GIS Based Quantitative Geomorphic Analysis of Fluvial System and Implications on the Effectiveness of River Basin Environmental Management

A. Venkatesan, A. Jothibasu and S. Anbazhagan

Abstract Rivers are sensitive to changes in tectonic deformation, and adjust themselves on different scales of time periods depending on the physical properties of the host rocks and climatic effects. The resultant changes are exhibited by the geomorphic indices and landform assemblages within a river basin. This paper presents the results of integrated quantitative geomorphic analysis conducted for understanding the prevalent tectonic activities in a medium sized drainage basin, the Thoppaiyar sub-basin, India. The major part of the study area is covered by gneisses and granites. The sub-basin is divided into fourteen fourth order micro basins (FOMBs) for quantitative geomorphic analysis. Prior to quantitative analysis, longitudinal river profile and channel morphology were studied. The channel morphology includes cross sections, width-to-depth ratio, entrenchment ratio, bank height ratio were measured during field investigation. Various geomorphic indices namely, the basin shape index (Bs), drainage basin asymmetry factor (Af), hypsometric integral (Hi), hypsometric curve (Hc), valley floor width-to-height ratio (Vf), transverse topographic symmetry (T) and stream length gradient index (SL) were derived using topographic maps and SRTM satellite data. The spatial distributions of these parameters were represented as thematic layers using. The results obtained from these indices were combined by ArcGIS 9.3 software to generate an index of relative active tectonics (I_{RAT}) in the sub-basin. It indicated the prevalence of differences among the FOMBs and an overall relatively low tectonic activity in the Thoppaiyar sub-basin.

Keywords GIS · Channel morphology · Geomorphic indices · Relative active tectonics

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1 Introduction

Geomorphology represents either qualitative or quantitative nature of landforms, landscapes and surface processes including their description, classification, origin, development and history highlighting the physical, biological, and chemical aspects (Baker 1986; Anbazhagan and Saranathan 1991; Easterbrook 1999; Keller and Pinter 2002; Morisawa 1958; Ramasamy et al. 2011). Tectonism in general has a geomorphic expression in the region where it occurs and its adjacent areas (Gerson et al. 1984). The study of tectonic affects in many fluvial systems shows that, rivers are valuable tools to understand the active and inactive tectonics prevailing in an area. Drainage system of a region records the evolution of tectonic deformation (Schumm 1986; Gloaguen 2008). Morphometric analyses in tectonic geomorphology studies basically refer to the measurement on topographic maps of quantitative parameters (Wells et al. 1988). Since the geomorphic indices were first introduced as indicators of seismic activity (Bull and McFadden 1977), the topographic and geologic maps serve as sources of elevation for determining the indices. Geomorphic indices are useful tools in the evaluation of active tectonics, because they can provide valuable insights concerning specific areas of interest (Keller 1986).

The quantitative measurement of landscape is based on the calculation of geomorphic indices using topographic maps or digital elevation models, aerial photographs or satellite imagery, and fieldwork (Keller and Pinter 2002). The development of LIDAR remote sensing technique had helped to extract high resolution topographic information and to understand the earth surface processes including river morphology and active tectonics (Tarolli 2014). Saberi et al. (2014) have adopted GIS technique for derivation of various geomorphic indices and to assess the active tectonics in Iran. Hurtgen et al. (2013) have adopted GIS technique to assess the tectonic activities in southern Spain, based on morphometric indices. Many workers have attempted morphotectonic analysis using remote sensing and GIS techniques (Jordan 2003; Korup et al. 2005; Harbor and Gunnel 2007; Peters and Van Balen 2007; Font et al. 2010; Ferraris et al. 2012; Maryam and Maryam 2013; Dutta and Sharma 2013; Bagha et al. 2014; Markose et al. 2014). Various indices including the normalized stream length gradient index (SL), valley floor width-to-height ratio (Vf), hypsometric curves (Hc), sinuosity of mountain front (Smf), asymmetry factor (Af), and elongation ratio (Bs) were demonstrated as useful geomorphic indices in evaluating relative tectonic activity classes (Seeber and Gornitz 1983; Brookfield 1998; Chen et al. 2003; Silva et al. 2003; Malik and Mohanty 2007).

The southern Indian Peninsula is considered to be a tectonically stable region consisting of ancient rocks, rivers and land surfaces. However, within this larger ensemble, certain portions of the lands show younger topographic surfaces and recent-historical seismicity and these in turn were evidenced by the investigations on the longitudinal profiles, morphotectonic indices of active tectonics and fluvial records (for example, Ramasamy et al. 2011; Kale et al. 2013). Except such generalizations on a regional scale, microscale studies on any of the river basins of

south India are scarce. In this paper, we attempt demonstrating the potential use of GIS technique in the evaluation of geomorphic indices of Thoppaiyar sub-basin, Southern India. The study also attempts quantification of several geomorphic indices of relative active tectonics and topographic development to produce a single index map that can be used to characterize relative active tectonics in this region.

2 Geological Setting

Quantitative geomorphic analyses were carried out to assess the relative active tectonics in the Thoppaiyar sub-basin, bounded between northern latitudes $11^{\circ}51'$ $47''–11^{\circ}59'56''$ and eastern longitudes $77^{\circ}53'5–78^{\circ}18'2''$ (Fig. 1), covering an area of about 462 km^2. Northern and southern parts of this sub-basin fall under the Dharmapuri and Salem districts respectively. The highest elevation in the sub-basin is 1,600 m above mean sea level (amsl) at Muluvi and the lowest elevation of 240 m amsl is observed at its confluence with the Cauvery River. Mean annual rainfall in the sub-basin is 707 mm, which is significantly lower than the state average (970 mm). It receives rainfall from northeast as well as southwest monsoons. The climate in the sub-basin is generally warm. The hottest period of the year spans from March to May reaching the peak of 38 $^{\circ}$C in April. The climate becomes cool during December to February, touches minimum of 15 $^{\circ}$C in January. The prevailing
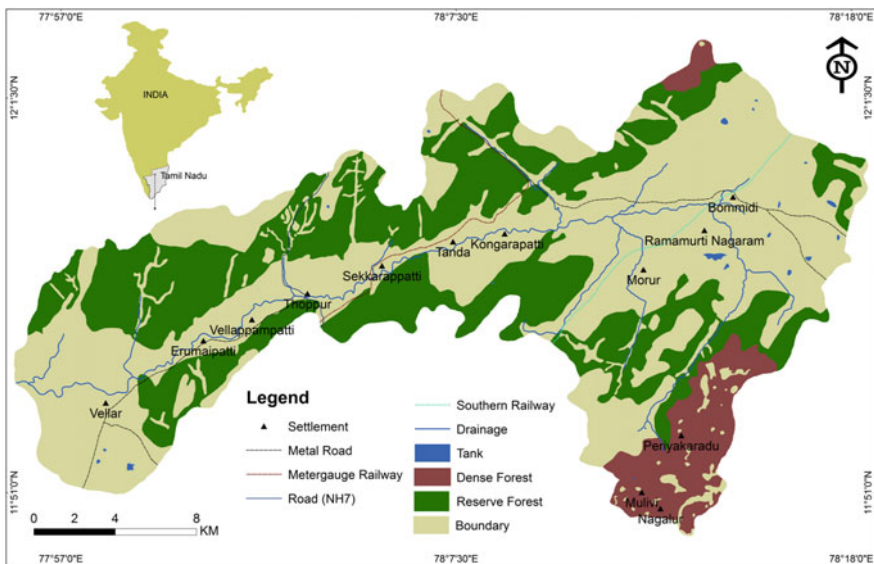

Fig. 1 Thoppaiyar sub-basin located in part of Dharmapuri and Salem districts in the state of Tamil Nadu, India selected for quantitative geomorphic analysis

hydrological, soil and climatic conditions support extensive floricultures in this sub-basin.

Structural hill system, denudational hill, fracture valleys and pediments are the major geomorphic units found to occurring in the study area. The structural hill system act as the boundary in the northern and southern part of the basin. The sub-basin is mostly covered by Precambrian crystalline rocks and recent alluvium along the river course. The major rock types are garnetferous quartzo felspathic gneiss, granites, granitoid gneiss, pink migmatite, purple conglomerate, quartz vein, syenite, sandstone, shale and shale with bands of limestone. Granites occupy about 324 km^2 in the north and central part of the sub-basin. Pink migmatite and gneissic rocks dominate in the central and eastern parts of the sub-basin. Presence of quartz veins are commonly noticed in the study area with an aerial coverage of 44 km^2. All these rock types increase the direct runoff rather than base flow contribution. However, the contribution of overland flow to the runoff is limited, because the length of overland flow is only 0.20 km. The surface infiltration is mostly restricted with weathered portion of granites. The areas covered by agricultural land and forest cover are equal—about 35 % each.

