

PHYSICAL GEOGRAPHY

Physical Geography



ISSN: 0272-3646 (Print) 1930-0557 (Online) Journal homepage: http://www.tandfonline.com/loi/tphy20

River and basin morphometric indexes to detect tectonic activity: a case study of selected river basins in the South Indian Granulite Terrain (SIGT)

H. Vijith, V. Prasannakumar, M. A. Sharath Mohan, M. V. Ninu Krishnan & P. Pratheesh

To cite this article: H. Vijith, V. Prasannakumar, M. A. Sharath Mohan, M. V. Ninu Krishnan & P. Pratheesh (2017): River and basin morphometric indexes to detect tectonic activity: a case study of selected river basins in the South Indian Granulite Terrain (SIGT), Physical Geography, DOI: <u>10.1080/02723646.2017.1283478</u>

To link to this article: <u>http://dx.doi.org/10.1080/02723646.2017.1283478</u>



Published online: 23 Jan 2017.

-	-	-	۰.	1
E .		14	4	h
	14	A	0	٢
	- 1	υ	r 1	t
ι.		~	1	ł

Submit your article to this journal 🗹

Article views: 8



View related articles 🗹

🔰 View Crossmark data 🗹

Full Terms & Conditions of access and use can be found at http://www.tandfonline.com/action/journalInformation?journalCode=tphy20



River and basin morphometric indexes to detect tectonic activity: a case study of selected river basins in the South Indian Granulite Terrain (SIGT)

H. Vijith^a ^(D), V. Prasannakumar^b, M. A. Sharath Mohan^b, M. V. Ninu Krishnan^a and P. Pratheesh^{b,c}

^aFaculty of Engineering and Science, Department of Applied Geology, Curtin University Sarawak, Miri, Malaysia; ^bCentre for Geoinformation Science and Technology, University of Kerala, Thiruvananthapuram, India; ^cDepartment of Geology, School of Earth Science Systems, Central University of Kerala, Kasaragod, India

ABSTRACT

The effects and influence of tectonic processes on the Anjarakandy, Thalassery, Mahe, and Kuttiyadi watersheds and rivers of the South Indian Granulite Terrain in Kerala were examined to determine their spatial heterogeneity. Drainage basin asymmetry (Af), transverse topographic symmetry factor (T), hypsometric integral and curve (HI), longitudinal profile, stream length gradient index (SL), and stream concavity index (SCI) suggest heterogeneity in tectonic influence. Clusters of geomorphic anomalies in similar lithology rule out lithologic control on drainage development. However, the orientations of the drainage networks and predominant fractures/ lineaments compare closely and reveal strong tectonic influence. Though the watersheds are considered to be in an advanced stage of erosion by the low HI (<30) and high values of SCI, variations in the shape of the hypsometric curves and differences in the SCI values indicate the different influence of tectonic process from watersheds in the north to the south. Among the watersheds, the Mahe and Kuttiyadi are more sensitive to tectonic processes than the Anjarakandy and Thalassery and indicate spatial heterogeneity in the influence of tectonic activity, confirming the grouping of watersheds based on structural and drainage patterns.

Introduction

Quantitative assessment of geomorphic expressions of rivers, caused due to recent and ongoing tectonics is considered to be the quickest and most trusted method for generating baseline information about the tectonics in a region where the related data are otherwise rare. Since river systems are highly sensitive to changes caused by various geological processes, such as folding, faulting, base-level change in relation to the sea level fall, or uplift, and also by a sudden change in lithology (Keller, 1986; Rhea, 1993; Štěpančíková, Stemberk, Vilímek, & Košťák, 2008), analysis of drainage networks, drainage-network patterns, and their orientations is being increasingly used, especially in the last few decades, to infer the

ARTICLE HISTORY

Received 26 May 2016 Accepted 14 January 2017

KEYWORDS

Tectonic influence; geomorphic indices; watershed; spatial heterogeneity

2 🔄 H. VIJITH ET AL.

underlying tectonic and structural framework. Spatial characterizations of rivers and the river basins through morphometric and morphotectonic analysis are considered to be basic, essential techniques that give clues about the aerial, linear, and relief characteristics of the drainage basin and analyzed streams (Schumm, 1956; Strahler, 1964). In accordance with the increased understanding of stream networks, various geomorphic indices, which are powerful enough to identify and delineate the characteristic expressions associated with the stream networks, have also been proposed (Cox, 1994; Hack, 1973; Strahler, 1952, 1964). The most widely used geomorphic indices are drainage basin asymmetry (Af), transverse topographic symmetry factor (T), stream length gradient index (SL), hypsometric curve and integral (HI), valley floor width–valley height ratio (Vf), drainage basin shape (Bs), mountain-front sinuosity (smf), concavity, and steepness (Dehbozorgi et al., 2010; Garrote, Heydt, & Cox, 2008; Kale, Sengupta, Achyuthan, & Jaiswal, 2014; Keller & Pinter, 2002; Troiani & Della Seta, 2008).

Geomorphic indices, coupled with high resolution elevation datasets and geographical information systems (GIS), have equipped the analyst to quantify the geomorphic expressions associated with river networks in a detailed manner (e.g. Ahmad, Bhat, Madden, & Bali, 2014; Dar, Chandra, & Romshoo, 2013; Ehsani & Arian, 2015; Elias, 2013; Özkaymak, 2015; Toudeshki & Arian, 2011; Trevisani, Cavalli, & Marchi, 2010; Viveen et al., 2012). The present study aims to understand the spatial differences of the effect of tectonic processes in four adjoining watersheds and streams originating from the Western Ghats, India, and flowing through the hard crystalline rocks to reach the Arabian Sea. Geomorphic indices capable of differentiating the effects of tectonic influences and highlighting the expressions embedded in the streams are used to quantify the spatial heterogeneity of the region under investigation.

