Arab J Geosci (2016) 9: 393
DOI 10.1007/s12517-016-2401-2

ORIGINAL PAPER

Evaluation of geomorphic expressions of bedrock Channels in the Western Ghats of southern Kerala, India, through quantitative analysis

H. Vijith [1,2] · **V. Prasannakumar** [1] · **P. Pratheesh** [1] · **M.V. Ninu Krishnan** [3] · **M.A. Sharath Mohan** [1]

Received: 27 March 2015 / Accepted: 26 February 2016 / Published online: 29 April 2016

Abstract Geomorphic expressions embedded within the bedrock channels, originating from the southernmost part of the Western Ghats, India, are quantitatively characterized through well-defined geomorphic indices using digital elevation models (DEM) and geographical information system (GIS) tools. Drainage basin asymmetry (Af), transverse topographic symmetry factor (T), longitudinal profile, stream length gradient index (SL), hypsometric integral and curve (I_{hyp}), spatial parameters like drainage density (Dd) and dissection index (DI) are used for extraction of information related to the characteristic pattern and behaviour associated with the Karamana river and its two major tributaries. The independent and cumulative analysis of each geomorphic indices indicates adjustment of Karamana river in response to the tectonic activities. Karamana basin, while showing symmetric character as a single unit, exhibits segments of asymmetric nature associated with the terrain tilting and is evidenced from the variable directional oscillation from E, SSE, S, NW and W. Varying characteristics of the longitudinal profiles and abrupt change in the SL index suggest knick points and uplift of the terrain due to tectonic processes. The influence of tectonic process over the stream characteristics is confirmed by identifying higher levels of SL anomalies in unique lithology. The inferences correlate with the low drainage density and high dissection index zones in the region with varying influence of tectonic processes. Though, the Karamana river basin as a single unit shows old age characteristics in the hypsometric analysis and symmetric nature, the longitudinal profile-assisted SL and SL anomaly indices are found to be capable of revealing evidences of differential effects of tectonic activities over the stream characteristics. The deductions are in agreement with field observations on landforms and channel attributes.

Keywords Geomorphic indices · Asymmetry · Hypsometry · Dissection index · Tectonics · Karamana

Introduction

Rivers and river basins are highly sensitive to tectonic processes and readjust over a span of time, depending on the physical properties of basement rocks, climatic effects, fluvial processes and nature of tectonic activity in the region (Schumm et al. 1987; Burbank and Anderson 2001; Kirby and Whipple 2012; Malik 2014). Hence, drainage networks may contain and reflect vital information about the past and present tectonic regime (Keller and Pinter 2002; Štěpančíková et al. 2008), which can be extracted quantitatively by analysing the morphotectonic characteristics of the river basin using different geomorphic indices. The geomorphic indices are considered as valuable tools in the analysis of tectonic implication and behaviour of the drainage basins, because these indices reveal the role of geological processes and tectonic activities which modified the terrain to the present shape (Peters and van Balen 2007; Gloaguen 2008). Tectonic disturbances can cause uplift or subsidence, and the resultant relief

✉ H. Vijith
vijithh@gmail.com

[1] Inter University Centre for Geoinformation Science and Technology, University of Kerala, Kariavattom, Thiruvananthapuram, Kerala 695 581, India

[2] Department of Applied Geology, Faculty of Engineering and Science, Curtin University, Sarawak Campus, CDT 250, 98009 Miri, Sarawak, Malaysia

[3] State Emergency Operation Centre (SEOC), Kerala State Disaster Management Authority, Institute of Land and Disaster Management, P.T.P Nagar, Thiruvanathapuram, Kerala 695 038, India

variation guides the interpretation of various geomorphic indices, related to the river basins. However, the general denudational processes and lowering of the elevated surfaces make the interpretation of the evidences of the tectonic activity more complex. The differential erosion can also be due to abrupt changes in underlying lithology, development of weaker structural surfaces, changes in valley floor morphology and the gradients of rivers, either by uplift or subsidence, deflection of streams and creation of knick points (Schumm et al. 1987; Whipple and Tucker 1999; Snyder et al. 2000). The advancements in the field of spatial information technology enable the geomorphologists to carry out more qualitative and precise analysis of morphotectonics and modelling of surface processes, especially where the field-related measurements and assessment are difficult or impractical (Garrote et al. 2008; Kale and Shejwalkar 2008; Ferraris et al. 2012; Mahmood and Gloaguen 2012; Gao et al. 2013; Malik 2014).

Tectonic influence on the rivers and river basins of Kerala, the southernmost state in India, with its typical topographic characteristics, distinct geology and geomorphology, is yet to be estimated, though such studies have been reported from various parts of India (Singh et al. 2008; Singh and Awasthi 2010; Markose and Jayappa 2011; Jayappa et al. 2012; Ch. Kothyari and Rastogi 2013). Kerala, with 44 rivers of various dimensions, flowing through the multiply deformed crystalline terrain, makes it an excellent region to study the morphodynamics and terrain evolution in relation to the tectonics. The state has also witnessed geomorphic changes, during the Quaternary period, including basin upliftment, river capture, rejuvenation of rivers, migration, and knick point development as well as uplift of Western Ghats scarp with distinct regional tilt in drainages over the region (Soman 2000). Inspite of a variety of structural and geomorphological features, little attempt has been made to study the geomorphological expressions of the river basins in relation to the tectonic disturbance (John and Rajendran 2008; Ambili and Narayana 2014; Vijith et al. 2015). In the present study, an attempt is made to analyse the geomorphic expressions and morphological variations in a medium size river basin (Karamana River basin), which originates from the Western Ghats, south of Achankovil Shear Zone in Kerala, by quantitatively analysing the different geomorphic indices.

Regional geological setting

Kerala forms a part of the South Indian Granulite Terrain (SGT) composed of high grade metamorphic rocks of amphibolite-granulite facies and divided into different blocks by major transcrustal shear zones (Drury and Holt 1980; Drury et al. 1984; Ramakrishnan 1993). The SGT is dissected by major shear zones such as the Achankovil Shear Zone and the Palghat-Cauvery Shear System consisting of Moyar-Bhavani- and Palaghat Cauvery-Attur shear zones (Satheeshkumar and Prasannakumar 2009). The region has undergone repeated deformation involving deep-seated faults/lineaments and shear zones (Nair et al. 1981; Sinha Roy et al. 1984; Drury et al. 1984; Satheeshkumar and Prasannakumar 2009), which controlled the major geomorphic process and stream patterns in the region (Fig. 1). The area selected for the present study is located to the south of the Achankovil Shear Zone and forms a part of the Kerala Khondalite Belt (KKB) and composed mostly of khondalites, quartzites, graphite bearing garnetiferous charnockites, garnet-biotite gneiss and leptynites (Kumar and Chacko 1988). Variation in the geological and structural characteristics of the region has made a spectacular and distinct geomorphology, ranging from high elevated denudational structural hills to low lying coastal plains within short distance. An escarpment parallel to the coastline and marked with numerous waterfalls and rapids along with various regional and local planation surfaces with steeply sloping scarps strongly indicate the role of tectonic processes in shaping the geomorphic features in the region.

Study area

Quantitative assessment of tectonically controlled geomorphic expression in and around the Karamana River basin was carried out using spatial information technology-assisted evaluation of geomorphic indices to evaluate the tectonic influence over the river basin and channel networks. The Karamana river basin is located in between N latitudes 8° 31′ 49” to 8° 40′ 55″ and E longitudes 76° 49′ 46″ to 77° 14′ 35″, covering a total area of 702 km^2, with high variation in terrain characteristics. Karamana river originates from the dual peaks, Chemmunji Motta and Aathiramala (>1800 m asl), in Agasthiarkoodam in the Western Ghats and flows 68 km before debouching into the Arabian sea and is dammed in two places, namely Peppara and Aruvikkara, for drinking water supply to the Thiruvanathapuram city. The basin is underlain by Precambrian crystalline rocks comprising predominantly of garnet-biotite gneiss, charnockite, pyroxene granulite, garnet-biotite–sillimanite gneiss, gneissic charnockite, younger intrusives and recent alluvium (floodplain deposits and sandstone-clays lignite admixture), of which garnet-biotite–sillimanite gneiss occupies a major part (Fig. 1). All these rocks, except the intrusives and recent alluvium, have suffered polyphase deformation and metamorphism (Drury et al. 1984; Battacharya and Kar 1998). Geomorphologically, the area forms denudational (structural) hills, residual hills and mounds, linear ridges, valley fills, vast stretch of floodplains and coastal land forms like lagoons, beaches and swale complexes. The area, mostly covered with lateritic soil and forest