3 Materials and Methods

The Survey of India topographic maps, SRTM data, IRS P6 LISS III satellite data and data collected from field measurements were utilized in the present study. The ArcGIS 9.3 software was utilized for data generation and spatial integration. The topographic maps were utilized for the extraction of basin information such as roads, drainages and contours. Fluvial geomorphology of the sub-basin provided detailed information for quantitative geomorphic analysis. In the present study, the river profile, terrain characteristics, channel morphology and quantitative geomorphology were evaluated and discussed. The profile for 65.5 km length was plotted for the sub-basin. The sub-basin was divided into 14 fourth order micro basins (Fig. 2) and selected for further analyses. The channel morphology including, bankfull area, width-depth ratio, entrenchment ratio, height ratio were estimated. For quantitative geomorphic analysis, the stream length-gradient index, asymmetric factor, hypsometry and integral, valley floor width to height ratio, basin shape index and topographic symmetry factor were estimated. All the measurements were carried out with the help of drainages and contours extracted from the SRTM DEM in GIS environment. The geomorphic indices were imported in the form of point data along with georeferences (latitude and longitudes) and then spatially interpolated using 'Inverse Distance Weightage (IDW)' method. The interpolated geomorphic index maps were digitized and converted into 'shape file'. All the thematic maps were commonly projected to 'geographic coordinate system' with WGS 1984 datum. The fluvial geomorphic parameters were assessed for clues on the sub-basin development and relative tectonic condition of the sub-basin. Each theme was
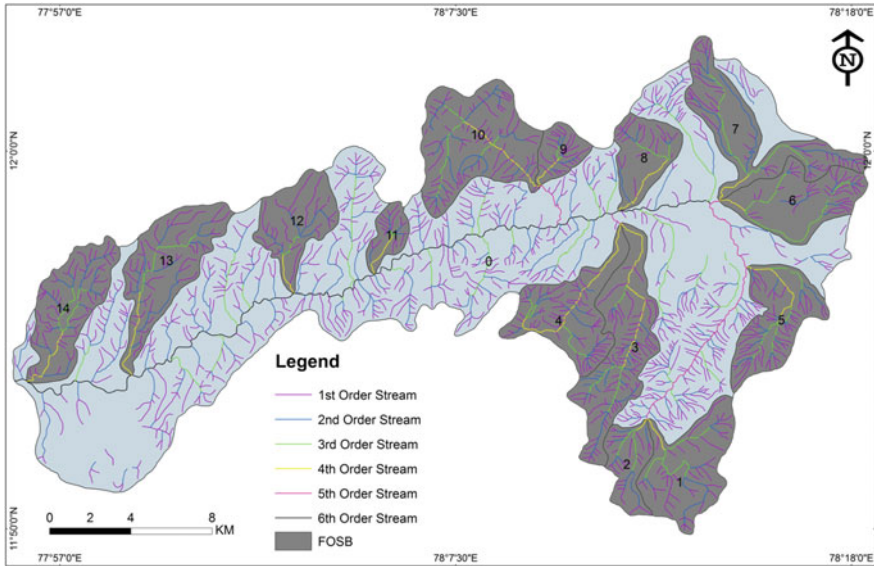
Fig. 2 Fourth order micro basins (FOMBs) in Thoppaiyar sub-basin considered for quantitative geomorphic study

divided into relative tectonic activity classes based on the range of values of individual indices (Hamdouni et al. 2008). Finally, the relative tectonic activity in the study area was divided into three classes.

4 Longitudinal River Profile

As fourth order sub-basins constitute more than 45 % of the study area, and most of the watershed management schemes elsewhere are based on fourth or lower order sub-basins (Joji and Nair 2013), the present study attempted delineating the study area, the Thoppaiyar sub-basin into 14 Fourth Order Micro Basins (FOMBs) for understanding terrain characteristics through longitudinal river profile and quantitative analysis of relative tectonic activities.

The longitudinal river profile is a curve that connects points from the source to the mouth of a river and the net effect of coarse particle inputs are presented in this profile. Individual rapids represent small-scale convexities in the longitudinal profile. They exhibit considerable changes on various time scales resulting from the frequent debris flow, deposition and river reworking (Horton 1932; Thornbury 1954 and Leopold et al. 1964). The longitudinal river profile prepared from source of Thoppaiyar to its mouth by considering the elevation and distance (Fig. 3). Survey of India (SOI) topographic maps and SRTM satellite data were utilized for preparation of river profile. The SRTM data were plotted for the 10 m contour interval.
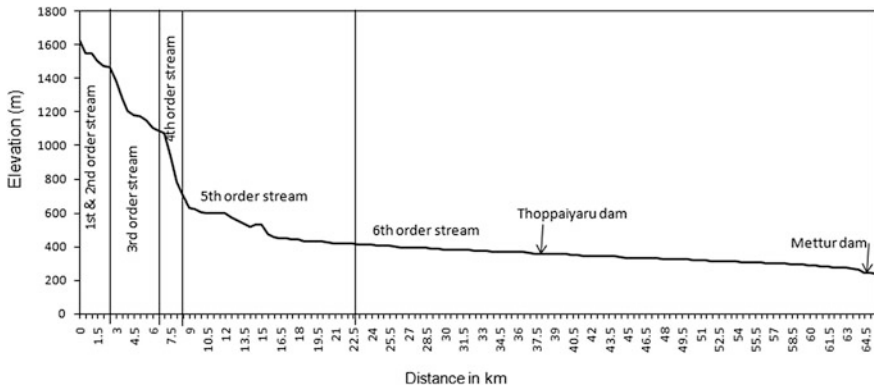
Fig. 3 Longitudinal river profile of Thoppaiyar sub-basin

In GIS environment, elevation data were collected for every 0.5 km interval from source to confluence. IRS P6 LISS III satellite data were utilized to interpret the geomorphology for all the micro basins. Other parameters including, geology, drainage density and bifurcation ratios were collected at an interval of 0.5 km for 132 points from the source to the mouth (Table 1).

5 Channel Morphology

Rosgen and Silvey (1996) developed a system for the classification of stream reaches based on their form. The system gives letter and number designations to different stream types, depending on their combination of bankfull channel characteristics such as entrenchment ratio, width to depth ratio, slope, sinuosity and bed material size. Cross-section is a line across a stream perpendicular to the flow along which measurements were taken, so that the morphological and flow characteristics of the section are described from bank to bank (Fig. 4). Stream channel morphology is often described in terms of a width/depth ratio related to the bankfull stage cross-section (Table 2; Fig. 5). The width-to-depth ratio varies primarily as a function of the channel cross-section for a given slope; the boundary roughness as a function of the stream flow and sediment regime, bank erodibility factors, including the nature of stream bank materials; degree of entrenchment; and the distribution of energy in the stream channel (Rosgen 1994).

$$\text{Width to depth ratio} = \frac{\text{Bankfull width}}{\text{Average depth}} \tag{1}$$

The direct and most reliable method of estimating channel depth is from the thickness of stratified units of point bars (Moody-Stuart 1966; Elliot 1976) and from

Table 1 Fourth order micro basins (FOMBs) along with lithology, geomorphology and morphometric parameters