Regional geology and tectonic settings

The watersheds selected for the present study form a part of the South Indian Granulite Terrain (SIGT), composed of high-grade metamorphic rocks (granulite-amphibolite facies) of Archaean age. The SIGT is a composite continental segment, formed by the accretion of various crustal blocks, and is traversed by a number of intracrustal ductile shear zones (Drury & Holt, 1980; Radhakrishna, 1989; Prasannakumar & Lloyd, 2007). The Palghat-Cauvery Shear System (PCSS), consisting of the Moyar, Bhavani, Palghat, Cauvery, and Attur shear zones, is the predominant structure that transects the SIGT. The Moyar shear zone (MSZ), forming the northwestern segment of the shear system, has a dominant NW-SE to E-W trend and is in close proximity to the study area. Lithological variations in the area are represented by hornblende biotite gneiss, charnockite, quartzo-feldspathic gneiss, pyroxene granulite, banded magnetite quartzite, younger granite, gabbro, and mafic dikes (Praveen, Prasannakumar, & Mamtani, 2009). The rocks, except the younger granites and other intrusives, have been subjected to polyphase deformation and metamorphism resulting in mesoscopic- to microscopic-scale structures. Systematic analysis of the meso- and microfabrics in different segments of the shear zone has revealed multistage reactivation history (Prasannakumar & Lloyd, 2010). Such reactivations, during different periods, were responsible for both strike-slip and dip-slip movements of varying dimensions resulting in the exhumation of the crustal blocks of south India (Satheeshkumar & Prasannakumar, 2009). Thus the lower crustal equivalents have been brought to the present level by processes related to repeated uplift and erosion, as observed in other shield areas also. The Cretaceous age of the dike swarms (Radhakrishna, Maluski, Mitchell, & Joseph, 1999) indicates reactivated tectono-thermal activity during Cretaceous–Tertiary time also. The anastomosing shear zones and associated structures, like faults and fractures, have hosted younger intrusives and have also served as conducive loci for potential localisation of stresses. Ancient and recent seismic activities in the vicinity of the area and elsewhere in the PCSS (Rajendran, John, Sreekumari, & Rajendran, 2009) reveal stress buildup and tectonic activities in various microdomains of the region.

Seismic activities: evidence of neotectonism

The study area, generally considered as tectonically stable, comes under Zone III in the seismic zonation map of India, indicating low vulnerability to earthquakes (Bureau of Indian Standards [BIS], 2002). However, earthquakes of varying magnitude (<2.5 to > 5 M, but with an increasing trend), experienced in the region during the last four decades, are being considered as tempting evidence of probable change in the tectonic framework of the region (Bhattacharya & Dattatrayam, 2002; Raj, Paul, Hegde, & Nijagunappa, 2001; Rajendran & Rajendran, 1996; Rajendran et al., 2009). The earthquakes, athough of low magnitudes, have caused fissures and cracks in the ground as well as buildings, and have affected the hydrologic regime as water-level fluctuation, bubbling effect in ponds/wells, and even collapse of wells (Singh, Mathai, Neelakandan, Shankar, & Singh, 2005). The locations of earthquake epicenters and associated phenomena in the region show proximity to the prominent faults/ lineaments present (Centre for Earth Science Studies [CESS], 2009; Rajendran et al., 2009). The increasing occurrence of earthquakes in the region can be considered as an indication of neotectonics, which, in turn, may influence the general characteristics of the rivers. Changes due to tectonic influence will be expressed as a variation in the valley floor (increase of gradient) and longitudinal profile (presence of numerous knick points and rapids), increased aggregation and degradation along with the change in channel pattern, and river stream capture (Keller & Pinter, 2002; Schumm, 1986).

Study area

Four adjoining west-flowing rivers of varying dimensions, namely the Anjarakandy, Thalassery, Mahe, and Kuttiyadi, which originate from the Western Ghats, flow through midland rolling plains and drain into the Arabian Sea (Figure 1). Basic characteristics of the watersheds selected for the present study are summarized in Table 1. Among the watersheds selected, the Thalassery is the smallest, with a total area of 132 km², and the Kuttiyadi is the largest (1320 km²). The others, the Anjarakady and Mahe, drain 421 and 394 km² of land, respectively. The spatial appearance of the watersheds ranges from elongated to semi-circular, with varying dimensions in different parts. Irrespective of size and flow length, all the watersheds have a wide open river mouth near the coastal region. Spatial characteristics of the rivers selected include the presence of bedrock in more than 90% of flow length, while river segments in the lower reaches flow through alluvial or coastal plains. Terrain characteristics vary from high elevated hills (>2000 m above sea level) with steep slopes, escarpments, gently sloping midlands having small mounds, rolling plains, and low-lying coastal stretches with elevations <2 m above sea level.

4 😉 H. VIJITH ET AL.



Figure 1. Location map.

Most of the study area is composed of hard crystalline rocks and then by laterite, recent floodplain, and beach sediments. Another striking geological feature is the abundance of dolerite dikes with two prominent trends: NNW–SSE and ENE–WSW. Major structural features present in the area are faults (strike-slip), showing concordant orientation with dolerite dikes (Geological Survey of India [GSI], 1995). Parallel running numerous fractures/ lineaments subparallel to the dikes are also inferred from the satellite images.

The study region receives comparatively high rates of rainfall (>3500 mm), and the geomorphology of the terrain helps rainwater flow from the higher regions to reach the coastal plains within hours after the rainfall. Estimated annual average flow of the studied rivers varies from 155 M m³ (Thalassery River) to 1273 M m³ (Kuttiyadi River), which directly depends on the watershed area. Due to the high gradient and short distance of flow, the river action in the headwaters region is quite high, which favors transport of huge debris, derived from mass-wasting processes, to lower reaches of the streams. Denudational processes and fluvial erosion have resulted in the development of various geomorphic features in the region. Geomorphologic features common to the western slopes of the Western Ghats are present in the study area also. These include a gradational change from structural hills in the uppermost region, followed by denudational hills, slopes, lateritic local planation surfaces, residual mounds, gently sloping valleys that change to low-lying features such as valley fills, flood and alluvial plains, and finally to beaches. Though the study area includes alluvial plains, coastal stretches occupy less area (<5%) of each watershed.