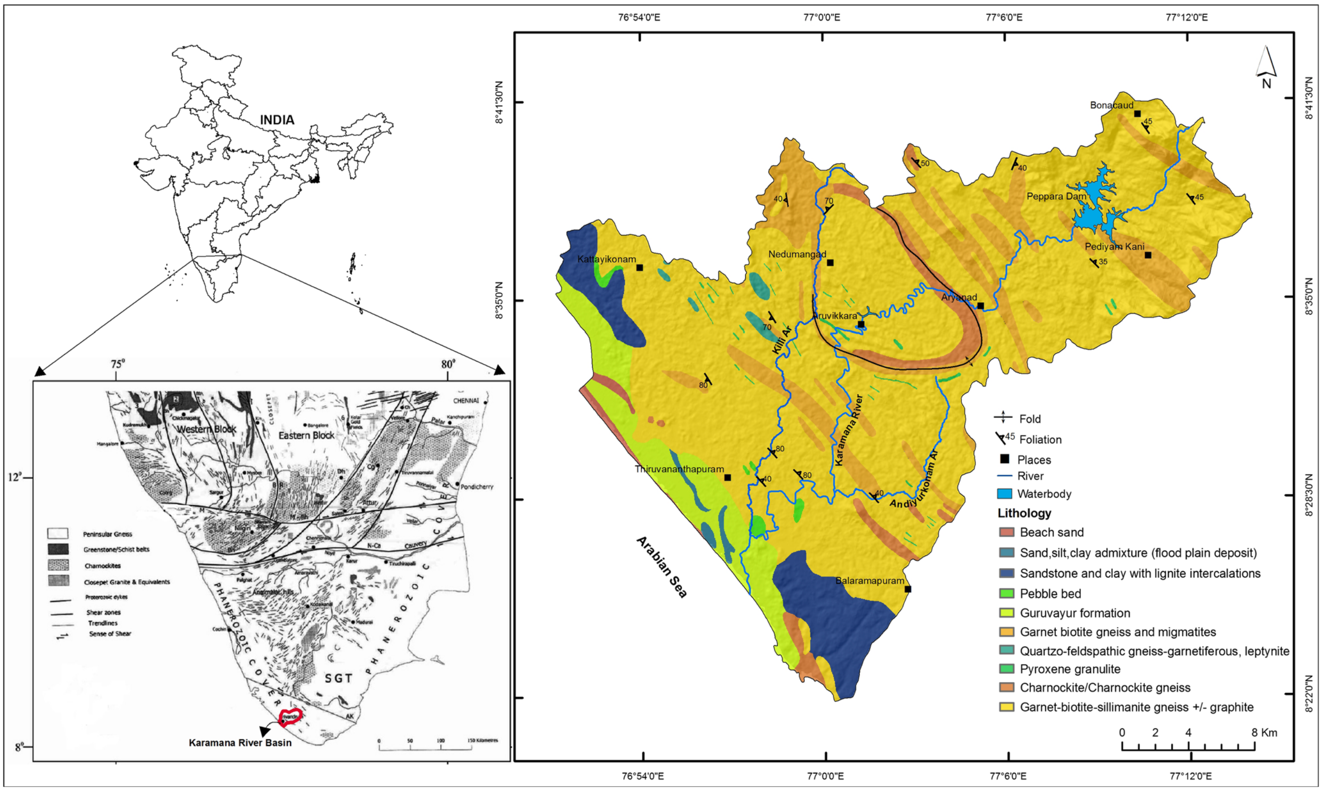


Fig. 1 Study area location map with regional geological settings. **a** Regional geology of SGT (modified after Drury and Holt 1980) and **b** geological map of Karamana river basin (after GSI 1995)

loam in the upper catchment regions, experiences a tropical humid climate and receives an annual average rainfall of 2600 mm from both South-West (June–September) and North-East (October–December) monsoons. The sub-aerial relief of the river basin ranges from 5 to 1800 m. The moderate elevation hill peaks are used for farming and is vegetated with rubber, coconut trees, tapioca, pepper and plantain, whereas the higher range hills are covered with forest of varying density (dense mixed forest to open forest). Valley fills and floodplains have paddy and plantain cultivation, though rubber and mixed crops occupy a major portion of the area.

Materials and methodology

Quantitative geomorphic indices are used to assess the tectonic control over the development of Karamana river basin. The geomorphic indices, capable of differentiating features generated due to normal fluvial process and local changes caused by the tectonic disturbances, are calculated based on the analysis of the drainage network and relief anomalies in the area. The indices used to assess the geomorphic expressions associated with the selected rivers are drainage basin asymmetry (Af), transverse topographic symmetry factor (T), longitudinal profile, stream length gradient index (SL), hypsometric integral and curve (I_{hyp}), spatial parameters like drainage density (Dd) and dissection index (DI). For the assessment of selected geomorphic indices, the main river (Karamana) and two major tributaries, namely, Killi and Andiyurkonam Ar, are selected. The concept behind the analysis of relief parameters for the assessment of impacts of tectonic activity is that the relief holds clues to the pattern of differential motion of rock in relation to the varying degree of erosion rates and landform formation caused due to tectonic processes in the region. Datasets used in the analysis are Survey of India toposheets (1:50,000), geological map (Geological Survey of India with the scale of 1:50,000) and space born digital elevation model with a resolution of 30 × 30 m derived from Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) images (freely available from the website of GDEM- ASTER GDEM V2, which offers a horizontal and vertical accuracy of 8.68 and 17.01 m). All the datasets are processed and the geomorphic indices are derived using ArcGIS ArcInfo version 9.3 and its spatial analyst extension.

Data analysis and derivation of geomorphic indices

Drainage basin asymmetry (Af)

The asymmetry of drainage basin in relation to the midline (long axis) is a tool for the identification of response of the drainage basin to the recent tectonic activity (Hare and Gardner 1985; Cox 1994; Keller and Pinter 2002; Salvany 2004; Virdi et al. 2006; Garrote et al. 2008). The Af, expressed as the percentage of the area in the basin that is found on the right bank side (towards down flow direction) of the main stream to the whole area of the basin (Hare and Gardner 1985; Keller and Pinter 2002) and calculated using the Eq. (1)

$$\mathrm{Af} = (\mathrm{Ar}/\mathrm{At})^{*}100 \tag{1}$$

where Ar is the area of the basin to the right side of the major river and At is the total area of the drainage basin. The asymmetry factor is highly sensitive to tectonic activity. An asymmetry factor of 50 % indicates stable settings of a drainage network formation and basin which has not experienced any tectonic activity. However, Af index greater or less than 50 % indicates the possibility of tilting in the left and the right side of the basin, respectively. For the study area, the Af factor is calculated separately for the whole river basin and the two subwatersheds.

Transverse topographic symmetry factor (T)

Transverse topographic symmetry factor (T) indicates the possible tilt direction of the drainage basin, lateral tilting and the level of asymmetry or symmetry of a river within the drainage basin, stream migration in connection with the active meander belt and the basin midline (Cox 1994; Cuong and Zuchiewicz 2001; Keller and Pinter 2002; Salvany 2004; Virdi et al. 2006). This index can be used to provide significant asymmetry information in larger drainage systems and regions of rapid uplift. The *T* is the ratio of the distance between the midline of the drainage basin and the active meander belt midline (Da) to the distance between the midline and the basin divide (Dd) and can be assessed using the Eq. (2) as proposed by Cox (1994);

$$T = \mathrm{Da}/\mathrm{Dd} \tag{2}$$

Generally, *T* ranges from 0 to 1 and the values close to 0 indicate a symmetric basin, while values close to 1 an asymmetric basin. In the present study, the *T* index was calculated for the Karamana river, Killi Ar and Andiyurkonm Ar by applying a different length criteria for the total length of the stream.

Longitudinal profile

Streams, from the origin to the mouth, have to adjust with various landscape evolution induced due to climate change, lithological variations and tectonic upliftment. Longitudinal profile of the stream is the transient expression of fluvial processes, reflecting geological influences such as the available relief or tectonic history and base level change, on the processes of erosion and deposition and of the distribution of outcrops of different lithology (Hack 1960; Rhea 1993; Stepancikova et al. 2008; Ambili and Narayana 2014). The shape of the longitudinal profile is used to analyse and differentiate the influence of fluvial cycle and tectonics over the development of stream morphology and the shape will vary from concave, convex and combination (concave-convex). Generally, convex profiles represent tectonic uplift of the area while the concave profiles indicate graded river bed characteristics dominated by fluvial process. The variable shape indicates the effect of lithological variations or tectonic uplift present in the area which can be marked as knick points, representing the major changes in the stream-bed characteristics (Snyder et al. 2000; Singh and Awasthi 2010; Giaconia et al. 2012; Ch. Kothyari and Rastogi 2013). The longitudinal profile of the selected streams was generated by extracting the elevation at defined interval (500 m each) from the digital elevation data along the stream channel and is plotted on an XY graph.