| FOMBs	Geology	Geomorphology	Bifurcation ratio	Drainage density (km/km^2)
1	Granitoid gneiss	Moderately weathered pediment, shallow weathered pediment, structural hills	4.03	2.83
2	Granitoid gneiss, pink migmatite, nepheline syenite, corundum syenite	Shallow weathered pediment, structural hills	3.86	2.60
3	Granite	Linear ridge/dyke, moderately weathered pediment, structural hills, shallow weathered pediment	3.03	2.27
4	Granite, pink migmatite	Moderately weathered pediment, shallow weathered pediment, structural hills	2.53	3.24
5	Garnetiferous quartz felspathic gneiss, syenite	Fracture valley, linear ridge/dyke, shallow weathered pediment, structural hills	4.20	2.60
6	Granite	Fracture valley, shallow weathered pediment, structural hills	2.88	3.57
7	Granite, pink migmatite	Moderately weathered pediment, shallow weathered pediment, structural hills	2.90	2.32
8	Granite, pink migmatite	Moderately weathered pediment, shallow weathered pediment, structural hills	3.70	2.71
9	Granite	Moderately weathered pediment, shallow weathered pediment, structural hills, residual hill	3.30	2.21
10	Granite	Moderately weathered pediment, shallow weathered pediment, structural hills, residual hill	3.83	3.51
11	Granite	Structural hills	3.51	2.35
12	Granite	structural hills, hill top weathered	2.66	2.99
13	Granite	Shallow weathered pediment, structural hills, hill top weathered, residual hill	4.53	3.08
14	Granite	Shallow weathered pediment, structural hills, hill top weathered, residual hill	4.00	3.07
Mean			3.49	2.81
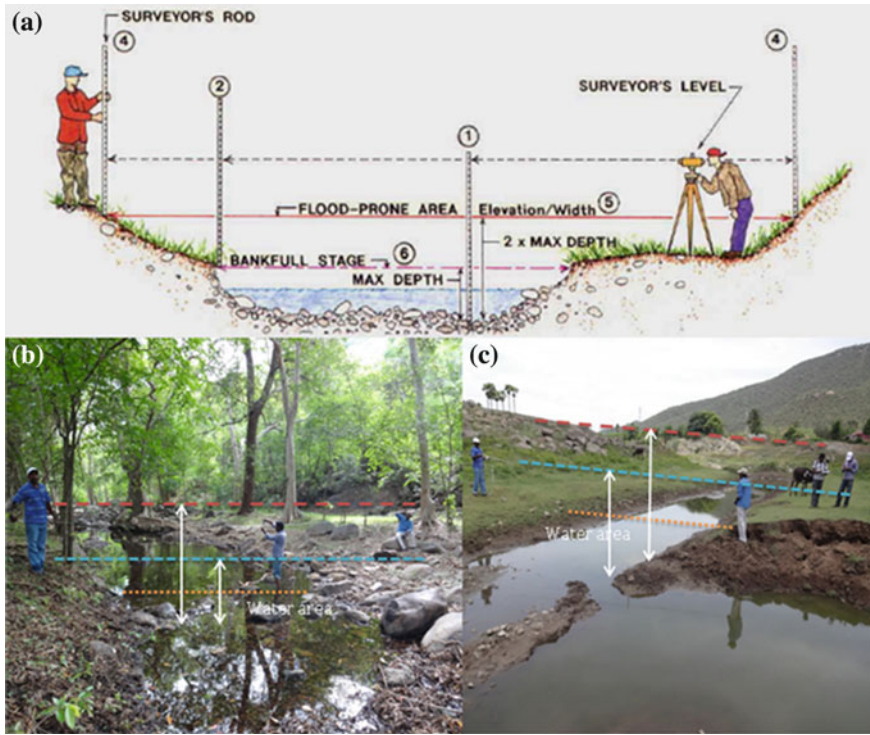
Fig. 4 Bank full estimation in Thoppaiyar river basin. **a** Bankfull model, **b** bankfull estimation at Anaimaduvu and **c** Kongarapatti

the average thickness of the coarse member in fining upward cycles (Jackson 1979). Frequently, point bar accretion surfaces cannot be recognized in ancient deposits, and it has not been possible to estimate channel depth from the thickness of the coarse sand members, because of the presence of multilevel sandstone bodies and paucity of complete cycles. Owing to this difficulty, Allen (1968) worked out an alternative relationship for estimating channel width for lower to moderate channel sinuosity streams. Alternatively, an estimate of average channel depth has been made from the thicknesses of cross-beds.

Entrenchment ratio is equal to the floodplain width at two times the bankfull depth divided by bankfull width. When a reach of stream is either straightened or narrowed, the power of the stream flow is increased. The stream may then cut down into its bed, so that flood flows are less likely to spill out into the floodplain. Through this process, the reach has incised, and that the channel has become entrenched, which can occur to varying degrees. When large flood flows are confined to the narrow channel of an incised stream, the water becomes very deep and erosive; the stream may cut down even deeper into its bed. Eventually the banks may become so high and steep that they erode away on one or both sides, widening the channel. This in turn can change previously stable areas downstream.

Table 2 Bankfull estimation in Thoppaiyar sub-basin

S. No.	Location	FPW (m)	BFW (m)	BFD (Centre) (m)	WD (m)	FPLB Alt (m)	BFLB Alt	BFD Alt	BFRB Alt	FPRB Alt	Width to depth ratio	Entrenchment ratio	BHR/Classification	
1	Aanai Maduvu	17.6	8.5	1.1	0.8	459.94	459.64	458.84	459.64	460.25	13.55	2.07	1.0	Stable
2	Annaikat	15.8	8.6	1.5	0.9	449.88	449.58	448.38	449.58	449.88	11.42	1.84	1.0	Stable
3	Bommidi	14.6	4.5	1.7	0.0	426.72	426.11	425.02	426.11	426.42	5.87	3.22	1.0	Stable
4	Karungalur	22.1	12.6	1.5	0.6	386.49	385.88	385.03	385.87	386.18	19.30	1.75	1.0	Stable
5	Thoppur dam	45.4	21.8	1.3	0.9	369.72	369.11	368.38	369.11	369.42	36.75	2.08	1.1	Moderately unstable
6	Sekkarapatti	34.7	16.2	1.8	0	340.16	339.55	338.36	339.54	339.85	19.61	2.15	1.1	Moderately unstable
7	Chinmakanavai	26.9	16.0	1.6	0	336.19	335.89	334.57	335.89	336.19	19.82	1.68	1.0	Stable
8	Vattampatti	30.2	10.7	1.1	0	335.58	335.28	334.53	335.28	335.58	20.48	2.82	1.0	Stable
9	Thoppur	36.0	13.1	2.1	0	334.06	333.76	331.96	333.75	334.06	12.46	2.75	1.1	Moderately unstable
10	Thoppur ropecar	69.5	13.2	2.3	0	332.84	331.93	330.54	331.92	333.15	10.79	5.25	1.1	Moderately unstable
11	Upparapatti	20.5	7.0	2.5	0	330.10	329.79	327.60	329.78	330.40	5.26	2.93	1.0	Stable
12	Vellappampatti	39.6	11.0	2.7	0	325.53	324.31	322.78	324.30	325.52	8.01	3.61	1.1	Moderately unstable
13	Pappireddiyur	30.2	10.9	3.1	0	317.91	317.60	314.81	317.60	318.21	6.73	2.76	1.0	Stable
14	Erumappatti	46.6	19.5	3.3	0	316.99	316.38	313.69	316.38	317.30	11.28	2.39	1.1	Moderately unstable
15	Kambampatti	31.1	12.7	3.7	0	303.28	302.97	299.58	302.97	303.27	6.89	2.44	1.1	Moderately unstable
16	Vellar	63.4	20.7	4.2	0	289.56	288.65	285.36	288.64	289.26	10.23	3.06	1.1	Moderately unstable
17	OoruVellaru	62.5	21.8	5	0	281.94	281.64	276.94	281.63	281.64	9.00	2.86	1.1	Moderately unstable
18	Soliyanur	76.5	41.1	5.2	4.8	277.06	274.02	271.88	274.01	276.15	17.42	1.86	1.2	Moderately unstable
19	Thoppaiyaru	90.5	24.0	5.5	5.1	246.58	242.01	241.10	242.01	245.36	9.86	3.76	1.2	Moderately unstable

FPW flood prone width, *BFW* bankfull width, *BFD* bankfull depth, *WD* water depth, *FPLB* flood prone left bank, *BFLB* bankfull left bank, *BFD* bankfull depth, *BFRB* bankfull right bank, *FPRB* flood prone right bank, *BHR* bank height ratio
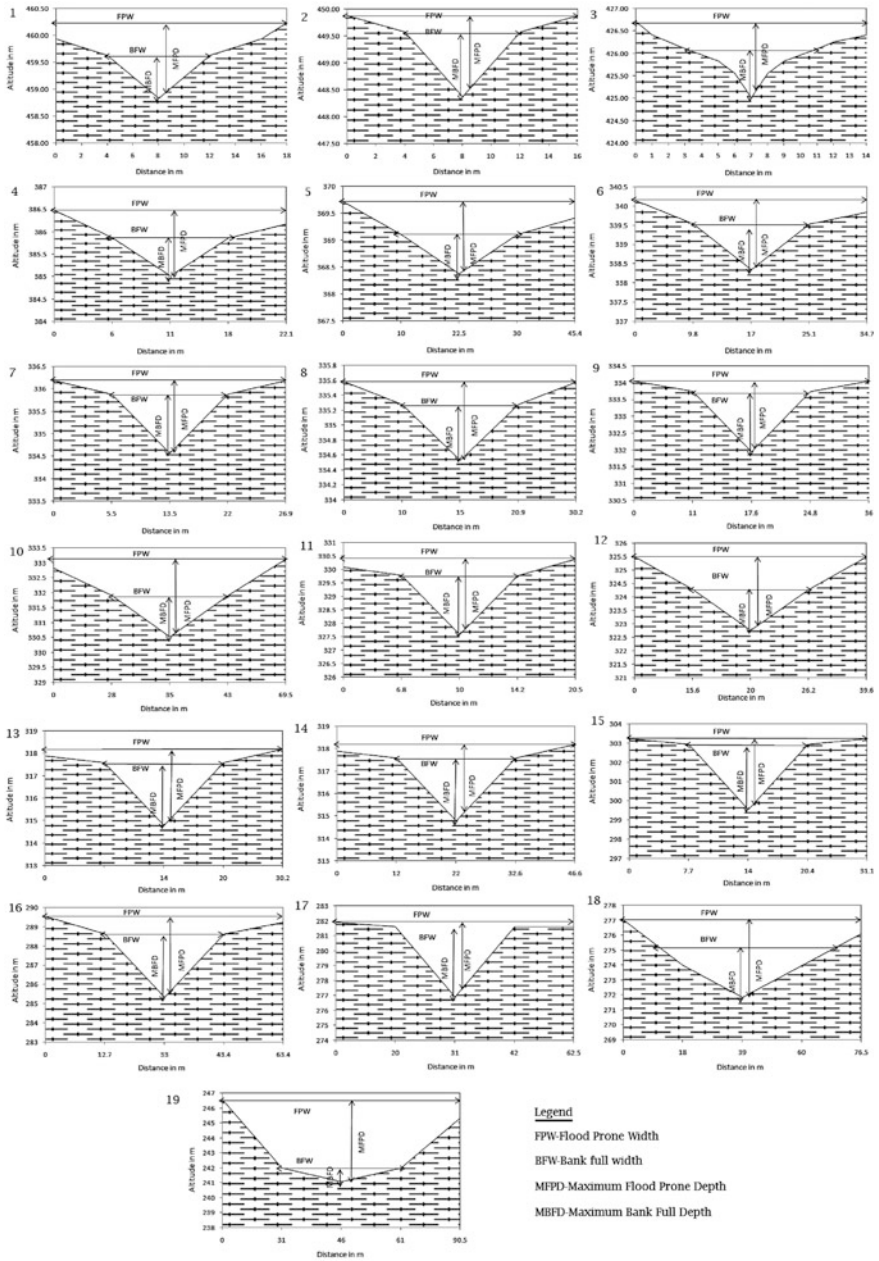
Fig. 5 Bankfull estimation at 19 locations in Thoppaiyar sub-basin