Methodology

The present analysis is an attempt to examine the influence and spatial variation of neotectonic activity in the watersheds, particularly in stream networks. The impact of tectonic processes over the stream networks will be reflected in the morphological characteristics, which vary depending on the severity of the tectonic activity and the response of the

Table 1. Basic ch	naracteristics of th	e analyzed watersh	ieds.					
Watershed		Flow length of		Maximum	Annual average	Average annual		
name	Area (km²)	river (km)	Watershed order	elevation (m)	rainfall (mm)	stream flow (Mm ³)	Origin point	Major tributories
Anjarakandy	412	76	S	1165	3500	413	Kannoth Reserve forest	Kappu thodu, Idumha thodu
Thalassery	132	28	4	660	3500	155	Kannoth Reserve	
Mahe	394	54	5	1350	3900	248	Vanchimagate Hill (Wavanad Hills)	Ottani puzha
Kuttiyadi	1320	74	9	2034	4500	1273	Narikot Hills	Onipuzha,
							(Wayanad Hills)	Alamparathodu,
								Kadiyangad pu-
								zha, Kadanthara-
								puzha, Niduvali
								puzha

Ð
4
S
5
8
a
5
>
a)
Ň
~
2
5
10
Ð
<u> </u>
Ŧ
4
0
10
Ŭ
·Ξ
5
·=
ē
÷
Q
o,
E
ĕ
÷.
.9
S
a
В
<u> </u>
d)
-
-0

6 😉 H. VIJITH ET AL.

Geomorphic indices	Equation	Explanations
Drainage basin asymmetry (Af)	$Af = ((Ar/At) \times 100)$	Ar – area of the basin to the right side of the major river At – total area of the drainage basin
Transverse topographic symmetry factor (T)	T=Da/Dd	Da – distance between the midline of the drainage basin and the active meander belt midline
		Dd – distance between the midline and the basin divide
Longitudinal profile	Elevation – distance plot	X, Y plot of elevation and distance along the river channel from head water to mouth
Stream length gradient index (SL)	$SL = (\Delta H / \Delta L) \times L$	ΔH – change in elevation of the reach ΔL – change in length of the reach L – total length of the channel to the point where the SL index is being calculated
Hypsometric integral (HI)	$HI = (h_{mean} - h_{min})/(h_{max} - h_{min})$	h_{mean} – average height h_{min} and h_{max} are the minimum and maximum height of the catchment
Stream concavity index (SCI)	$SCI_i = 1 - \sum_{i=0}^{1} ((x_i - y_{i+1})(y_i + y_{i+1}))$	x_i = upstream distance (m), and y_i = alti- tude (m) at point <i>i</i>

Table 2. Methodology	and formulas used for	the computation of	of geomorphic indices.

lithological units to such processes. Morphotectonic impressions and their variations in the selected watersheds and rivers were assessed using drainage basin asymmetry (Af), transverse topographic symmetry factor (T), hypsometric integral and curve (HI), longitudinal profile, stream length gradient index (SL), and stream concavity index (SCI), derived from the digital elevation model (DEM). Methodology and formulas used in the study are shown in Table 2 and are briefly explained. Though the study required data sets from different sources, the most important one is the DEM. Shuttle Radar Topographic Mission (SRTM) digital elevation data with a resolution of 30 m, downloaded from the website of the United States Geological Survey (http://earthexplorer.usgs.gov/) and used to extract the elevation details required for the present study. Other datasets used are Survey of India (SoI) topographical sheets and geological map of the region (Geological Survey of India) at 1:50,000 scale. Landsat 8 Operational Land Imager (OLI) images, acquired on 22 December 2015, were also used to extract structural features and prominent river networks of the area. ArcInfo ArcGIS 9.3 and SAGA 2.1.2 were used for the data processing (especially the DEM) and analysis. Digital elevation data extracted for the study areas were conditioned with the Fill DEM tool available in the ArcGIS Spatial Analyst to fill voids present in the DEM and make it suitable for further analysis. Information related to the occurrence of earthquakes in the region was also analyzed to consolidate the inferences made from the interpretation of geomorphic indices.

The river basin, channel networks, and structural features present in the region were analyzed with the generation and interpretation of rosette diagrams of stream networks (DEM derived) and lineaments (inferred from the Landsat 8 OLI image), before extracting the geomorphic variables. These rosette diagrams were prepared irrespective of stream order and length of lineaments to understand the structural control over the drainage pattern. The effect of tectonic disturbances in an area will be reflected in the stream shape, its orientation, and the asymmetric nature of the watershed. Asymmetry of the drainage basins can be easily identified by calculating the drainage basin asymmetry factor (Af), which facilitates identification of changes in stream patterns and displacements in response to tectonic forces that cause terrain tilting (Cox, 1994; Elias, 2013; Garrote et al., 2008; Hare & Gardner, 1985; Keller & Pinter, 2002). Any change in the equilibrium condition of the terrain due to uplift or tilt will be reflected as changes in the normal course of the river toward the direction of terrain tilt and variations of the rivers from the basin midline can be easily detected by comparing the area belonging to the right bank of the river with the total drainage area. The computed percentage will reflect symmetry and asymmetry of the basin. Af values far above or far below the threshold of 50% indicate asymmetry, and those close to the cut-off indicate the symmetric nature of a watershed.

Tectonic activities strongly influence the stream pattern, which will be manifested as changes in the symmetry with respect to the basin midline. The transverse topographic symmetry factor (T) is capable of detecting such changes (Cox, 1994; Cox, Roy, Van Arsdale, & James, 2001; Garrote et al., 2008; Keller & Pinter, 2002) in quantity (T index) and direction (T vector). The T index varies from 0 to 1, in tune with the severity of changes from basin midline, and indicates perfect symmetry and maximum asymmetry, respectively, while the T vectors correspond to the direction of oscillation with respect to the T index (Salvany, 2004; Toudeshki & Arian, 2011; Virdi, Philip, & Bhattacharya, 2006). In the present study, the T index was analyzed for the total length of the major stream by selecting points to represent maximum, minimum, and no oscillation from the basin midline.