Stream length gradient index (SL) and SL anomaly index

The variation in the stream channel characteristics from steady state equilibrium to inequilibrium can be identified by the abrupt changes in stream profiles, presence of knick points and changes in stream pattern and slope. The major reason for the development of inequilibrium state of the stream is the uplift of the terrain. The effects can be evaluated by calculating the stream length gradient index (SL index), which is an excellent indicator of river pattern and characteristic changes in relation to tectonic disturbance (Hack 1973; Keller 1986; Zovoili et al. 2004). The SL is used to infer stream power and rock erodibility owing to its sensitivity to the inequilibrium state of channels due to tectonic and climatic perturbation in the channel slope (Štěpančíková et al. 2008; Troiani and Della Seta 2008). The SL index can be calculated using the Eq. (3):

$$\mathrm{SL} = (\Delta H/\Delta)L \times L, \tag{3}$$

where ΔH is the change in elevation of the reach, ΔL is the change in length of the reach and L is the total length of the channel to the point where the SL index is being calculated upstream to the highest point of the channel.

In order to identify anomalies in the stream channel and differentiate the stream channel morphology discontinuities, SL anomaly indices were generated by dividing SL index of each stream segment by the total SL index ($\mathrm{SL}_{\mathrm{total}}$) of the stream. The SL anomaly index classifies the stream segments into different orders of anomaly based on the values such as no anomaly (SL anomaly <2), second-order anomaly (2 > SL anomaly <10) and first-order anomaly (SL anomaly >10) (Seeber and Gornitz 1983; de Araújo Monteiro et al. 2010).

The results of the analysis facilitated the identification of knick points and associated stream characteristics in the highly disturbed sections. In the present study, SL index and SL anomaly index were calculated for the three rivers by considering 500 m segments in the river as a single unit of analysis.

Hypsometric curve and integral (I_{hyp})

Hypsometric curves are non-dimensional area-elevation curves, which allow a ready comparison and differentiation between tectonically active and inactive area in a basin based on the shape and integral values (Strahler 1952; Willgoose and Hancock 1998; Singh et al. 2008; Gao et al. 2013). The hypsometric curve obtained by plotting the proportion of the total height (h/H) against the proportion of the total area (a/A) of the basin, where H is the total relative height, A is the total area of the basin and ‘a’ is the area of the basin above a given line of elevation h and the hypsometric integral (I_{hyp}) by assessing the area under the hypsometric curve (Strahler 1952; Keller and Pinter 2002). The shape of the hypsometric curve is used to characterize the terrain as youth (convex), mature (S-shaped) and old (concave) and is influenced by climate, tectonics and lithology, whereas the I_{hyp} indicates the percentage volume of the original basin that remains unaltered (Strahler 1952; Awasthi et al. 2002; Kale and Shejwalkar 2008). The hypsometric curves and integrals, generated for the whole river basin and its selected major subwatersheds, show variable characteristics, while comparing with standard curves.

Drainage density and dissection index (Dd and DI)

Stream network is the major denudational agent which shapes the watershed landforms by the combined action of erosion and transportation (Rajakumar et al. 2007). At the same time, streams respond effectively to tectonic disturbances taking place in the watersheds (Selvan et al. 2011; Malik 2014). The spatial distribution of drainage density indicates the landscape dissection and runoff potential of the area in relation to fluvial geomorphic process and tectonic activity in the area. Characteristic patterns of both depend on the bedrock properties like strength, fracture density, infiltration and mass wasting tendencies. At the same time, the dissection index (DI) helps in estimating the nature and magnitude of dissection in relation to the vertical exaggeration of terrain which might be caused due to the tectonic activity in the region (Schumm 1956; Malik 2014). Dissection index is defined as a ratio between actual dissection made by the rivers and potential dissection up to base levels and calculated by the ratio between relative relief and absolute relief of an area to express the sharpness of the terrain. DI is dimensionless and expressed as a ratio or percentage. The value of the DI varying from 0.0 to 1 can be used to discriminate the stages of the erosional cycles and associated terrain development which helps to classify the region as young, mature or old stage (Selvan et al. 2011). The drainage density is assessed for the whole study area by calculating the total length of drainages in unit area (square km) and the dissection index by processing elevation information from the ASTER DEM using the spatial analyst extension and raster calculator functions of the ArcGIS software.

Results and discussion

River basins are ideal units of the landscape to understand the varying influence of tectonic activities over the landform development because drainage networks reflect changes in the surface slope and have the potential to record the evolution of tectonic structures related to uplift. The geomorphic indices were analysed and discussed in detail to understand the characteristics associated with the Karamana river and its tributaries.

Basin asymmetry factor (Af) identifies tectonic tilting of a drainage basin and characterizes its asymmetry or symmetry, as it is sensitive to rotations normal to the axis of the mainstream and can be applied irrespective of the size of the study area (Adams 1980). The deviation of Af values from 50 % suggests terrain tilting, either to the left or right of the major river segment. Karamana river basin as a single unit shows an Af value of 51 % indicating symmetrical nature. However, while considering the subwatersheds, the Andiyurkonam subwatershed has the Af of 32 % with north-north-westerly tilt and the Killi Ar shows an easterly tilt with a higher Af value of 61 % (Fig. 2). Though the Karamana basin as a whole shows symmetric basin character, the variability in the Af values within the area indicates differential response of terrain to various geological processes operated in the region.

The variation in the effect of tectonic processes can also be deducted from the overall elongated shape of the Killi Ar subwatershed. Effect of the terrain tilting over the stream networks can be reinforced by the assessment of transverse topographic symmetric factor (T), which indicates the asymmetry and symmetry of the stream segments and its direction of oscillation with respect to the basin midline. T index was calculated for all the three rivers under consideration by a criteria based on the length of the segments. In the major river, a total of 30 points of interest were selected, each at 2-km separation whereas 17 and 8 points were selected from the Killi and the Andiyurkonam Ar, respectively, at a common distance of separation of 1.5 km (Table 1). The calculated T index of the Karamana river varies from 0 to 0.47 implying ground tilting and indicating a lateral shift of the stream and change of the basin from symmetrical to asymmetrical nature. Similar nature of variable ground tilting and associated stream oscillation were found in Killi Ar with the values ranging from