$$\text{Entrenchment ratio} = \frac{\text{Flood prone width}}{\text{Bankfull width}} \quad (2)$$

Bank height ratio (BHR) is the height of the top of the bank divided by the bankfull discharge height typically measured from the toe. The BHR is a relative measure of the floodplain connectivity to the bankfull channel.

6 Quantitative Geomorphic Analysis

The geomorphic indices are important indicators to interpret landform responses to deformation processes and together with field investigations, have been widely used to differentiate zones deformed by active tectonics (Keller and Pinter 2002; Chen et al. 2003). The tectonic quiescence or activeness in a drainage basin is reflected in the drainage pattern, lineaments, intermontane valleys, and valley incisions (Howard 1967; Cox 1994) and influences the fluvial process through the changes in slope, discharge, sediment load and bedrock erodibility. Human interventions such as gravel mining, dredging (Fig. 6) significantly alter natural conditions and can have longer impact on riparian condition. The topographic variations in a drainage basin result from adjustments between the tectonic, climatic and lithological controls as streams and rivers flow over rocks and soils of variable settings (Hack 1973). This adjustment eventually reaches a dynamic equilibrium and river systems display slightly concave longitudinal profiles. Deviation from this normal river profile may be interpreted as the result of active tectonic, lithological and/or climatic factors (Hack 1973). Many studies, including Perez-Pena et al. (2010), Mahmood and Gloaguen (2012) and Rebai et al. (2013) have demonstrated the utility of quantitative geomorphic analysis to assess the active tectonic process in a river basin.

In the present study, six geomorphic indices namely stream length gradient index (SL), asymmetrical factor (Af), hypsometric integral (Hi), valley floor width-to-height ratio (Vf), elangation ratio (Bs) and traverse topographic symmetry (T) were
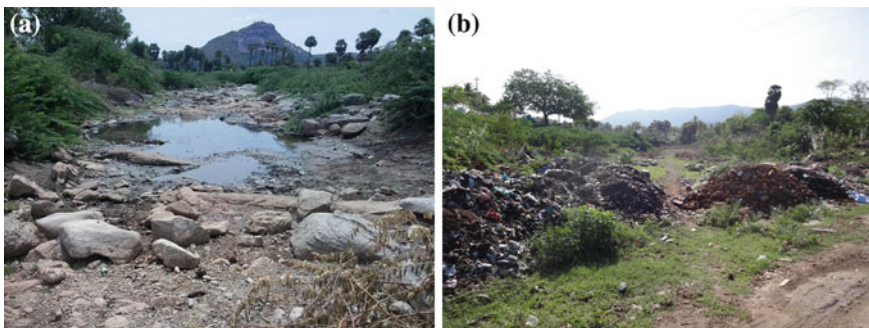

Fig. 6 River bed modification due to human intervention. **a** Caving and ponding in exposure of boulders, **b** garbage dumping which obstruct the flow and contaminant surface and ground water

analyzed for 14 FOMBs of the Thoppaiyar sub-basin. The total value of each index were worked out, averaged and divided into relative tectonic classes (Hamdouni et al. 2008).

6.1 Stream Length Gradient Index (SL)

Stream length gradient index (SL) describes the morphology of a stream network using distribution of topographic gradients along rivers (Hack 1973). It is sensitive to change in channel slope, and allows evaluating the relative roles of possible tectonic activities and rock resistance (Keller and Pinter 2002; Azor et al. 2002). The topographic evolution results from an adjustment between the erosional processes as streams and river flow over rocks and soils of variable strength (Hack 1973). 'SL' was first used to reflect the stream power or differential rock erodibility and calculated using the following formula (Hack 1973),

$$SL = \frac{\Delta H}{\Delta L_r} L_t \qquad (3)$$

where SL is stream length-gradient index, $\Delta H/\Delta L_r$ is the channel slope or gradient of the reach, ΔH is change in altitude for a particular channel of the reach with respect to ΔL_r. ΔL_r is the length of a reach. L_t is the horizontal length of the watershed divide to the midpoint of the reach.

The calculated SL values for each reach of the micro basins were converted into a point shape file and the average value was estimated for each micro basin. The point data were interpolated through Inverse Distance Weighted (IDW) method available in GIS Software and a spatial map on SL index was then generated. This has been classified into three categories namely, class 1, class 2 and class 3 that contain the range values of 203−653, 98−203 and 13−98 respectively (Fig. 7a).

6.2 Asymmetry Factor (Af)

The calculations of Asymmetric Factor (AF) and Topography (T) help rapid quantitative determination of ground tilting (Cox 1994; Cox et al. 2001; Keller and Pinter 2002). Asymmetry factor (Af) is an aerial morphometric variable used in detecting the presence or absence of the regional tectonic tilt in the basin on a regional scale. 'Af' is defined as

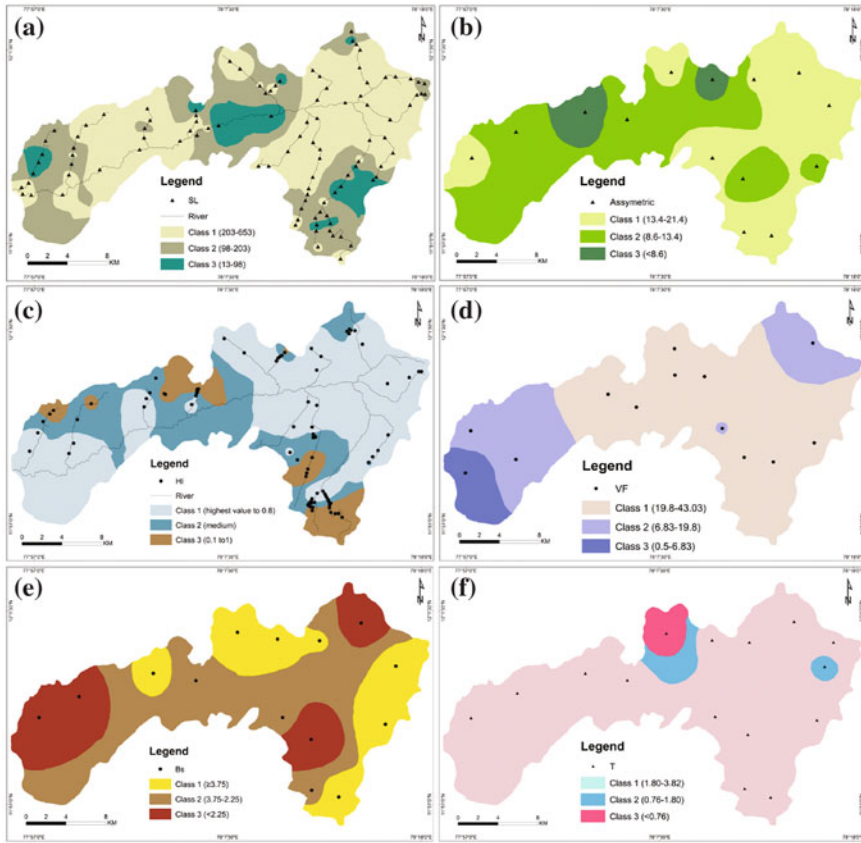$$Af = \frac{A_R}{A_T} \times 100 \qquad (4)$$