The graphical representation of the elevation-distance profile from origin to downstream of a river (the longitudinal profile) reflects the bed characteristics of the river. Ideally, the longitudinal profile of the stream with a smooth concave curve indicates steady-state equilibrium of the channel. Any change in the smoothness of the concave curve indicates disequilibrium condition of the riverbed due to the influence of geological processes that affected the region (Whipple & Tucker, 1999). Influencing factors can vary from tectonic process (uplift or faulting) to lithological variations (Antón, De Vicente, Muñoz-Martín, & Stokes, 2014; Hack, 1957, 1960; Jain, Preston, Fryirs, & Brierley, 2006; Leopold & Bull, 1979; Rhea, 1993; Schumm, 1977; Trevisani et al., 2010). Hack (1973) proposed the stream length gradient (SL) index to analyze the response of streams to lithological changes and tectonic processes by considering unique length segments along the whole length of the stream. The SL index is capable of differentiating anomalies in the streambed by showing higher values than the neighbouring segments analyzed. These anomalies are present in the streambed as knickpoints (either as waterfall or rapids), which might have formed due to sudden changes in underlying lithology or faults/uplift of the region in response to the tectonic process (Keller, 1986; Štěpančíková et al., 2008; Troiani & Della Seta, 2008). In order to generate the longitudinal profile and SL index, stream channels were segmented to 500-m unique channels from the origin to the mouth. Further analyses were carried out based on the elevation information extracted using the starting, middle, and end nodes of these stream segments.

Strahler (1952) proposed the analysis of area-altitude relationships to find out the geomorphic evolution stage of the watershed/river basin through the analysis and interpretation of the hypsometric curve and hypsometric integral (HI). The shape of the non-dimensional area-elevation (hypsometric) curve and the area under the hypsometric curve are two components capable of revealing the characteristics of the analyzed area (Hurtrez, Lucazeau, Lavé, & Avouac, 1999; Singh, Sarangi, & Sharma, 2008). The shape of the hypsometric

8 🔶 H. VIJITH ET AL.

curve varies from concave to concave-convex and convex. At the same time, the value of HI indicates the percentage of the area remaining to be eroded.

The SCI is the measure of concavity or convexity of the channel based on the area measurement taken from the normalized channel profile and the straight line connecting the highest and lowest points in the profile (Demoulin, 1998; Zaprowski, Pazzaglia, & Evenson, 2005). SCI values can vary between negative and positive corresponding to the convexity or concavity of the channel. Higher positive SCI values represent concave channels with equilibrium or steady-state conditions, whereas negative values correspond to convex channels, indicating terrain transition. The SCI was generated for all four rivers by normalizing the elevation–distance plots (longitudinal profiles) and calculating the area between the profile and the diagonal line.

Results and discussion

Drainage and fracture pattern

Drainage pattern is generally controlled by the underlying lithology, structural features and terrain characteristics of the region, along with rainfall and runoff. Disturbances in the region, caused by geological processes such as uplift, faulting, or folding, will affect the equilibrium condition of the region and, hence, will affect the geomorphic characteristics of the stream networks which, in turn, will result in channel pattern changes and development of sinuosity. Drainage networks derived from the DEM were used to assess the characteristic drainage patterns and stream orientations in each of the watersheds considered in the present study. Drainage networks of the Anjarakandy watershed show mixed characteristics dominated by dendritic and rectangular patterns, whereas the streams in the Thalassery watershed show only a dendritic pattern. At the same time, streams in the Mahe and Kuttiyadi watersheds have rectangular and trellis patterns along with the dendritic pattern (Figure 2). Major portions of all the watersheds are covered with hard crystalline rocks, and the dominant drainage pattern observed is dendritic, but with variations at places. The variation of drainage pattern from dendritic to rectangular and trellis indicates the presence of structural control over the drainage pattern development. This points to the dominance of tectonic activity in the development of stream networks and pattern in the region.

Rosette diagrams were used to understand the dominant direction of streams and lineaments present in the watersheds. A common pattern of stream orientation with major trends such as N–S, NE–SW, E–W and NW–SE was observed in the rosette diagrams of all four watersheds (Figure 2(a)). Lineaments/fractures also show orientation similar to the drainage networks. Major directions of orientation shown by the lineaments/fractures are N–S, NNE–SSW, ENE–WSW, E–W, and NW–SE (Figure 2(b)). Drainage networks present in the Anjarakandy watershed show three prominent directions of stream orientation, such as N–S, NE–SW, and E–W, with a less distinct NW–SE component; whereas lineaments or fractures present in the watershed show two major directions, N–S and E–W, which coincide with those of the stream networks. Similar patterns of orientation are also observed in the Thalassery watershed, in which both the stream network and lineaments show common directions of orientation as NE–SW, E–W, and NNE–SSW, ENE–WSW, respectively. Drainage networks in the Mahe and Kuttiyadi watersheds show a common trend of N–S, NE–SW, E–W and NW–SE, similar to the other two watersheds, but the lineaments show



Figure 2. Drainage networks, faults and lineaments with corresponding rose diagrams: (a) for drainages and (b) for faults / lineaments.

N–S, NNE–SSW, and E–W in the Mahe and NNE–SSW, NNW–SSE, and E–W trends in the Kuttiyadi watershed. Variations in drainage pattern and orientation of lineaments/fractures, inferred from images for the four watersheds, enable the grouping of the watersheds into two clusters: (1) Anjarakandy–Thalassery and (2) Mahe–Kuttiyadi. Overall, the inferred structural features and streams in the watersheds show a common orientation similar to that of the strike-slip faults and dolerite dikes (NNW–SSE, NW–SE, and NNE–SSW) present in the region, except for noticeable differences in the Mahe and Kuttiyadi watersheds. This suggests the differential influence of structural features over stream characteristics in the area due to different episodes of tectonic activity in the region. These inferences can be addressed through the analysis and interpretation of geomorphic indices.

Drainage basin asymmetry (Af)

Af factors calculated for the watersheds under investigation show values above and below the 50% cutoff, indicating varying degrees of asymmetry of the watersheds with a prominent, general southerly tilt (Figure 3). Among the watersheds analyzed, the Anjarakandy shows the maximum value of 66%, followed by Kuttiyadi (63%), Thalassery (60%), and Mahe (43%). Though the study area, as a single unit, shows a common direction of tilt (SSE), it is also noted that, within the watersheds, the mouth regions of all the rivers, indicate varying directions of tiling. This points towards the influence of structural features (strike-slip faults), present in the region, in producing varying directions of tilt. This assumption can be reinforced by the assessment of the topographic symmetry (T) factor, which facilitates segment-wise characterization of the terrain tilt in association with stream migration.

H. VIJITH ET AL. (🛥)



Figure 3. Lithology of the study area, with basin asymmetry (Af) and transverse topographic symmetry factor (T) vectors showing stream migration direction and tilt directions.