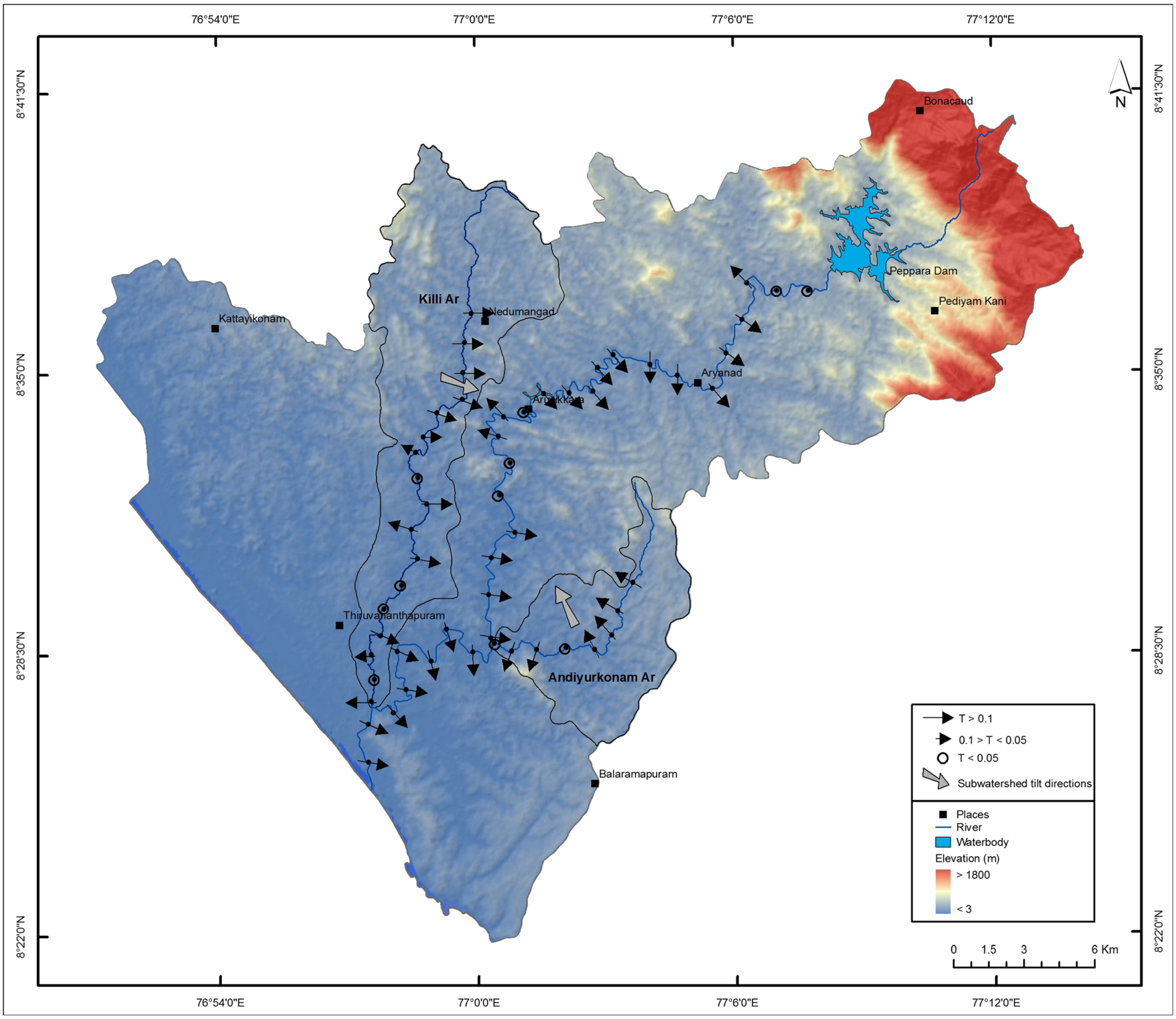


Fig. 2 Basin asymmetry (Af) and transverse topographic symmetric factor (T) vector showing stream migration direction and tilt directions

0 to 0.69 and the Andiyurkonam with 0.02 to 0.85. In order to identify the direction of terrain tilt and deviation of stream channel from the midline of the basin, the T vector, which indicates both the direction and magnitude (severity) of the stream channel variability, was plotted against each points of T index. The length of the vector (arrow) is equivalent to the T-index, and its direction is perpendicular to the segment of the stream. The direction of the arrow indicates movement of the river segment, with respect to the basin midline (Fig. 2). The resultant map shows that the rivers are more asymmetrical in nature with respect to the basin midlines and indicates varying tilt directions and magnitudes. The major river Karamana shows both symmetric and asymmetric stream stretches with predominant directions of inclinations as east and south-southeast, and the T vectors in the Killi Ar subwatershed show easterly and westerly directional tilt with slight variations from true angle. At the same time, the Andiyurkonam Ar shows north-westerly and southerly tilt, which is entirely different from those of Karamana and Killi Ar. It is also noted that between the segments of asymmetry few segments show symmetric nature and maximum variation is observed in the middle reach of the river basin. This variation can be attributed to the presence of a major antiform in the middle reach of the river basin with NW-SE axial trend. The Af as well as T index with its directional vectors and variable nature points towards the influence of regional tectonic activity over the stream characteristics.

Analysis of river longitudinal profile is regarded as one of the best tools to study the landscape evolution in relation to climatic, geologic and tectonic factors. The longitudinal profiles generated for the Karamana river and other two tributaries show high variation in shape and pattern (Fig. 3). The

Table 1 Topographic transverse symmetric (T) factor calculated for the selected segments with major tilt directions

Lower reach of the river ↑	Karamana River			Killi Ar			Andiyurkonam Ar		
	Segment ID	T	Major direction of tilt	Segment ID	T	Major direction of tilt	Segment ID	T	Major direction of tilt
	1	0.24	E	1	0.47	W	1	0	
	2	0.20		2	0.00		2	0.40	SSW
	3	0.27		3	0.08		3	0.22	
	4	0.30		4	0.25	ESE	4	0.02	
	5	0.26		5	0.05		5	0.09	NNW
	6	0.38	SE	6	0		6	0.26	
	7	0.38		7	0.18		7	0.22	
	8	0.47		8	0.11		8	0.85	
	9	0.47		9	0.27	E			
	10	0.39	E	10	0.04				
	11	0.24		11	0.08				
	12	0.16		12	0.06				
	13	0		13	0.27	ESE			
	14	0.04		14	0.69				
	15	0.15	WWN	15	0.41	E			
	16	0.17		16	0.37				
	17	0.05	SE	17	0.16				
	18	0.06							
	19	0.22							
↓	20	0.34							
Upper reach of the river	21	0.29							
	22	0.25							
	23	0.34	S						
	24	0.39							
	25	0.39	SE						
	26	0.18							
	27	0.06							
	28	0.12	NW						
	29	0.02							
	30	0.01							

Karamana river shows almost smooth, graded profile with slight undulations in between the middle reach of the river indicating the changes in base level equilibrium condition. At the same time, profiles of Killi and Andiyurkonam Ar show undulating nature with concave and convex characteristics. This undulating nature of the profiles may result from the differential uplift of the terrain in response to tectonic disturbances or lithological variations. A field-based assessment was carried out to verify and understand the undulating, anomalous characteristics of the profile segments. During the field verification, anomalous features like smooth, flat bed with pebbles and cobbles, vast stretch of floodplain associated with unpaired terraces and exposed bed rock with pot-holes were observed in the middle and lower reaches of the river, which correlates with the profile segments showing undulating nature. From this cross relation, it is inferred that the river has undergone different stages of changes in relation to differential uplifts caused due to tectonic process and the variations present in the profiles can be considered as knick points.

Tectonically induced terrain morphology, which exerts a control over the channel profile, can be quantified by deriving stream length gradient index (SL). The SL index can be used to recognize the influence of tectonic activity by identifying irregular high index values over particular rock type and the value of the SL index will increase as the rivers flow over active uplifted areas (Keller and Pinter 2002; Troiani and Della Seta 2008). SL index was computed for the whole length of all the three rivers at unique distance of 500 m. The SL index calculated for the Karamana river varies from 14 to 973 m and that of Killi and Andiyurkonam Ar varies between 1 to 506 m and 1 to 129 m, respectively, (Fig. 4). The sudden increase in SL value in the adjacent segments indicates