Fig. 7 Geomorphic indices. **a** SL, **b** Af, **c** Hi, **d** Vf, **e** Bs and **f** T and its classification of Thoppaiyar sub-basin

where A_R is the area of the basin to the right (facing downstream) of the trunk stream and A_T is the total area of the drainage basin. 'Af' greater or smaller than 50 indicates basin tilting, either due to active tectonics, lithological, structural control and differential erosion (Hamdouni et al. 2008). For the purpose of evaluating the relative tectonic activity (Iat), the absolute difference of Af is important. The absolute Af was calculated by subtracting the neutral value 50 from the calculated Af. The absolute Af is expressed as (Perez-Pena et al. 2010);

$$\text{Af} = \left[\frac{A_R}{A_T} \times 100\right] - 50 \tag{5}$$

Any drainage basin that was subjected to a tectonic rotation will most likely have an impact on the tributary. In case, the tectonic activity caused a tilt on the left side of the drainage basin, the tributaries located on the left of the mainstream will be

shorter compared to the tributaries on the right side of the stream with an asymmetry factor greater than 50 (Hare and Gardner 1985; Keller and Pinter 2002). The absolute values of Af were are classified into three classes as class 1 (<8.6), class 2 (8.6−13.4) and class 3 (13.4−21.4) (Fig. 7b).

6.3 Hypsometry and Integral (Hi)

Hypsometry means the relative proportion of an area at different elevations within a region, and the hypsometric curve depicts the distribution of the area with respect to altitude (Strahler 1952). The hypsometric curves have been used to understand the stage of development of the original network i.e. original stage of the catchment. The hypsometric integral is the area between the curves, which relates the percentage of total relief to cumulative percent of the area. It expresses the measure of the distribution of land mass volume remaining beneath, or above a basal reference plane, otherwise it expresses the volume of a basin that has not been eroded (Pike and Wilson 1971; Keller and Pinter 2002). The hypsometric curves are obtained by plotting the proportion of total basin height (h/H_0 relative height) against the total basin area (a/A_0 relative area), and the hypsometric integrals were calculated for all the 14 micro basins in GIS environment. The maximum height (H) equals the maximum elevation minus the minimum elevation and represents the relief within the basin and (A) represents the total area of the basin. The area (a) is the surface area within the basin above a certain line of elevation (h). The relative area (a/A) measures between 1.0 at the lowest point in the basin, where relative height (h/H) equals zero, and zero at the highest point in the basin where relative height (h/H) equals 1.0 (Strahler 1952; Keller and Pinter 2002). Hypsometric integral is generally derived for a particular drainage basin and is an index that is independent of the basin area. It varies from 0 to 1. A portion of the drainage basin with hypsometric value close to 0 indicates a highly eroded nature and a value close to 1 indicate weakly eroded nature. The HI may be calculated using a following equation (Meyer 1990; Kellar and Pinter 2002).

$$HI = \frac{H_{mean} - H_{min}}{H_{max} - H_{min}} \tag{6}$$

where H_{mean} is the average height; H_{max} and H_{min} are the maximum and minimum heights of the catchments.

The topography produced by stream channel erosion and associated processes of weathering mass-movement, and sheet runoff is extremely complex, both in the geometry of the forms themselves and in the interrelations of the process which produce the forms. The formations of hypsometric curve and the value of the integral are important elements in topographic form.

The 'Hi' is similar to the 'SL' index in the rock strength as well as other factors that affect the value. Higher values generally represent that not as much of the

uplands have been eroded and reflect the younger landscape, possibly produced by recent tectonics. The 'Hi' could also be interpreted as recent initiation into a geo-morphic surface formed by deposition.

The 'Hi' values were grouped into three classes with respect to the convexity and concavity of the hypsometric curve. Class 1 with convex hypsometric curve (highest value to 0.8), class 2 with concave-convex hypsometric curve (medium) and class 3 with concave hypsometric curve (0.1–1). Spatial distributions of these three classes are represented in Fig. 7c.

6.4 Valley Floor Width to Height Ratio (Vf)

Valley floor width to height ratio (Vf) is a geomorphic index that discriminates the V and U shaped and flat-floored valleys. This index was adopted particularly to identify the tectonically active fronts (Pedera et al. 2009; Koukouvelas 1998; Zuchiewicz 1988; Azor et al. 2002; Silva et al. 2003) and is defined as (Bull and McFadden 1977),

$$Vf = \frac{2Vfw}{Eld + Erd - 2Esc} \qquad (7)$$

where 'Vfw' is the width of the valley floor, 'Eld' and 'Erd' are the elevations of the left and right valley divides respectively and 'Esc' is the elevation of the valley floor.

The valley floors tend to become progressively narrow upstream from the mountain front (Ramirez-Herrera 1998). The Vf is usually calculated at a given distance upstream from the mountain front (Silva et al. 2003). 'Vf' values were calculated for 14 micro basins where the main valleys cross the mountain fronts, using cross-sections drawn from the digital elevation model prepared from topo-graphic map of the study area. The Vf value were categorized into three classes as class 1 (0.5−6.83), class 2 (6.83−19.8) and class 3 (19.8−43.09) and their spatial distributions are presented in the Fig. 7d.

6.5 Basin Shape Index

The elongation ratio (Bs) describes the planimetric shape of a basin. It is expressed as:

$$Bs = \frac{Bl}{Bw} \qquad (8)$$

where Bl is the length of the basin measured from its mouth to the distal point in the drainage divide, and Bw is the width of the basin measured across the short axis defined between left and right valleys divides (Ramirez-Herrera 1998).

The young drainage basins in active tectonic areas tend to be elongated in shape parallel to the topographic slope of a mountain. The index reflects the differences between the elongated basins that have high values of 'Bs' associated with relatively higher tectonic activity and circular basins that have low 'Bs' values generally associated with low tectonic activity (Bull and McFadden 1977). The 'Bs' of the 14 micro basins range from 0.58 to 5.56 and this was classified into 3 classes to assess the relative active tectonic activity in the area. The class 1 is categorized by high Bs value (≥3.75), the class 2 by moderate values (3.75−2.25) and class 3 by low values (<2.25) (Fig. 7e).

6.6 Transverse Topographic Symmetry Factor (T)

Transverse Topographic Symmetry Factor (T) is a quantitative geomorphic index that helps evaluating the basin asymmetry and is defined as:

$$T = \frac{D_a}{D_d} \qquad (9)$$

where 'D_a' represents the distance from the midline of the drainage basin to the midline of the active channel or meander belt, and the 'D_d' corresponds to the distance from the basin midline to the basin divide.

For different segments of river valleys, the calculated T values indicate migration of streams perpendicular to the drainage-basin axis. For perfectly symmetric basin T = 0. As the symmetry increases, 'T' increases and approaches a value of 1.0 and indicates tilted basins (Burbank and Anderson 2000; Cox 1994; Cox et al. 2001; Keller and Pinter 2002). The T factor calculated for the 14 micro basins of the Thoppaiyar sub-basins were classified into three categories as class 1 (<0.76), class 2 (0.76–1.80), class 3 (1.80–3.82) (Fig. 7f).

7 Discussion

The longitudinal profile of the Thoppaiyar sub-basin has shown as overall concavity, which reflects a pronounced decrease in the stream gradient. The upstream condition of Thoppaiyar sub-basin is more concave than the downstream. The concave nature of the profile indicates an increase of stream discharge in the downstream direction of the Thoppaiyar sub-basin. The river profile reveals that a pronounced decrease in gradient from origin to confluence (65.5 km). The elevation difference is 1,460 m. The profile has breaks at 6th, 9th and 16.5th km. An elevation difference of 500 m has

been observed in between 0 and 6th km. The profile takes sharp changes from 6th to 9th km with a difference of 400 m. This zone is probably controlled by fault. The knick point at 15th km once again indicates the structural control. The river flows along a gentle profile from 16.5th km onwards and this gentle profile forms more than 2/3rd of the river profile. The Thoppaiyar sub-basin is a sixth-order Hortonian stream and the number of streams in the first, second, third, fourth, fifth and sixth orders are 1141, 290, 60, 14, 4 and 1 respectively. The stream ordering with respect to stream profiling has revealed the variation of stream order at 20 points in the profile with respect to elevation and distance. The major portion of the stream order (up to 4th order) has been found restricted only within 16 km.