Transverse topographic symmetry factor (T)

Calculated T index values are given in Table 3, along with the zonal tilt directions of segments analyzed (Figure 3). Lower T values indicate the symmetric character of the river and suggest that the river follows the basin midline. On the contrary, the higher values indicate asymmetry of the river due to significant shift away from the basin midline. In the Anjarakandy watershed, the T index ranges from .06 to .90 and shows three prominent directions (SSE, NNW, and SSW) of stream oscillation or tilt. The Thalassery watershed suggests less asymmetry (T index varies from .05 to .40), with a prominent river oscillation to the SSE. The Mahe River shows a lateral shift of stream and basin from symmetrical to asymmetrical nature (T index varies from .07 to .63), with two major zones of oscillation direction, i.e. NNW and SSW. At the same time, the T index of the Kuttiyadi River ranges from zero (perfect symmetry) to .87, indicating the highest rate of stream oscillation in accordance to the terrain tilt with three prominent zones of stream oscillation directions such as N, S, NNE, NNW, and SSE. Zonal variations in the T index and vector confirm varying degrees of the effects of terrain changes in different segments of streams and watersheds as deduced from the assessment of drainage basin asymmetry factors.

10

River segments	Aniarak	andy River	Thalas	serry River	Mal	ne River	Kuttiv	vadi River
Segments	/ lijurur		manas		With		Rattij	
Handwater	Ŧ	Zonal tilt	-	Zonal tilt	-	Zonal tilt	Ŧ	Zonal tilt
Headwater		direction	1	direction	I	direction		direction
1	.11	SSW	.15	SSE	.07	SSW	.09	S
/	.37		.12		.12		.09	
1	.47		.24		.62		.07	
l	.33		.40		.46		.16	
	.43		.18		.42		.16	
\ \	.27		.14		.14		.00	NNE
\	.30		.13		.20		.09	
1	.41		.31		.41		.32	
	.50		.30		.42		.30	NNW
	.38		.17		.48		.11	
į	.14		.25		.53		.09	SSE
1	.11		.24		.55		.17	
/	.10		.25		.34	NNE	.02	
/	.36		.18		.23	NNW	.09	
/	.26		.10	SSW	.09		.27	
(.12		.05		.20		.34	
1	.06		.38	NNW	.25		.78	
	.07				.44		.87	S
Ì	.27				.19		.65	
\	.35	NNW			.12		.33	
/	.23						.14	N
	.24	665					.33	
)	.16	SSE						
/	.32							
/	.62							
/	./9							
↓	.90							
Marith	./0							
wouth	.87							

 Table 3. Topographic transverse symmetry (T) factor calculated for the selected segments with zonal tilt directions.

Longitudinal profile

Longitudinal profiles of all the analyzed rivers show varying patterns of concavity, convexity, and the combination of concave and convex with flat segments (Figure 4). The longitudinal profile of the Anjarakandy River is concave, with changes in slope and minor steps in the lower and upper reaches, indicating zones of maximum variation in channel characteristics. A similar pattern is noticed in the Thalassery River, which also shows an open concavity with a small stretch of undulations. However, the Mahe River shows highly irregular characteristics, with convex–concave structures in the profile. The Kuttiyadi River shows an entirely different profile than the other three rivers, with a stepped profile having steep slopes, flat surfaces, and zones of maximum variation. The steep sloping nature of the profile indicates the steep slope of the terrain, with exposed rocky channels, whereas the flat surface corresponds to the reservoirs present at different levels of the river. These inferences were confirmed by validating the selected stream segments with a satellite image of the study area. In the longitudinal profiles, the segments marked as zones of maximum variation can be attributed to differences in lithology or the influence of tectonic processes.



Figure 4. Longitudinal profiles marked with zones of maximum variations: (a) Anjarakandy, (b) Thalassery, (c) Mahe, and (d) Kuttiyadi.

Stream length gradient index (SL)

In the present analysis, SL index was calculated for all four major rivers for the individual segments derived from origin point to the mouth of the river and are shown in Figure 5. The SL index, calculated for the Anjarakandy River, varies from 10 to 734 m (average SL = 113 m), with numerous abrupt variations in close proximity, whereas that of the Thalassery River ranges from 10 to 263 m (average SL = 50 m), with common trends and minor variations. The SL index of the Mahe and Kuttiyadi Rivers show high values of 331 m (average SL = 69) and 3898 m (average SL = 159 m), respectively. Among the rivers analyzed, the Anjarakandy, Thalassery, and Mahe show highly varying graphs with numerous highs and lows, indicating abrupt changes in the SL index in nearby segments. The Kuttiyadi River shows an overall uniform SL index over the total length of the river, with three definite zones of variation.

Tectonic process will influence differently the development of landforms and stream patterns in the region if the lithology of watersheds compared are different, i.e. sudden change in rock types from hard (crystalline rocks) to soft (sedimentary rocks) or vice-versa. In the present study, the four selected watersheds possess more or less similar lithology, with a slight change in areal distribution. Major types of hard crystalline rocks that cover most of the study area are charnockite gneiss, hornblende biotite gneiss, quartz mica schist, quartz mica kyanite schist, granite, and dolerite. Sedimentary formations cover less area and are found near the confluence point in the Arabian Sea (Figures 3 and 5). In the case of the



Figure 5. Comparative plot showing lithology along the stream path with stream length gradient index (SL) and longitudinal profiles of the streams: (a) Anjarakandy, (b) Thalassery, (c) Mahe, and (d) Kuttiyadi.

Anjarakandy River, hard crystalline rocks are observed down to a flow distance of 70 km, while the river is found to flow through sedimentary formations for less distance (<3 km). Similar conditions were noted in the other three rivers, which flow through most of their lengths over the hard crystalline rocks. The Thalassery River, in its 28 km length, flows only 3 km through sedimentary formations (floodplain deposits) in the lower segment. The Mahe River cuts across the hard rocks in its entire flow distance. In the Kuttiyadi watershed, the river flows <4 km through the floodplain deposit near the river's mouth. The remaining 70 km of the river flows through the hard rocks of various types described above.