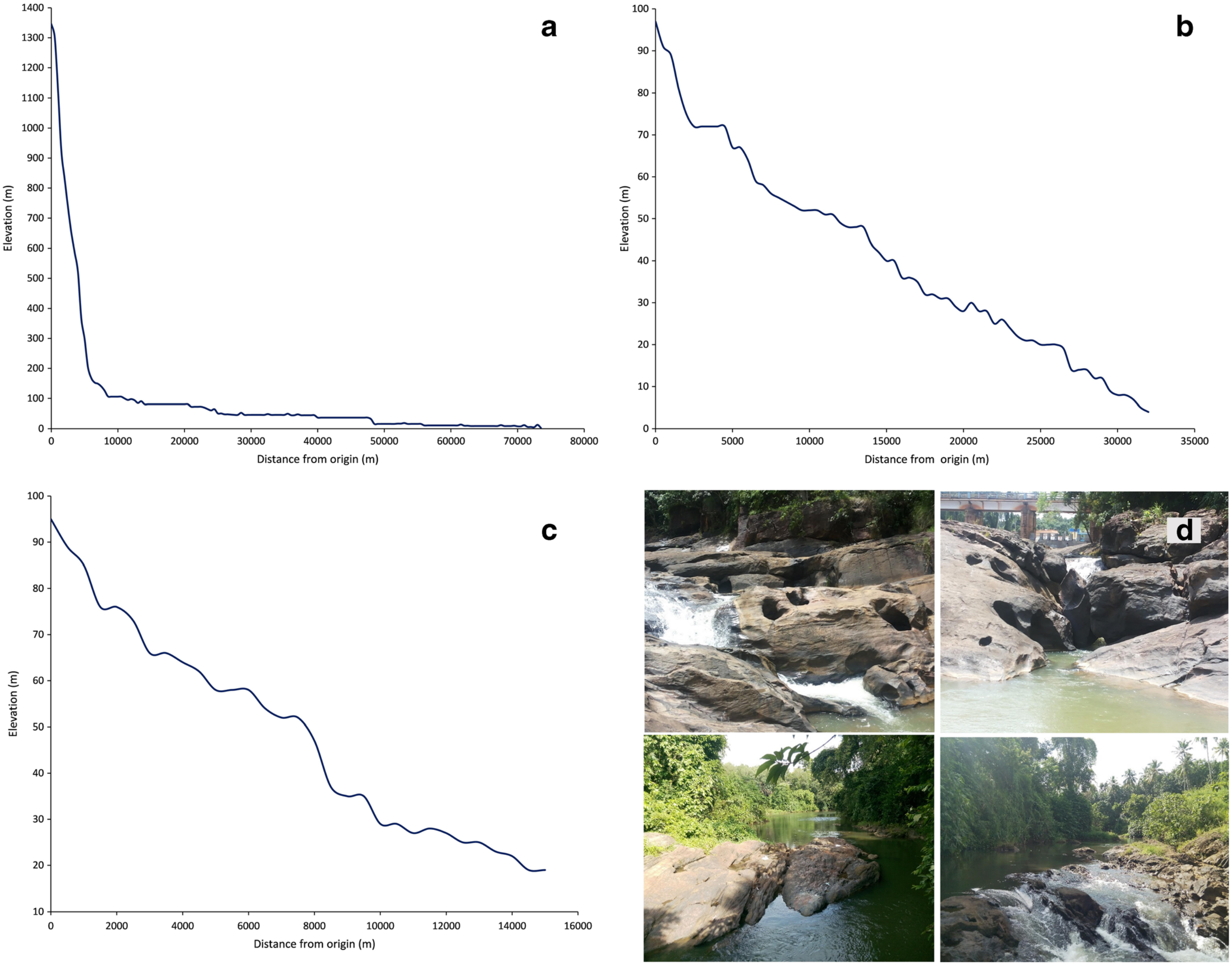


Fig. 3 Longitudinal profiles. **a** Karamana, **b** Killi Ar, **c** Andiyukonam Ar and **d** field photographs showing knick points in the stream bed

anomalies associated with the stream beds. Identification of the anomalies associated with the SL index has been facilitated by deriving the SL anomaly index, which is capable to differentiate different levels of anomalies associated with the stream channel like no anomaly, second-order and first-order anomaly. No anomaly refers to the smooth, graded profiled stream channel, second-order anomaly refers to steep channel characteristics and the first-order anomaly indicates very steep channel. The first- and second-order anomalies also imply the presence of knick points and associated stream characteristics in the highly disturbed sections (de Araújo Monteiro et al. 2010). SL anomaly index, calculated for all the three rivers, is shown in Fig. 5 with various levels of anomalies marked. In Karamana river, the calculated SL anomaly ranges from <1 to >7 indicating river sections with no anomaly and while the second-order anomaly is found to be present in upper, middle and lower reaches. SL anomaly index of the Killi Ar varies from less than 1 to greater than 56 with second-order anomaly in majority of the stream sections followed by the first-order anomaly from the midland reach of the stream. At the same time, the Andiyurkonam river shows maximum SL anomaly index >16 with varying distribution of higher order of anomaly (second and first order), in the stream segments analysed. The anomalous segments are of short length and indicate abrupt changes in the bed characteristics caused either due to uplift or lithological variation. In order to differentiate the role of tectonic uplift and lithological variation over the development of stream anomaly, the second- and first-order anomaly segments were cross compared with the lithological map of the basin (Fig. 6). The cross comparison shows the occurrence of higher anomaly stretches of the rivers in uniform (unique and single) lithology, which ruled out the contribution of lithological variation over SL anomaly and point towards the differential influence of tectonic activities in the region.

Fig. 4 Stream length gradient index (SL) with the longitudinal profiles of the streams studied **a** Karamana, **b** Killi Ar and **c** Andiyukonam Ar

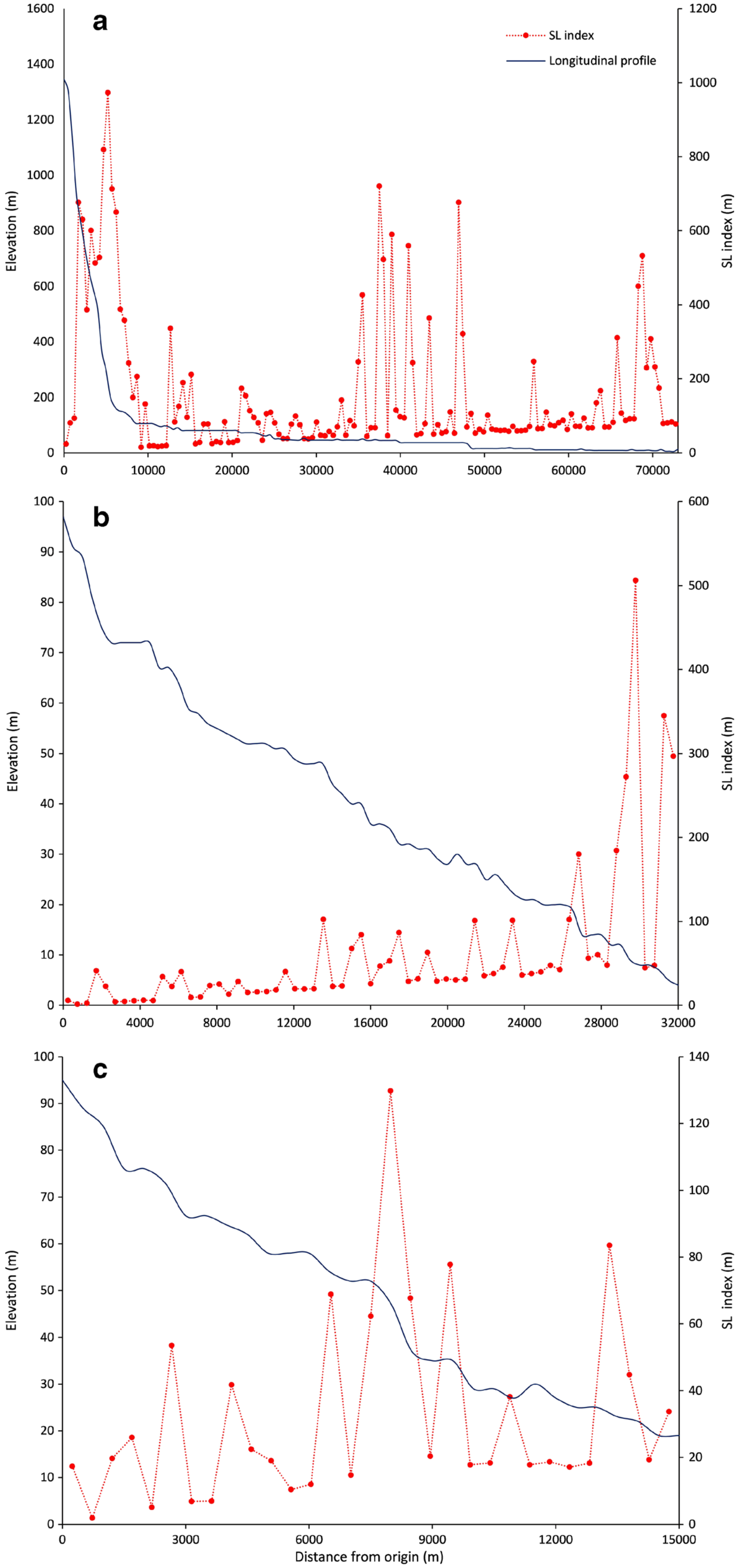
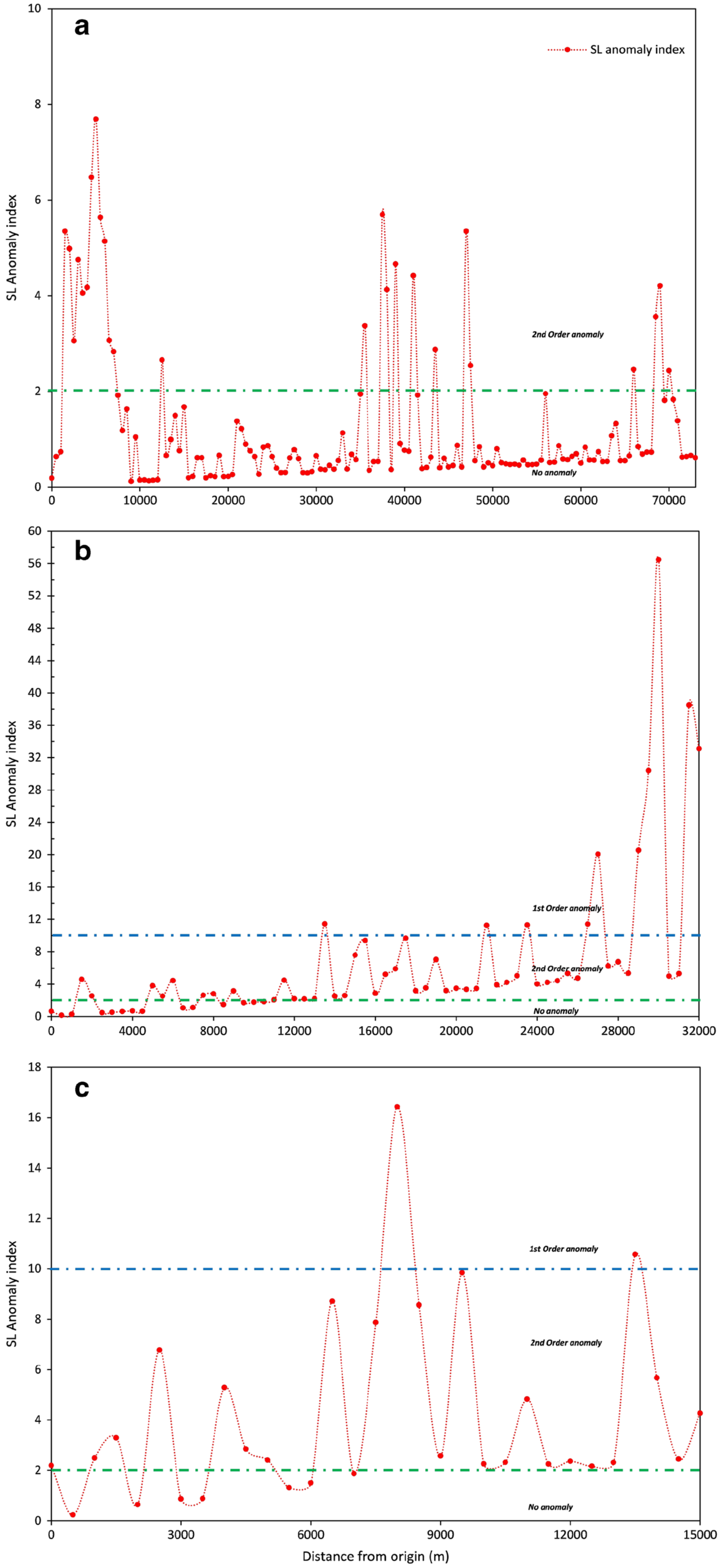


