (1956) Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey. Geol Soc Am Bull 67:597–646
Selby MJ (1968) Morphometry of drainage basins in areas of pumice lithology. In: Proceedings of 5th New Zealand Geological Conference, New Zealand Geological Society 169–174
Smith KG (1958) Erosional processes and landforms in Badlands National Monument, South Dakota. Geol Soc Am Bull 69:975–1008
Soman K (2002) Geology of Kerala. Geological Survey of India, Bangalore
Sreedevi PD, Subrahmanyam K, Ahmed S (2005) The significance of morphometric analysis for obtaining groundwater potential zones in a structurally controlled terrain. Environ Geol 47:412–420
Sreedevi PD, Owais S, Khan H, Ahmed S (2009) Morphometric analysis of a watershed of South India using SRTM data and GIS. J Geol Soc India 73:543–552
Strahler AN (1952) Hypsometric (area-altitude) analysis of erosional topography. Geol Soc Am Bull 63:1117–1141
Strahler AN (1954) Statistical analysis in geomorphic research. J Geol 62:1–25
Strahler AN (1957) Quantitative analysis of watershed geomorphology. Trans Am Geophys Union 38:913–920
Strahler AN (1964) Quantitative geomorphology of drainage basin and channel networks. In: Chow VT (ed) Handbook of applied hydrology. McGraw Hill, New York, pp 4–76
Thakkar AK, Dhiman SD (2007) Morphometric analysis and prioritization of miniwatersheds in Mohr watershed, Gujarat using remote sensing and GIS techniques. J Indian Soc Remote Sens 35(4):313–321
Thampi PK (1987) Geology of Munnar granite, Idukki district, Kerala, India. Thesis (PhD), University of Kerala, Thiruvananthapuram, Kerala, India
Thomas J, Joseph S, Thrivikramji KP (2010) Morphometric aspects of a small tropical mountain river system, the southern Western Ghats, India. Int J Digit Earth 3(2):135–156
Thomas J, Joseph S, Thrivikramji KP, Abe G (2011) Morphometric analysis of the drainage system and its hydrological implications in the rain shadow regions, Kerala, India. J Geogr Sci 21(6):1077–1088

Verstappen HTh (1983) Applied geomorphology-geomorphological surveys for environmental development. Elsevier, New York, pp 57–83

Vijith H, Satheesh R (2006) GIS based morphometric analysis of two major upland sub-watersheds of Meenachil River in Kerala. J Indian Soc Remote Sens 34(2):181–185

Vittala SS, Govindaiah S, Gowda HH (2004) Morphometric analysis of the sub-watersheds in the Pavagada area of Tumkur district, South India using remote sensing and GIS techniques. J Indian Soc Remote Sens 32(4):351–362

Wilson JP, Gallant JC (2000) Terrain analysis: principles and applications. Wiley, New York, p 479

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