The mean bifurcation ratio (Rb) of the Thoppaiyar sub-basin is 2.49 and the mean 'Rb' value of 14 FOMBs is 3.49 and the theoretical minimum value of 2.53 is reported for FOMB-4. Most of the values range in between 2 and 3; the highest value of Rb 4.53 is reported for FOSB-13 and the marked variation in the bifurcation ratio is due to difference in geological and structural characteristics of rock, relief and stages of basin development (Schumm 1956; Bridge 1993; Pittaluga et al. 2003; Burge 2006). Mean Rb of 3.49 indicates that this value fall well within the normal range and geological structures have not distorted the drainage pattern (Horton 1945; Gopalakrishnan et al. 1997; Federici and Paola 2003). The FOMB-13 with Rb value of 4.53 indicates that this micro basin suffered structural disturbances (Nautiyal 1994). As most of the FOMBs have Rb value ranging between 2 and 5, these microbasins can be considered to posses well-developed drainage network (Strahler 1957).

The channel morphology of the sub-basin namely, the cross section, width-depth ratio, bankfull depth, channel width, entrenchment ratio and bank height ratio were studied for 19 locations. The bank height ratio indicates the prevalence of moderately unstable conditions at 11 locations and remaining 8 locations with stable condition.

The spatial map of 'SL' index has shown that major part of the sub-basin falls in class 1 followed by class 2 and 3 respectively. The class 1 with high SL values reflects hard rock or high tectonic activity, whereas the class 3 with low SL value indicates relatively low resistance or low tectonic activity (Hack 1973; Keller and Pinter 2002). In order to assess the effect of lithology, relative rock resistance map was prepared based on rock types (Fig. 8). It is inferred from this figure that the class 1 SL values are observed in high resistance rocks namely, quartz vein, garnetiferous Quartzo felspathic gneiss, granite, granite gneiss and pink migmatite. The class 3 SL index is noticed in the middle southern part of the basin comprising limestone and conglomerate. Longitudinal river profiles for the selected micro basins and Thoppaiyar sub-basin were plotted along with SL values (Fig. 9). The highest value of index was observed in the upper reach of (6,000–14,000 m) the Thoppaiyar sub-basin. This anomaly could be considered as tectonically significant zone (Hamdouni et al. 2008).

The 'Af' values for 14 micro basins show that almost all micro basins are asymmetric in nature. It is observed that micro basins located along the right bank of main channel show high 'Af' value than those located along the left bank. The absolute Af calculated for the 14 FOMBs range from 0.84 to 27.49. The FOMBs 3,

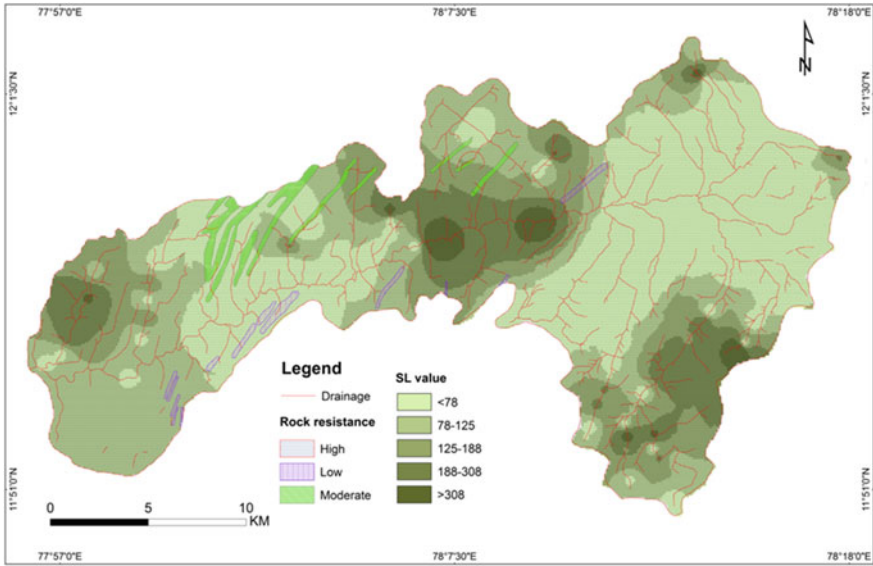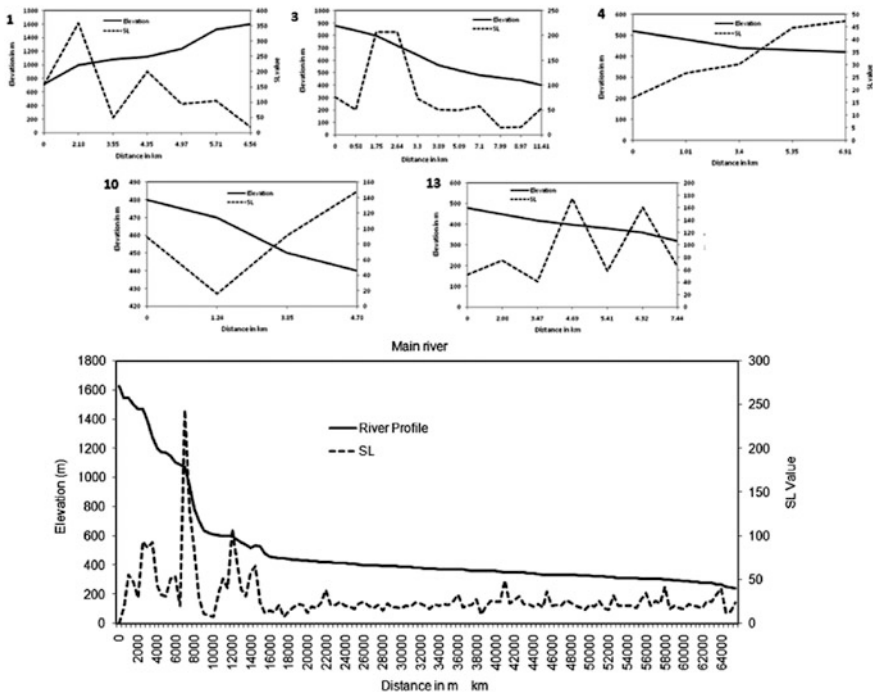**Fig. 8** Rock resistances with SL index of Thoppaiyar sub-basin

Fig. 9 Longitudinal river profiles and the measured SL index of selected micro-basins (*1*, *3*, *4*, *10*, *13*) in Thoppaiyar sub-basin

9, 11, 12 and 13 show high absolute of values and are indicative of relatively higher tectonic activity (Hamdouni et al. 2008).

The 'Hi' range from 0.11 to 0.81 and are categorized into three classes with respect to the convexity or concavity of the curves. A 'Hi' value of >0.6 indicate youthful stage, a range of 0.352−0.6 area indicative of mature stage, and 'Hi' below <0.35 characterize old stage of landscape (Strahler 1952). The higher values of 'Hi' are possibly related to young, active tectonics and the lower values of 'Hi' are indicative of the presence of older landscapes that have undergone greater erosion and less impacted by recent tectonic activities (Hamdouni et al. 2008). The hypsometric integral value of 50 % the basin area of the Thoppaiyar indicates mature stage of the watershed. The 'Hi' and hypsometric curve could be used for conceptual geomorphic models of landscape evolution. In this study, the hypsometric curves and hypsometric integral are interpreted in terms of degree of basin dissection and relative landform age. Convex up curves with high integrals are typical for youth, undissected (disequilibrium stage) landscapes; smooth, s-shaped curves crossing the center of the diagram characterize mature (equilibrium stage) landscape and concave up with low integrals typically old and deeply dissected landscapes. Accordingly, their distribution within the study area is depicted in the Fig. 10.

The "V" shaped valleys show lower 'Vf' values while higher values are associated with 'U' shaped valleys. Since the uplift is associated with incisions, were low values of 'Vf' are associated with higher rate of uplift and incisions, usually deep V shaped valleys (Vf<1) are connected with linear active down cutting streams, distinctive of zones subjected to active uplift. However, the flat and U shaped valleys (Vf>1) show an attainment of the base level of erosion, mainly in response to relative tectonic quiescence. The 'Bs' values indicate that half of the micro-basins were categorized under class 1 and 2, which indicate that the micro-basins are elongated as well as circular equally. The micro basins with elongated shape become progressively more circular with time and continued topographic evolution (Bull and McFadden 1977).

The 'T' value in the micro basin ranges from 0.01 to 0.9 which indicates that most of the micro basins are asymmetric in nature, which in turn indicates the role of regional dynamic activities. The class 1 and class 2 mostly indicate asymmetry nature of the sub-basin. In case of a negligible influence by the bedrock tilting on the relocation of the stream channels, the direction of the regional migration is an indicator of the ground tilting. The analysis of number of micro basins in a basin results in multiple spatially distributed T vectors, which, when averaged, define the irregular zones of the basin asymmetry.