Fig. 5 SL anomaly index showing different zones of anomaly **a** Karamana, **b** Killi Ar and **c** Andiyukonam Ar



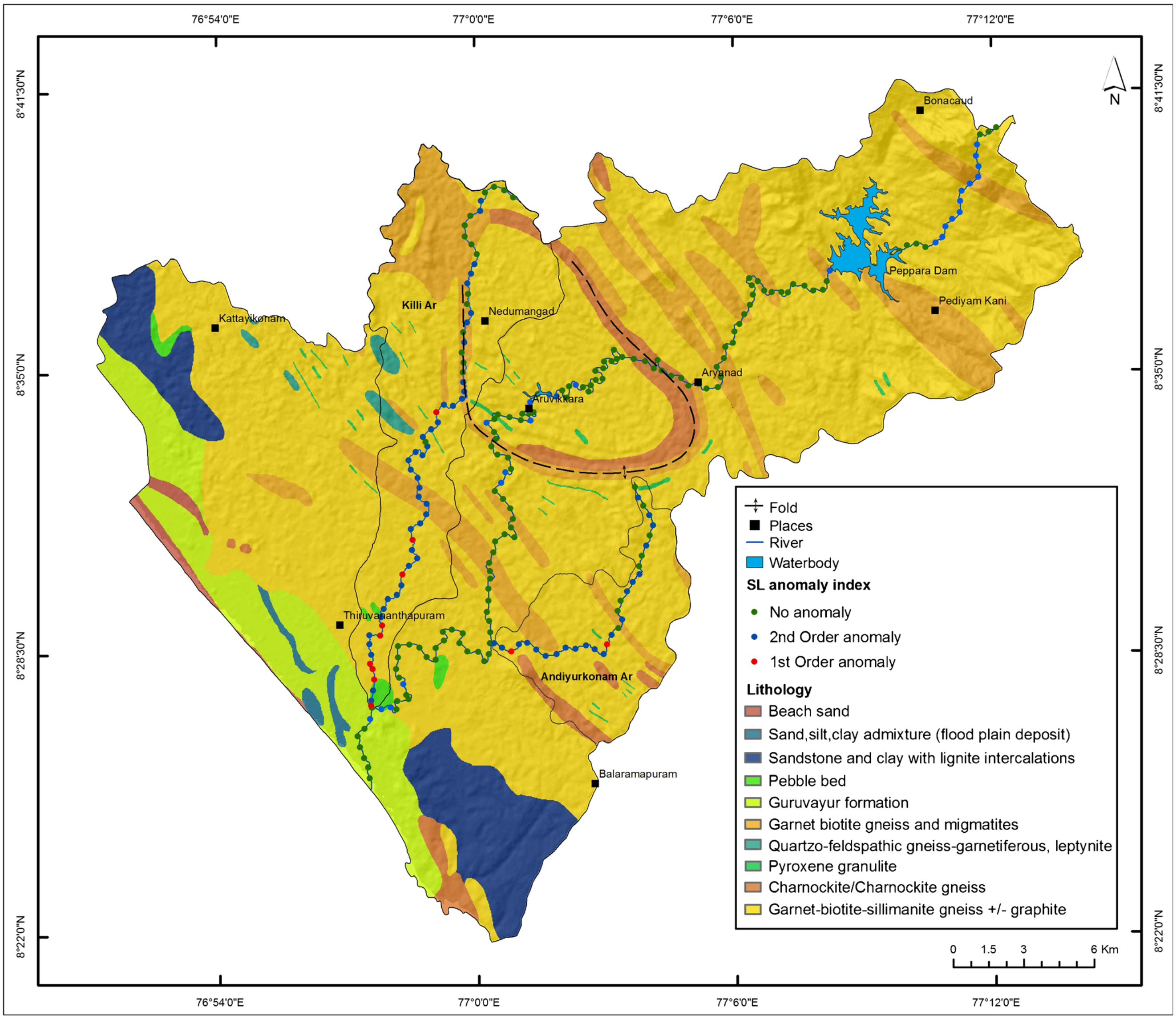


Fig. 6 Overlay of SL anomalies associated with streams against lithology of the river basin analysed

The geomorphic evolutional stage and erosional status of a drainage basin can be identified by analysing the hypsometric curve and calculating the hypsometric integral. Hypsometric curves and integrals generated for the whole Karamana river basin and two subwatersheds show very distinct shape of curves with variable hypsometric integrals, indicating differential effect of geological process in the region (Fig. 7). The whole basin as a single unit shows a smooth concave curve with an integral of 0.07 indicating almost old stage of the basin where very little amount (7 %) of the overburden remains to erode. At the same time, the Killi Ar subwatershed shows variable concavity in the hypsometric curve with integral of 0.24 (24 %). Though the hypsometric integral value of the Killi Ar subwatershed comes under the class of old age stage of basin evolution, the hypsometric curve characteristic indicates the transition between the mature to old age stage of the basin. Similarly, the Andiyurkonam subwatershed shows mature to old age transitional terrain characteristics with hypsometric integral 0.34 (34 %). The variation in the erosional characteristics reflected through the hypsometric curve and integral can be attributed to the influence of different scale of tectonic enhancement over the fluvial process, which makes the terrain eroded very fast in certain areas and wise versa and transformed the drainage basin into evenly dissected.

Drainage density is the numerical measure of landscape dissection and runoff potential of a basin or subwatershed, having direct bearing on the attributes of the river basin, and