A comparison of SL index plots, along with longitudinal profiles and lithology of the region, was carried out to assess the influence of lithological variation on the abrupt change in SL index and presence of knickpoints in longitudinal profiles. Though the watersheds possess different lithologies, sudden changes in the SL index and variations in the longitudinal profiles marked as zones of maximum variation (knickpoints) occur in a single, unique lithology. This finding rules out the role of lithological variation in the abrupt change in SL index and variation in the longitudinal profile, and points towards the plausible influence of tectonic activity, which can change the base level through uplift resulting in the present characteristics of the rivers.

Hypsometric curve and integral

Hypsometric curves and integrals were calculated for all the watersheds considered in the present study and found to be concave with variations in smoothness (undulation) and with low areas under the curves, i.e. hypsometric integral (Figure 6). Differences in

H. VIJITH ET AL. (-



Figure 6. Hypsometric curves showing different characteristics of watersheds.

the hypsometric curves can be attributed to the uplift caused by tectonic processes in the region, where relief corresponding to the area has been changed. HI values derived from an assessment of the areas under the hypsometric curves are .067 (Anjarakandy), .085 (Thalassery), .11 (Mahe), and .12 (Kuttiyadi), respectively, indicating more erosion and associated dissection of the drainage basins. It should be noted that the HI shows a gradual increase from the north to the south side of the study area, indirectly pointing toward a variation in the effect of tectonic processes.

Stream concavity index

The SCI of rivers in the study area shows high positive values, indicating a high degree of concavity and steady state equilibrium conditions of the rivers (Figure 7). Among the rivers analyzed, the Anjarakandy shows the highest degree of concavity (.88), followed by the Thalassery (.85), the Mahe (.81), and the Kuttiyadi (.70), with a mean concavity of .81. Comparatively higher rates of SCI point toward the erosive power of streams with more incision. Normalized stream profiles also reflect the variation in the channel base represented as an

14



Figure 7. Normalized longitudinal profile with diagonal cut-off used to calculate the stream concavity index (SCI) for (a) Anjarakandy, (b) Thalassery, (c) Mahe, and (d) Kuttiyadi rivers.

irregular convex-upward portion, confirming the presence of knickpoints, and can be attributed to base-level changes caused by tectonic processes in the region. The observed pattern of spatial variability in SCI shows close resemblance to the distribution of HI, with maximum SCI value in the river on the north side, (Anjarakandy) to the minimum value in the Kuttiyadi River on the south side of the study area. This confirms the inference of spatial variation in the influence of tectonic process over the geomorphic characteristics of the rivers analyzed.

The findings of the present study were supported by the geomorphic evolutional history of the region modeled by Soman (2002). Though a major portion of the Kerala region is a part of SIGT, during the period of the Recent-Pleistocene, the region has undergone major geomorphic changes in response to sea-level changes and uplift of the terrain. Geomorphic processes, such as uplift of drainage basins and river courses, formation of drowned valleys and lagoons, and regression and transgression, were also occurring during the period. The knickpoints present in the analyzed streams can be linked to processes of uplift and sea-level change. Control of rivers and stream networks by the strike-slip faults running parallel to the west coast of Kerala and NNW–SSE direction has been well documented by Chattopadhyay, Kumar, and Chattopadhyay (2006) and by Valdiya and Narayana (2007). They suggested variation in the effects of these structural features over the drainage networks in the region by identifying the changes in a channel pattern from its normal course to having more loops and rectangular bends. Studies conducted by Rajendran et al. (2009) about the repeated occurrence of seismic events in Kerala pointed toward the reactivation of long-running, NNW–SSE trending lineaments/fractures. Repeated seismic events are surface manifestations of ongoing neotectonism, and their effects are found to vary spatially. This also reinforces the concept of spatial heterogeneity in the effects of tectonic processes in the region with almost uniform lithology.

Conclusion

Heterogeneous morphotectonic expressions of four medium-range watersheds with uniform lithology in the high-grade crystalline terrain were studied in detail to assess the spatial variation of influential factors on drainage development. Though the dominant drainage pattern of the four rivers (Anjarakandy, Thalassery, Mahe, and Kuttiyadi) is dendritic, the presence of rectangular and trellis drainage patterns indicates influence of structural features over the development and orientation of stream networks in the area. The stream networks are mostly oriented in N–S, NE–SW, E–W, and NW–SE directions and coincide with the dominant structural trends of the region (NE–SW and NW–SE). However, minor variations in the directions of stream orientation and structural features differentiate the watersheds into two groups: Anjarakandy–Thalassery and Mahe–Kittiyadi, suggesting spatial heterogeneity of controlling factors.

Geomorphic indices, particularly the basin asymmetry, T index, longitudinal profile, SL index, and the SCI indicate significantly different influence of tectonic process over the drainage systems. Though the basin asymmetry factor indicates a common direction (SSE) of terrain tilt, the T index and vector show varying degrees of stream oscillation in the watershed, with respect to differential terrain tilt. The dominant directions of stream oscillation, indicated by the T vectors, are NNE, NNW, S, and SSE, which coincide with the orientations of strike-slip faults/lineaments in the study area and confirm the differential influence over the directional tilt of streams. The characteristic convex-concave pattern in the longitudinal profiles, marked as zones of maximum variation, indicates the presence of knickpoints, which might reflect tectonic disturbance and/or variations in lithology. At the same time, the SL index shows abrupt changes in near segments, pointing toward changes in the base level. The SL indices of Anjarakandy, Thalassery, and Mahe show changes in the whole length of the river, whereas that for Kuttiyadi is different, with specific, defined zones of anomalies. A comparison with the longitudinal profile, lithology, and SL index graph facilitates identification of co-occurrence of the zones of maximum variation and high SL index in uniform (single) lithology, indicating more control of the tectonic process than lithological changes over the development of anomalies in the streambed.

The low values (<.12) of hypsometric integrals represent an advanced stage of erosional characteristics of river basin evolution. However, the characteristic variation of hypsometric curves of each stream indicates a different response of each watershed and variations in the effects of tectonic process in the region. Though the streams possess high concavity-caused valley incision, as shown by the SCI, differences in values (.70–.88) reflect the response of

each stream to tectonic processes. HI shows an increase in the area to be eroded from river basin from north to south, whereas the SCI shows a decreasing trend in the concavity of the streams from the northern end (Anjarakandy watershed) to southern end (Kuttiyadi watershed), revealing spatial variation in the process and its effects over the stream networks. Though the study area is mostly covered by Precambrian crystalline rocks with uniform characteristics, streams in the region have responded differently to tectonic activities (uplift or terrain tilting), which is well documented by the analysis of geomorphic indices. Occurrence of seismic events and allied phenomena in the recent past in the region confirms neotectonic activity and spatial heterogeneity in the influence of tectonic process and its influence over the development of river and river basin characteristics of those rivers originating from the Western Ghats of India.