Several workers (Bull and McFadden 1977; Silva et al. 2003; Hamdouni et al. 2008) have attempted combining two or more indices to extract semi-quantitative information regarding the relative tectonic activity in Active Mountain ranges. Following their precedence, in the present context, an attempt was made to evaluate the index of relative tectonic activity (Irat) in the micro-basins using various geomorphic indices namely, SL, Af, Hi, Vf, Bs and T. Based on the value of each geomorphic index and their relationship with the tectonic activity, the indices were
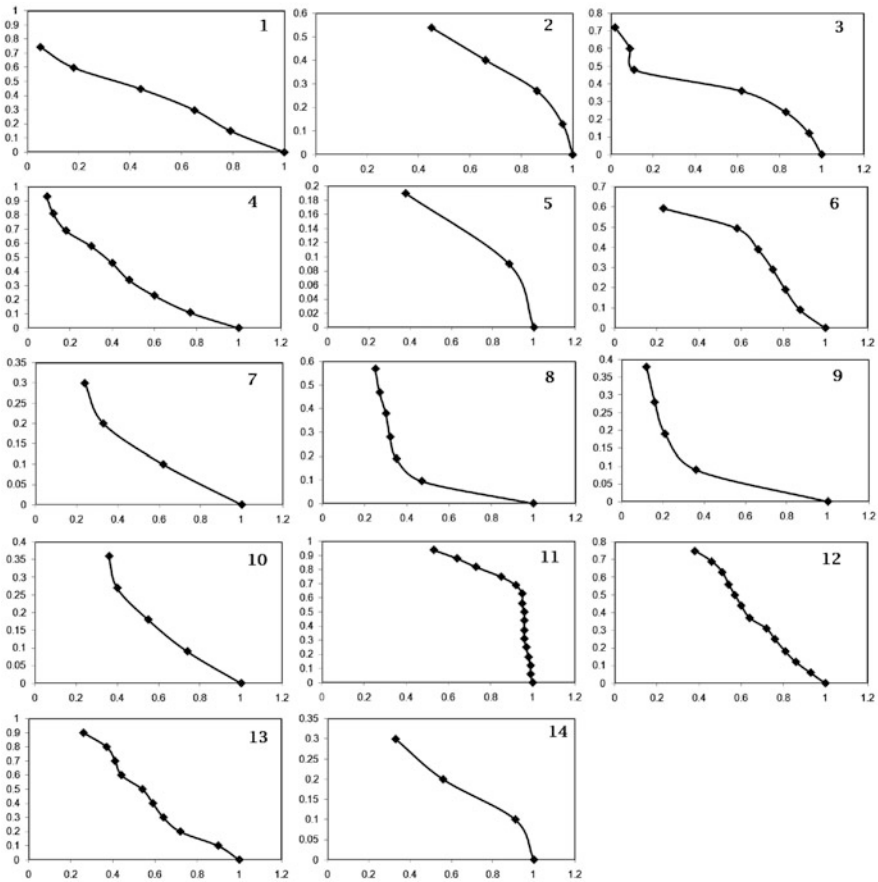
Fig. 10 Different types of hypsometric curves: downward convex curves with high Hi value and upward concave curves with low Hi values

divided into three classes; class 1 with higher geomorphic index, class 2 with moderate index, and class 3 with a lower index. The 'Irat' classes obtained by the average of different classes of geomorphic indices and again classified into three classes; class 1 high relative tectonic activity with values of Sn < 2; class 2 moderate relative tectonic activity with Sn > 2 to < 2.5; and class 3 low relative tectonic activity with values of Sn ≥ 2.5. Table 3 shows these three classes of geomorphic indices and 'Irat' classes of selected 14 micro-basins in the study area. From the table, it follows that majority of the micro basins are classified under low relative tectonic activity zones and only three micro-basins (1, 2, and 3) are in moderate category.

Table 3 Index of relative tectonic activity classes (Irat) in the selected micro-basins of the Thoppaiyar sub-basin

Micro basin	SL	Af	Hi	Vf	Bs	T	Sn	Irat	Category
1	2	3	2	1	3	1	2.2	2	Moderate
2	2	3	3	1	2	1	2.3	2	Moderate
3	3	2	2	1	1	1	2.2	2	Moderate
4	3	3	1	2	2	1	2.7	3	Low
5	2	3	3	2	3	3	3.5	3	Low
6	3	3	3	1	1	1	3.0	3	Low
7	3	3	3	1	3	1	3.5	3	Low
8	3	3	3	1	3	1	3.7	3	Low
9	2	1	3	1	3	2	3.5	3	Low
10	2	3	3	1	2	1	3.7	3	Low
11	2	2	1	2	3	1	3.7	3	Low
12	3	1	2	2	1	1	3.7	3	Low
13	3	2	1	3	1	1	4.0	3	Low
14	2	3	3	1	3	1	4.5	3	Low

SL stream length gradient index, *Af* asymmetric factor, *Hi* hypsometric integral, *Vf* valley floor width to depth ratio, *Bs* basin shape index, *T* topographic symmetry, *Sn* semi-quantitative information and Irat-Index of relative tectonic activity

8 Conclusions

The study of fluvial geomorphology provides information on the behavior of river and the influence of geology and structure on channel morphology. The analysis has shown that the majority of the micro basins currently experience low relative tectonic activity and only three micro-basins (FOMBs 1, 2, and 3) experience moderate tectonic activity. In the western, central and southern parts of the basin, SL values indicate variation of stream length gradient index, whereas in the eastern and down central part show low SL index. High SL values are associated with resistant rock formations such as quartz veins, garnetiferous quartzo felspathic gneiss, granite, granitoid gneiss and pink migmatite. The low SL values are found in limestone and conglomerate. Hypsometric integral low values in the sub-basin observed in the headward region and near the mouth, whereas high 'Hi' values are noticed in the middle part of the river basin, i.e., in the mountainous terrain. The majority of the FOMBs in the sub-basin show low 'Bs' values and indicate elongated shape. 'Vf' values of the micro basins range from 0.5 to 43 and the high 'Vf' were observed near the mouth. The class 1 and class 2 of 'T' mostly indicate the asymmetric nature of micro basins. Most of the fourth order micro-basins in the Thoppaiyar sub-basin are categorized under low index of relative tectonic activity. It is also brought out by the present study that, despite being a medium sized sub-basin located in a more or less homogenous climatic condition (within the studied basin area), prevalence of differential controls exercised by tectonic and lithological

characteristics with reference to FOMBs has been brought to light with the help of remote sensing and GIS techniques. Implications of this result is that, while designing water and other natural resource management programs, the variations at micro-basin scale need to be taken into consideration, failing which, the management programs may not yield desired results.

References

Anbazhagan S, Saranathan E (1991) Hydrogeomorphological mapping in northern part of Salem dt, Tamil Nadu. J Indian Geogr Soc 66–1:65–68

Allen JRL (1968) Current ripples. North Holland, Amsterdam, p 433

Azor A, Keller EA, Yeats RS (2002) Geomorphic indicators of active fold growth: south mountain-oak ridge ventura basin, southern California. Geol Soc Am Bull 114:745–753

Baker VR (1986) Introduction: regional landforms analysis. In: Short NM, Blair RW (eds) Geomorphology from space: a global overview of regional landforms. NASA, Washington, pp 1–26

Bagha N, Arian M, Ghorashi M, Pourkermani M, Hamdouni RE, Solgi A (2014) Evaluation of relative tectonic activity in the Tehran basin, central Alborz, northern Iran. Geomorphology 213:66–87

Brookfield ME (1998) The evolution of the great river systems of southern Asia during the Cenozoic India-Asia collision: rivers draining southwards. Geomorphology 22:285–312

Bridge JS (1993) The interaction between channel geometry, water flow, sediment transport and deposition in braided rivers. In: Best JL, Bristows C (eds) Braided rivers: from process and economic applications. Geological Society Special Publication 75, Bath, pp13-71

Bull WB, McFadden LD (1977) Tectonic geomorphology north and south of the Garlock fault, California. In: Doehring, DO (ed) Geomorphology in arid regions. Proceedings of the eighth annual geomorphology symposium. State University of New York, Binghamton, pp 115−138

Burge LM (2006). Stability, morphology and surface grain size patterns of channel bifurcation in gravel–cobble bedded anabranching rivers. Earth Surf Process Land 31(10):1211–1226

Burbank DW, Anderson RS (2000) Tectonic geomorphology. Blackwell, Oxford, p 274

Chen Y, Sung Q, Cheng K (2003) Along-strike variations of Morphometric features in the western foothills of Taiwan: tectonic implications based on stream gradient and hypsometric analysis. Geomorphology 56:109–137

Cox RT, Van Arsdale RB, Harris JB (2001) Identification of possible Quaternary deformation in the northeastern Mississippi Embayment using quantitative geomorphic analysis of drainage-basin asymmetry. Geol Soc Am Bull 113:615–624

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 Mississippi embayment. Geol Soc Am Bull 106:571–581

Dutta N, Sarma JN (2013) Morphotectonic analysis of Sonai river basin, Assam, NEIndia. Glob Res Anal 2(2):114–115

Elliot T (1976) The morphology, magnitude and regimen of a carboniferous fluvial distributary channel. J Sedim Petrol 46:70–76