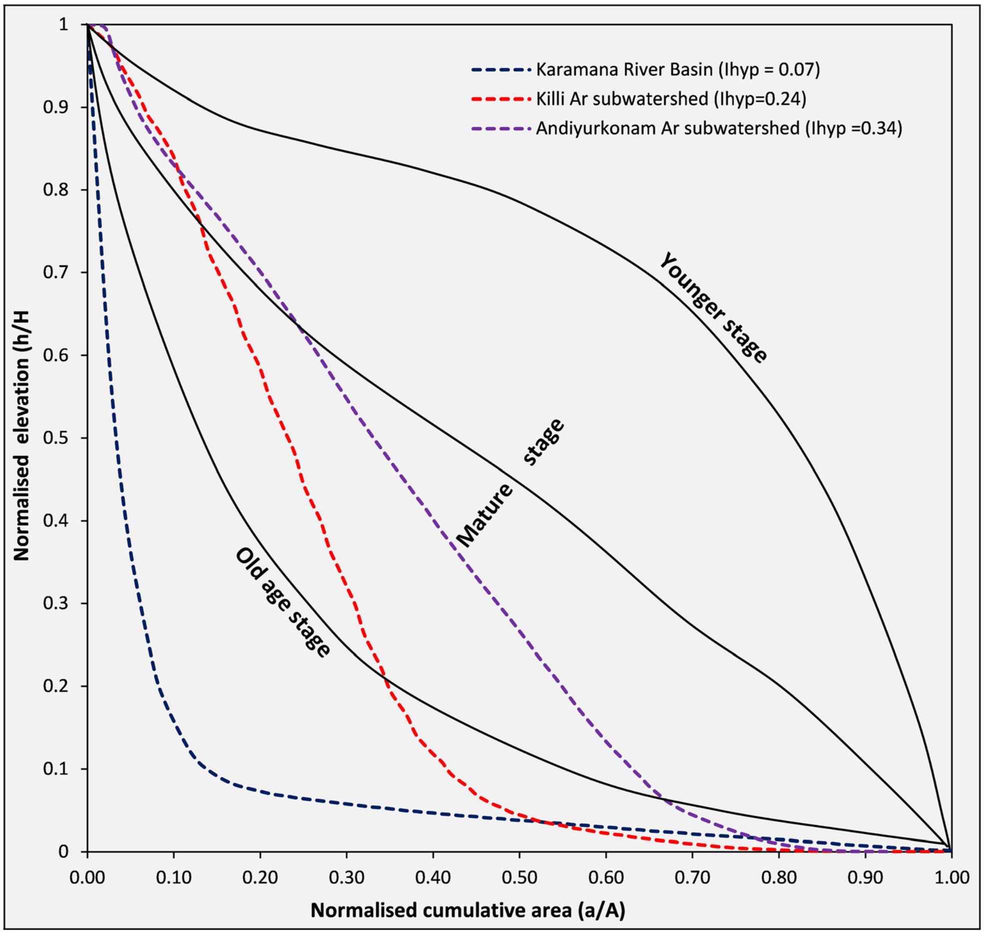


Fig. 7 Hypsometric curves showing varying characteristics of Karamana river basin and its major subwatersheds

the processes operating along the stream course which are lithology, soil structure and properties, vegetation cover, relief, climate and landscape evolution processes. The drainage density map prepared for the study area shows a maximum density of 8724 m/km^2 with wide variation in the spatial pattern (Fig. 8a). The higher density zones are concentrated on the left bank of the major river and the low to moderate zones are scattered on the right bank. The high drainage density

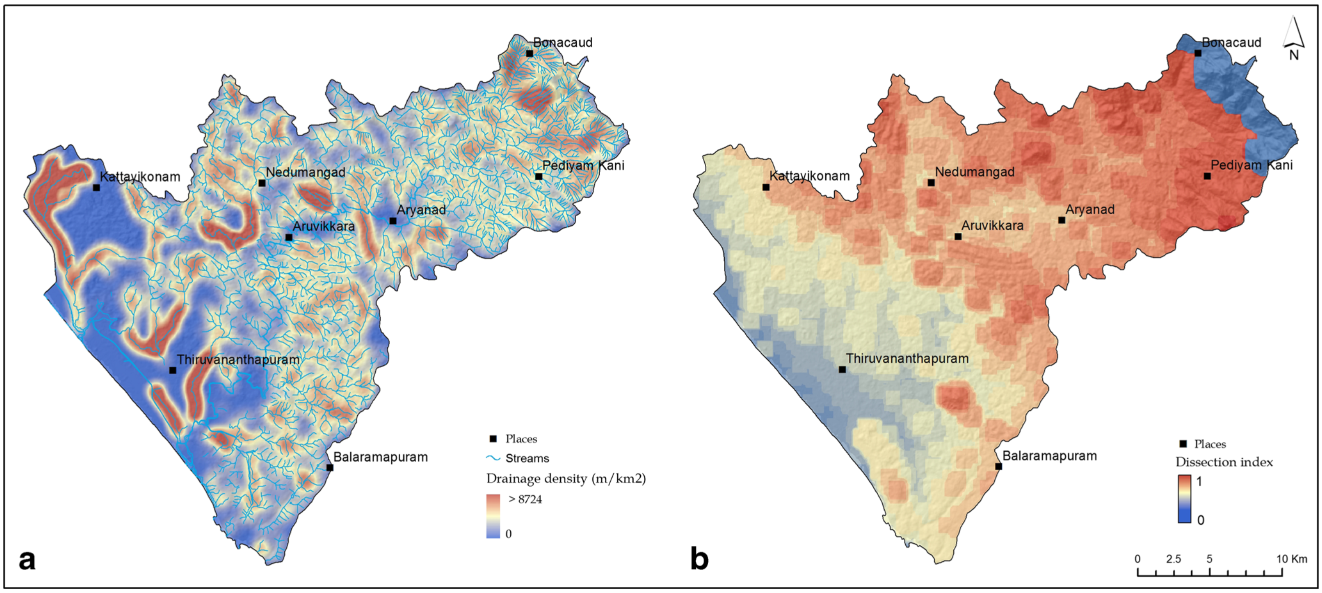


Fig. 8 Map showing spatial pattern of **a** drainage density and **b** dissection index

reflects highly dissected areas with a relatively rapid hydrological response to rainfall events, while low drainage density means a poorly drained basin with a slow hydrologic response. More specifically, the lower value zones were identified near Aruvikkara as well as Aryanad and are the results of the uplift occurred in the region. This inference is reconfirmed through the analysis of dissection index (DI), which portrays the degree of dissection or vertical erosion and stages of geomorphic evolution of the basin. DI map, generated for the entire basin, shows a range of values between 0 and 1 (Fig. 8b). The generated DI map is segmented into three classes representing youthful (0–0.10), mature (0.20–0.30) and monadnock stage/old age (>0.30) to understand the present stage of basin evolution. Higher the value of DI, the larger is the undulation and instability of the terrain. The Karamana basin shows a mean DI value of 0.93, which indicates the basin is significantly dissected (with high undulation and greater instability) and these dissection zones are spatially distributed in the middle to lower catchment regions. Usually high DI values are associated with lower order streams in the upper catchments where erosion and down cutting is predominant. But in the case of the Karamana river basin, dissection of the terrain is more in the middle and lower reaches suggesting the influence of regional as well as local uplift and related erosion of the terrain caused due to continued tectonic activities in the region.

Conclusion

The geomorphic expressions in the Karmana river and its major tributaries are elucidated through the quantitative analysis of geomorphic indices. The overall assessment of drainage basin asymmetry indicates symmetric character of the full basin with relatively high asymmetry in the subwatersheds in the left and the right bank side of the major river. A forceful deviation of the stream channel is evidenced from the topographic symmetric factor (T) and its varying orientations. The prominent direction of terrain tilt varying from east, west, south, northwest and southeast indicates varying influence of tectonic activity over the region, which forced the stream networks to change the pattern of flow based on the terrain tilt. Variability in the stream oscillation is maximum in the middle part of the basin, which could be due to the antiformal fold that controls the shape, behaviour and flow pattern of the central segment of the river (Vijith et al. 2015). Though the longitudinal profile and hypsometric curve and integral of the whole basin indicate the signatures of a graded basin, the changes in the profile characteristics in certain reaches of the Karamana river point towards variation from the proposed gradational characteristic. Unlike the total basin, the Killi and Andiyurkonam rivers show highly undulating longitudinal profile with convex, concave-convex segments and the transitional characteristics of the geomorphic evolutional stage from mature to old in the hypsometric curve. This indicates the influence of geological process over stream and basin characteristics. The SL index of all the three rivers shows abrupt changes in near segment values, indicating the effect of lithological changes or uplift of the basin in response to tectonic activities. But the SL anomaly index rules out the role of lithological variation over the development of different characteristics of the river. These inferences are authenticated by the spatial pattern of drainage density and dissection index, particularly in the middle and lower reaches, which suggest the influence of plausible tectonic processes over the stream and basin characteristics. Among the different geomorphic indices analysed, the T index, longitudinal profile, SL and SL anomaly indices seem to be more useful in analysing the geomorphic characteristics associated with stream channels and are capable of differentiating the causes of such characteristics. The findings can serve as the baseline information about the morphotectonic characteristics of the Karamana river basin, which is undergoing rapid urbanization.

Acknowledgments Authors are thankful to Prof (Dr.) François Roure and the anonymous reviewer for critical review, constructive comments and suggestions which helped to improve the manuscript significantly and to the Editor Abdullah M. Al-Amri for his generous support.