Acknowledgments

Authors are thankful to Prof. (Dr) Carol Harden, Prof. (Dr) Joann Mossa and the anonymous reviewers for their critical reviews, constructive comments, and suggestions, which greatly improved the manuscript.

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

H. Vijith D http://orcid.org/0000-0002-1064-2088

References

- Ahmad, S., Bhat, M. I., Madden, C., & Bali, B. S. (2014). Geomorphic analysis reveals active tectonic deformation on the eastern flank of the Pir Panjal Range, Kashmir Valley, India. *Arabian Journal of Geosciences*, *7*, 2225–2235.
- Antón, L., De Vicente, G., Muñoz-Martín, A., & Stokes, M. (2014). Using river long profiles and geomorphic indices to evaluate the geomorphological signature of continental scale drainage capture, Duero basin (NW Iberia). *Geomorphology*, 206, 250–261.
- Bhattacharya, S. N., & Dattatrayam, R. S. (2002). Earthquake sequence in Kerala during December 2000 and January. *Current Science*, *82*, 1275.
- Bureau of Indian Standards (BIS). (2002). Seismic zoning map of India. Author.
- Centre for Earth Science Studies (CESS). (2009). *Natural hazard zonation of map of Kerala*. Thiruvananthapuram: Centre for Earth Science Studies, Government of Kerala.
- Chattopadhyay, S., Kumar, S. S., & Chattopadhyay, M. (2006). Landscape evolution in parts of Varnanapuram drainage basin, Kerala: A hypsometric approach. *Geological Society of India*, 68, 841–856.
- Cox, R. T. (1994). Analysis of drainage basin symmetry as a rapid technique to identify areas of possible Quaternary tilt-block tectonics: An example from the Mississipi Embayment. *Geological Society of America Bulletin*, 106, 571–581.
- Cox, R. T., Roy, B., Van Arsdale, R. B., & James, B. H. (2001). Identification of possible Quaternary deformation in the northeastern Mississippi Embayment using quantitative geomorphic analysis of drainage-basin asymmetry. *Geological Society of America Bulletin*, 113, 615–624.
- Dar, R. A., Chandra, R., & Romshoo, S. A. (2013). Morphotectonic and lithostratigraphic analysis of intermontane Karewa basin of Kashmir Himalayas, India. *Journal of Mountain Science*, 10(1), 1–15.

18 🕢 H. VIJITH ET AL.

- Dehbozorgi, M., Pourkermani, M., Arian, M., Matkan, A. A., Motamedi, H., & Hosseiniasl, A. (2010). Quantitative analysis of relative tectonic activity in the Sarvestan area, central Zagros, Iran. *Geomorphology*, 121, 329–341.
- Demoulin, A. (1998). Testing the tectonic significance of some parameters of longitudinal river profiles: The case of the Ardenne (Belgium, NW Europe). *Geomorphology, 24*, 189–208.
- Drury, S. A., & Holt, R. W. (1980). The tectonic framework of South India, A reconnaissance involving Landsat imagery. *Tectonophysics*, 65, 1–15.
- Ehsani, J., & Arian, M. (2015). Quantitative analysis of relative tectonic activity in the Jarahi-Hendijan basin area, Zagros, Iran. *Geoscience Journal*, *19*, 751–765.
- Elias, Z. (2013). Quantitative geomorphology of analyzing tectonic activity in the Roczek and Shwork river valleys in the Zagros Mountains (Iraqi Kurdistan). *International Journal of Enhanced Research in Science Technology and Engineering*, *2*, 22–34.
- Garrote, J., Heydt, G. G., & Cox, R. T. (2008). Multi-stream order analyses in basin asymmetry: A tool to discriminate the influence of neotectonics in fluvial landscape development Madrid Basin, Central Spain. *Geomorphology*, *102*, 130–144.
- Geological Survey of India (GSI). (1995). *Geological and mineral map of Kerala*. Kolkata: Geological Survey of India, Government of India, Ministry of Mines.
- Hack, J. T. (1957). Studies of longitudinal stream profiles in Virginia and Maryland (No. 294-B).
- Hack, J. T. (1960). Interpretation of erosional topography in humid temperate regions. *American Journal of Science*, 258-A, 80–97.
- Hack, J. T. (1973). Stream-profile analysis and stream-gradient index. U.S. Geological Survey Journal of Research, 1, 421–429.
- Hare, P. W., & Gardner, T. W. (1985). Geomorphic indicators of vertical neotectonism along converging plate margins, Nicoya Peninsula, Costa Rica. In M. Morisawa & J. T. Hack (Eds.), *Tectonic geomorphology* (pp. 75–104). Proceedings of the 15th Annual Binghamton Geomorphology Symposium. Boston, MA: Allen and Unwin.
- Hurtrez, J. E., Lucazeau, F., Lavé, J., & Avouac, J. P. (1999). Investigation of the relationship between basin morphology, tectonic uplift and denudation from the study of an active fold belt in the Siwalik Hills (Central Nepal). *Journal of Geophysics Research*, 104, 779–796.
- Jain, V., Preston, N., Fryirs, K., & Brierley, G. (2006). Comparative assessment of three approaches for deriving stream power plots along longitudinal profile in the upper Hunter River catchment, New South Wales, Australia. *Geomorphology*, *74*, 297–317.
- Kale, V. S., Sengupta, S., Achyuthan, H., & Jaiswal, M. K. (2014). Tectonic controls upon Kaveri River drainage, cratonic Peninsular India: Inferences from longitudinal profiles, morphotectonic indices, hanging valleys and fluvial records. *Geomorphology*, 227, 153–165.
- Keller, E. A. (1986). Investigation of active tectonics: Use of surficial earth processes. In *Active tectonics*. Washington, DC: National Academy Press.
- Keller, E. A., & Pinter, N. (2002). *Active tectonics: Earthquakes, uplift, and landscape* (p. 362). Saddle River, NJ: Prentice Hall.
- Leopold, L. B., & Bull, W. B. (1979). Base level, aggradation, and grade. *Proceedings of the American Philosophical Society*, *123*, 168–202.
- Özkaymak, Ç. (2015). Tectonic analysis of the Honaz Fault (western Anatolia) using geomorphic indices and the regional implications. *Geodinamica Acta, 27*, 110–129.
- Prasannakumar, V., & Lloyd, G. E. (2007). Development of crystal lattice preferred orientation and seismic properties in Bhavani shear zone, Southern India. *Journal Geological Society of India*, 70, 282–296.
- Prasannakumar, V., & Lloyd, G. E. (2010). Application of SEM-EBSD to regional scale shear zone analysis: A case study of the Bhavani Shear Zone, South India. *Journal Geological Society of India*, 75, 183–201.
- Praveen, K. R., Prasannakumar, V., & Mamtani, M. A. (2009). Time relationship between regional deformation and fabric development in the Peralimala pluton, South India – Inferences from magnetic fabric. *Journal of the Geological Society of India*, 73, 803–812.
- Radhakrishna, B. P. (1989). Suspect tectono-stratigraphic terrane elements in the Indian subcontinent. *Journal Geological Society of India*, 34, 1–24.