Easterbrook DJ (1999) Surface processes and landforms, 2nd edn. Prentice Hall, New Jersey

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

Federici B, Paola C (2003) Dynamics of channel bifurcations in noncohesive sediments. Water Resour Res 39(6):271–284

Font M, Amorese D, Lagarde JL (2010) DEM and GIS analysis of the stream gradient index to evaluate effects of tectonics: the Normandy intra plate area (NW France). Geomorphology 119:172–180

Gerson R, Grossman G, Bowman D (1984) Stages in the creation of a large rift valley – geomorphic evolution along the southern Dead Sea Rift. In Morisawa M, Hack TJ (eds) Tectonic Geomorphology. State university of New York, Binghamton, pp 53–73

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

Gopalakrishnan KS, Sakthivel M, Sunilkumar R (1997) Geomorphometric study of the Kodayar river basin in Western Ghat regions of Kanyakumari district, Tamil Nadu. Natl Geogr J India 43(4):295–306

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

Hamdouni RE, Irigaray C, Fernandez T, Chacon J, Keller EA (2008) Assessment of relative active tectonics, southwest boarder of Sierra Nevada (southern Spain). Geomorphology 96:150–173

Harbor D, Gunnell Y (2007) Along-strike escarpment heterogeneity of the Western Ghats: a synthesis of drainage and topography using digital morphometric tools. J Geol Soc India 70:411–426

Hare PW, Gardner TW (1985) Geomorphic indicators of vertical neotectonism along converging plate margins, Nicoya Peninsula, Costa Rica. In: Morisawa M, Hack JT (eds). Tectonic Geomorphology. Proceedings of the 15th annual Binghamton geomorphology symposium. Allen and Unwin, Boston, pp 123−134

Horton Robert E (1932) Drainage basin characteristics. Trans Am Geophys Union 13:350–361

Horton RE (1945) Erosional development of streams and their drainage basins. Bull Geol Soc Am 56:275–370

Hurtgen J, Rudersdorf A, Grutzner C, Reicherter K (2013) Morphotectonics of the Padul-Nigüelas Fault Zone, southern Spain. Ann Geophys, 56(6). doi:10.4401/ag-6208

Howard AD (1967) Drainage analysis in geologic interpretation: a summation, bulletin of american association of petroleum geology, 21:2246−2259. http://srtm.usgs.gov/data/

Jackson RG (1979) Preliminary evaluation of lithofacies models for meandering alluvial streams In: Miall AD (ed) Fluvial sedimentology. Canadian society of petroleum and geological memoir, 5:543−576

Jordan G (2003) Morphometric analysis and tectonic interpretation of digital terrain data: a case study. Earth Surf Proc Land 28:807–822

Joji VS, Nair ASK (2013) Terrain characteristics and longitudinal, land use and land cover profiles behavior—a case study from Vamanapuram River basin, southern kerala. Indian Arab j geosci. doi:10.1007/s12517-012-0815-z

Kale VS, Senguptab S, Achyuthanc H, Jaiswal MK (2013) Tectonic controls upon Kaveri river drainage, cratonic peninsular India: inferences from longitudinal profiles, morphotectonic indices, hanging valleys and fluvial records. Geomorphology. doi:10.1016/j.geomorph.2013.07.027

Keller EA (1986) Investigation of active tectonics: use of surficial earth processes. In: Wallace RE (ed) Active tectonics, studies in geophysics. National Academy Press, Washington DC, pp 136–147

Keller EA, Pinter N (2002) Active tectonics: earthquakes uplift and landscape. Prentice Hall, New Jersey, p 362

Korup O, Schmidt J, Mcsaveney MJ (2005) Regional relief characteristics and denudation pattern of the western southern Alps, New Zealand. Geomorphology 71:402–423

Koukouvelas IK (1998) The Egion Fault: earthquake related and long term deformation, Gulf of Corinth. Greece. J Geodyn 26(2–4):501–513

Leopold LB, Wolman MG, Miller JB (1964) Fluvial processes in geomorphology. W. H. Freeman, San Francisco

Malik JN, Mohanty C (2007) Active tectonic influence on the evolution of drainage an landscape: geomorphic signatures from frontal and hinterland areas along the northwestern Himalaya, India. J Asian Earth Sci 29:604–618

Mahmood SA, Gloaguen R (2012) Appraisal of active tectonics in HinduKush: insights from DEM derived geomorphic indices and drainage analysis. Geosci Front 3(4):407−428 (July 2012)

Meyer L (1990) Introduction to quantitative geomophology. Prentice-Hall, Englewood Cliffs, NJ,p 380

Markose VJ, Dinesh AC, Jayappa KS (2013) Quantitative analysis of morphometric parameters of Kali River basin, southern India, using bearing azimuth and drainage (bAd) calculator and GIS. Envir Earth Sci 70(2):839–848

Maryam E, Maryam AA (2013) Active tectonic analysis of Atrak river subbasin located in NE Iran (East Alborz). J Tethys 1(3):177–188

Moody-Stuart M (1966) High and low sinuosity streams deposits with examples from the Devonian of Spitsbergen. J Sedim Petrol 36:1110–1117

Morisawa Marie (1958) Measurement of drainage-basin outline form. J Geol 66:587–591

Nautiyal MD (1994) Morphometric analysis of a drainage basin using aerial photographs: a case study of Khairakulli Basin, Dehradun, Uttar Pradesh. J Indian Soc Remote Sens 22(4):251−261

Perez-Pena JV, Azor A, Azanon JM, Keller EA (2010) Active tectonics in the Sierra Nevada (Betic Cordillera, SE Spain): insights from geomorphic indexes and drainage pattern analysis. Geomorphology 119:74–87

Peters G, van Balen RT (2007) Tectonic geomorphology of the Upper Rhine Graben, Germany. Glob Planet Chang 58:310–334

Pedera A, Perez-Pena JV, Galindo-Zaldívar J, Azanon JM, Azor A (2009) Testing the sensitivity of geomorphic indices in areas of low-rate active folding (eastern Betic Cordillera, Spain). Geomorphology 105:218–231

Pike RJ, Wilson SE (1971) Elevation-relief ratio, hypsometric integral and geomorphic area altitude analysis. Geol Soc Am Bul 82:1079–1084

Pittaluga M, Repetto R, Tubino M (2003). Channel bifurcation in braided rivers: equilibrium configurations and stability. Water Resour Res 39:1046

Ramasamy SM, Kumanan CJ, Selvakumar R, Saravanavel J (2011) Remote sensing revealed drainage anomalies and related tectonics of South India. Tectonophysics 501:41–51

Ramirez-Herrera MT (1998) Geomorphic assessment of active tectonics in the Acambay graben, Mexican volcanic belt. Earth Surf Proc Land 23:317–332

Rebai N, Achour H, Chaabouni R, Bou KR, Bouaziz S (2013) DEM and GIS analysis of sub-watersheds to evaluate relative tectonic activity. a case study of the north–south axis (Central Tunisia). Earth Sci Inf 6(4):187−198. ISSN: 1865-0473 doi:10.1007/s12145-013-0121-7Springer Berlin Heidelberg, Berlin/Heidelberg (December 2013)

Rosgen DL (1994) A classification of natural rivers. Catena 22:169–199

Rosgen DL, Silvey HL (1996) Applied river morphology. Wildland Hydrology Books, Pagosa Springs, CO

Saberi MR, Pourkermani M, Nadimi A, Ghorashi M, Asadi A (2014) Geomorphic Assessment of Active Tectonics in Tozlogol Basin, Sanandaj-Sirjan Zone, Iran. Curr Trends Technol Sci 3 (3):146–154

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

Schumm SA (1986) Alluvial river response to active tectonics. In: Active tectonics, studies in geophysics. National Academy Press, Washington, pp 80–94

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

Silva PG, Goy JL, Zazo C, Bardaji T (2003) Fault generated mountain fronts in Southeast Spain: geomorphologic assessment of tectonic and earthquake activity. Geomorphology 50:203–226

Strahler AN (1952) Hypsometric (area–altitude) analysis of erosional topography. Geol Soc Am Bull 63:1117–1142

Strahler AN (1957) Quantitative analysis of watershed geomorphology. Trans Am Geophys Union 38:913–920

Thornbury WD (1954) Principles of geomorphology. Wiley, London 29

Tarolli P (2014) High-resolution topography for understanding earthsurface processes: opportunities and challenges. Geomorphology 216:295–312

Wells SG, Bullard TF, Menges CM, Drake PG, Karas PA, Kelson KI, Ritter JB, Wesling JR (1988) Regional variations in tectonic geomorphology along a segmented convergent plate boundary, Pacific coast of Costa Rica. Geomorphology 1:239–365

Zuchiewicz W (1988) Quaternary tectonics of the Outer West Carpathians, Poland. Tectonophysics 297:121–132