References

Adams J (1980) Contemporary uplift and erosion of the Southern Alps. N Z: Geol Soc Am Bull 91:1–114

Ambili V, Narayana AC (2014) Tectonic effects on the longitudinal profile of the Chaliyar River and its tributaries, southwest India. Geomorphology 217:37–47

Awasthi KD, Sitaula BK, Singh BR, Batajracharya RM (2002) Land-use change in two Nepalese watersheds: GIS and geomorphometric analysis. Land Degrad Dev 13:495–513

Battacharya S, Kar R (1998) Structural constraints on reworking in the Western Ghats Granulite Belt, India and the Antarctic Analogue. Gondwana Res 1(1):285–290

Burbank DW, Anderson RS (2001) Tectonic Geomorphology. Blackwell Science, Oxford

Ch. Kothyari G, Rastogi BK (2013) Tectonic control on drainage network evolution in the upper Narmada valley: implication to neotectonics. Geography Journal 2013:9. doi:10.1155/2013/325808

Cox RT (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. Geol Soc Am Bull 106:571–581

Cuong NQ, Zuchiewicz WA (2001) Morphotectonic properties of the Lo River Fault near Tam Dao in North Vietnam. Nat Hazards Earth Syst Sci 1:15–22

de Araújo Monteiro K, Missura R, de Barros Correa AC (2010) Application of the Hack index–or stream length-gradient index (SL index)–to the Tracunhaém river watershed, Pernambuco, Brazil. Geociências 29(4):533–539

Drury SA, Holt RW (1980) The tectonic frame work of South India, A reconnaissance involving LANDSAT Imagery. Tectonophysics 65: 1–15

Drury SA, Harris NBW, Holt RW, Reeves–Smith GJ, Wightman RT (1984) Precambrian tectonics and crustal evolution in South India. J Geol 92:3–20

Ferraris F, Firpo M, Pazzaglia FJ (2012) DEM analyses and morphotectonic interpretation: The Plio-Quaternary evolution of the eastern Ligurian Alps, Italy. Geomorphology 149–150:27–40

Gao M, Zeilinger G, Xu X, Wang Q, Hao M (2013) DEM and GIS analysis of geomorphic indices for evaluating recent uplift of the northeastern margin of the Tibetan Plateau, China. Geomorphology 190:61–72

Garrote J, Heydt GG, Cox RT (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

Giaconia F, Booth-Rea G, Martínez-Martínez JM, Azañón JM, Pérez-Peña JV, Pérez-Romero J, Villegas I (2012) Geomorphic evidence of active tectonics in the Sierra Alhamilla (eastern Betics, SE Spain). Geomorphology 145–146:90–106

Gloaguen R (2008) Remote sensing analysis of crustal deformation using river networks http://www.igarsso8.org/abstracts/pdfs/3197.pdf

Hack JT (1960) Interpretation of erosional topography in humid temperate regions. Am J Sci 258-A:80–97

Hack JT (1973) Stream-profile analysis and stream-gradient index. U.S. Geol Surv J Res 1:421–429

Hare PW, Gardner TW (1985) Tectonic Geomorphology. Proceedings of the 15th Annual Bighamton Geomorphology Symposium. In: Morisawa M, Hack JT (eds) Geomorphic indicators of vertical neotectonism along converging plate margins, Nicoya Peninsula, Costa Rica. Allen and Unwin, Boston, pp. 75–104

Jayappa KS, Markose VJ, Nagaraju M (2012) Identification of geomorphic signatures of neotectonic activity using DEM in the Precambrian Terrain of Western Ghats, India. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, vol. XXXIX-B8 (2012) XXII ISPRS Congress, 25 August – 01 September 2012, Melbourne, Australia

John B, Rajendran CP (2008) Geomorphic indicators of neotectonism from the Precambrian terrain of Peninsular India: a study from the Bharathapuzha Basin, Kerala. J Geol Soc India 71:827–840

Kale VS, Shejwalkar N (2008) Uplift along the western margin of the Deccan Basalt Province: Is there any geomorphometric evidence? J Earth Syst Sci 117(6):959–971

Keller EA (1986) Active Tectonics. In: Investigation of Active Tectonics: Use of Surficial Earth Processes. National Academy Press, Washington D.C.

Keller EA, Pinter N (2002) Active tectonics. Earthquakes, Uplift, and Landscape. Prentice Hall, Upper Saddle River, p. 362

Kirby E, Whipple KX (2012) Expression of active tectonics in erosional landscapes. J Struct Geol 44:54–75

Kumar GRR, Chacko T (1988) Petrology and tectonic development of supracrustal sequence of Kerala Khondalite Belt, Southern India. Lunar and Planetary Inst., Workshop on the Deep Continental Crust of South India; p 149–150. Accessed from http://ntrs.nasa.gov/search.jsp?R=19890012873 on 11.08.2014

Mahmood SA, Gloaguen R (2012) Appraisal of active tectonics in Hindu Kush: Insights from DEM derived geomorphic indices and drainage analysis. Geosci Front 3(4):407–428

Malik S (2014) Determination of stages of landscape evolution of Sankha Nadi, Jharkhand; an integrated approach of morphometry and GIS. J Environ Earth Sci 4(3):46–55

Markose VJ, Jayappa KS (2011) Hypsometric analysis of Kali River Basin, Karnataka, India, using geographic information system. Geocarto International 26(7):553–568

Nair PKR, Prasannakumar V, Mathai T (1981) Structure of the western termination of the Bhavani lineament. J Geol Soc India 22: 285–291

Peters G, Van Balen RT (2007) Pleistocene tectonics inferred from the fluvial terraces of the northern Upper Rhine Graben, Germany. Tectonophysics 430:41–65

Rajakumar P, Sanjeevi S, Jayaseelan S, Isakkipandian G, Edwin M, Balaji P, Ehanthalingam G (2007) "Landslide susceptibility mapping in a hilly terrain using remote sensing and GIS." J Indian Soc Remote Sens 35(1):31–42

Ramakrishnan M (1993) Tectonic evolution of the granulite terrains of southern India. Geological Society of India Memoir 25:35–44

Rhea S (1993) Geomorphic observations of rivers in the Oregaon coast range from a regional reconnaissance prospective. Geomorphology 6:135–150

Salvany JM (2004) Tilting neotectonics of the Guadiamar drainage basin, SW Spain. Earth Surf Process Landf 29:145–160

Satheeshkumar R, Prasannakumar V (2009) Fabric evolution in Salem-Attur shear zone, south India and its implications on the kinematics. Gondwana Res 16:37–44

Schumm SA (1956) Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey. Natl Geol Soc Am Bull 67:597–646

Schumm SA, Mosley MP, Weaver WE (1987) Experimental Fluvial Geomorphology. Wiley, New York

Seeber L, Gornitz VM (1983) River profiles along the Himalayan arc as indicators of active tectonics. Tectonophysics 92:335–367

Selvan MT, Ahmad S, Rashid SM (2011) Analysis of the geomorphometric parameters in high altitude glacierised terrain using SRTM DEM data in Central Himalaya, India. ARPN J Sci Technol 1(1):22–27

Singh O, Sarangi A, Sharma MC (2008) Hypsometric integral estimation methods and its relevance on erosion status of northwestern Lesser Himalayan Watersheds. Water Resour Manag 22:1545–1560

Singh T, Awasthi AK (2010) Stream profiles as indicator of active tectonic deformation along the inter-foreland thrust, Nahan Salient, NW India. Curr Sci 98(01):95–98

Sinha Roy S, Mathai J, Narayanaswamy (1984) Structure and metamorphic characteristics of cordierite baring gneiss of south Kerala. Journal of Geological Society of India 25(4):231–244

Snyder N, Whipple KX, Tucker GE, Merritts DJ (2000) Landscape response to tectonic forcing: digital elevation model analysis of stream profiles in the Mendocino triple junction region, northern California. Geol Soc Am Bull 112(8):1250–1263

Soman K (2000) Geology of Kerala. Geological Society of India, Bangalore, p. 335

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 AN (1952) Hypsometric (area-altitude) analysis of erosional topography. Geoloical Society of America Bulletin 63:1117–1141

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

Vijith H, Prasannakumar V, Sharath Mohan M, Pratheesh P (2015) Channel response in structurally disturbed terrain: evaluation of implication of neotectonic activity through an integrated approach. Geocarto International. doi:10.1080/10106049.2015.1006528

Virdi NS, Philip G, Bhattacharya S (2006) Neotectonic activity in the Markanda and Bata river basins, Himachal Pradesh, NW Himalaya: A morphotectonic approach. Inter J Rem Sen 27(10): 2093–2099

Whipple KX, Tucker GE (1999) Dynamics of bedrock channels in active orogens: implications for the height limits of mountain ranges, landscape response time scale, and research needs. J Geophys Res 104: 17661–17674

Willgoose G, Hancock G (1998) Revisiting the hypsometric curve as an indicator of form and process in transport-limited catchment. Earth Surf Process Landf 23(7):611–623

Zovoili E, Konstantinidi E, Koukouvelas IK (2004) Tectonic geomorphology of escarpments: the cases of Kompotades and Nea Anchialos faults. Bull Geol Soc Greece 36:1716–1725