- Radhakrishna, T., Maluski, H., Mitchell, J. G., & Joseph, M. (1999). ⁴⁰Ar/³⁹Ar and K/Ar geochronology of the dykes from the South Indian granulite terrain. *Tectonophysics*, *304*, 109–129.
- Raj, K. G., Paul, M. A., Hegde, V. S., & Nijagunappa, R. (2001). Lineaments and seismicity of Kerala A remote sensing based analysis. *Journal of the Indian Society of Remote Sensing*, 29, 203–211.
- Rajendran, C. P., John, B., Sreekumari, K., & Rajendran, K. (2009). Reassessing the earthquake hazard in Kerala based on the historical and current seismicity. *Journal Geological Society of India*, 73, 919–924.
- Rajendran, C. P., & Rajendran, K. (1996). Low-moderate seismicity in the vicinity of Palghat Gap, South India and its implications. *Current Science*, *70*, 305–308.
- Rhea, S. (1993). Geomorphic observations of rivers in the Oregon coast range from a regional reconnaissance prospective. *Geomorphology*, *6*, 35–150.
- Salvany, J. M. (2004). Tilting neotectonics of the Guadiamar drainage basin, SW Spain. *Earth Surface Processes and Landforms*, 29, 145–160.
- Satheeshkumar, R., & Prasannakumar, V. (2009). Fabric evolution in Salem-Attur shear zone, south India and its implications on the kinematics. *Gondwana Research*, *16*, 37–44.
- Schumm, S. A. (1956). Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey. *Geological Society of America Bulletin, 67*, 597–646.
- Schumm, S. A. (1977). The fluvial system. New York, NY: Wiley.
- Schumm, S. A. (1986). Alluvial river response to active tectonics. *Active Tectonics* (pp. 80–94). Washington, DC: National Academy Press.
- Singh, N. H., Mathai, J., Neelakandan, V. N., Shankar, D., & Singh, V. P. (2005). A database on occurrence patterns of unusual geological incidents in southwest Peninsular India and its implication on future seismic activity. *Acta Geodaetica et Geophysica Hungarica*, 40, 69–88.
- Singh, O., Sarangi, A., & Sharma, M. C. (2008). Hypsometric integral estimation methods and its relevance on erosion status of northwestern Lesser Himalayan Watersheds. *Water Resource Management*, 22, 1545–1560.
- Soman, K. (2002). Geology of Kerala. GSI Publications, 2(1).
- Štěpančíková, P., Stemberk, J., Vilímek, V., & Košťák, B. (2008). Neotectonic development of drainage networks in the East Sudeten Mountains and monitoring of recent fault displacements (Czech Republic). *Geomorphology*, *102*, 68–80.
- Strahler, A. N. (1952). Hypsometric (area-altitude) analysis of erosional topography. *Geological Society* of America Bulletin, 63, 1117–1141.
- Strahler, A. N. (1964). Quantitative geomorphology of drainage basin and channel networks. In V. T. Chow (Ed.), *Handbook of applied hydrology* (pp. 439–476). New York, NY: McGraw-Hill.
- Toudeshki, V. H., & Arian, M. (2011). Morphotectonic analysis in the Ghezel Ozan river basin, NW Iran. *Journal of Geography and Geology, 31*, 258–265.
- Trevisani, S., Cavalli, M., & Marchi, L. (2010). Reading the bed morphology of a mountain stream: A geomorphometric study on high-resolution topographic data. *Hydrology and Earth System Sciences*, 14, 393–405.
- Troiani, F., & Della Seta, M. (2008). The use of the stream length–gradient index in morphotectonic analysis of small catchments: A case study from Central Italy. *Geomorphology*, *102*, 159–168.
- Valdiya, K. S., & Narayana, A. C. (2007). River response to neotectonic activity: Example from Kerala, India. *Journal Geological Society of India, 70*, 427–443.
- Virdi, N. S., Philip, G., & Bhattacharya, S. (2006). Neotectonic activity in the Markanda and Bata river basins, Himachal Pradesh, NW Himalaya: A morphotectonic approach. *International Journal of Remote Sensing*, 27, 2093–2099.
- Viveen, W., van Balen, R. T., Schoorl, J. M., Veldkamp, A., Temme, A. J. A. M., & Vidal-Romani, J. R. (2012). Assessment of recent tectonic activity on the NW Iberian Atlantic Margin by means of geomorphic indices and field studies of the Lower Miño River terraces. *Tectonophysics*, 544, 13–30.
- Whipple, K. X., & Tucker, G. E. (1999). Dynamics of the stream-power river incision model: Implications for height limits of mountain ranges, landscape response timescales, and research needs. *Journal of Geophysical Research: Solid Earth*, 104, 17661–17674.
- Zaprowski, B. J., Pazzaglia, F. J., & Evenson, E. B. (2005). Climatic influences on profile concavity and river incision. *Journal of Geophysical Research: Earth Surface, 110*(F3).