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River Profile Modeling and Fluvial Geomorphological Evaluation of Thoppaiyar Sub-Basin Using Geoinformatics Technology

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Abstract: *The curvature of river profiles has long been taken to be a fundamental indicator of the underlying processes governing fluvial erosion and thereby of landscape evolution. Longitudinal profile is a graph of distance verses elevation is an x-y plot showing bed elevation as a function of downstream distance. Due to the plate movement is considerably slow, the human history record is too short to register landscape change for such a long time scale. In the present study, an attempt has been made the quantitative analysis of geomorphic indices coupled with some mathematical models for the Thoppaiyar sub-basin and its 16 micro-basins, including the gradient index (SL), normalized gradient index (SL/k), Profile complexity index (PCI) and slope–area relationship (Slr). Based on quantitative results of these geomorphology indices, this study suggests that the important factor influencing landscape of the Thoppaiyar sub-basin. Topographic map, IRS P6 LISS III satellite data, 10m contour interval, SRTM data and ArcGIS 9.3 software were utilized. The contour lines of topographic maps of the main river and 14 micro basins are digitized as control points. Models of the longitudinal profiles using simple mathematical functions were made considering four functions for describing the form of longitudinal profiles. The abnormally high SL and SL/k values indicated that a decreasing trend from lower to mid-stream areas and the result of slope–area relationship also indicated that the regression line of the upper and lower steam exhibit an obvious right-shift could be explained by geodynamic models of active deformation in Thoppaiyar sub-basin.*

Keywords: *River profile, gradient index, mid-stream, fluvial geomorphology, thoppaiyar*

1. Introduction

Longitudinal river profile can display watershed landscape characteristics (Lee and Tsai, 2010). Drainage network has geometric properties that can be quantitatively described (Leopold et al., 1964). Analysis of the river morphologies from longitudinal profiles of bedrock rivers (e.g., rivers of the study area) has been widely used to determine incision and uplift rates in tectonically active landscapes (Snyder et al. 2000; Kirby and Whipple 2001; Kirby et al. 2003; Schoenbohm et al. 2004; Whipple 2004; Clark et al. 2005; Harkins et al. 2007).

This quantitative relationship has been widely applied for channels in steady-state condition with a balance between incision and uplift (Lague and Davy 2003). For tectonically active landscapes, i.e., landscapes adjusting to changes in tectonic forcing (cf., Safran et al. 2005; Stock et al. 2005), base-level fall (Anderson et al. 2006; Berlin and Anderson 2007), climate change, and drainage reorganization (Clark et al. 2004), a systematic exploitation of the above indices can extract valuable information for transient rivers. Depending on retreat rate, knick points (sharp change in channel slope if river) may be preserved in present day longitudinal river profiles, providing information on past uplift events (Jakica et al., 2011, Quigley et al., 2010, and Flament et al., 2014). The geomorphic indices are important indicators capable of decoding landform responses to active deformation processes and have been widely used as a reconnaissance tool to differentiate zones deformed by active tectonics (Keller and Pinter, 2002; Chen et al., 2003).The stream gradient index proposed by Hack (1973) allows the identification of anomalies in the longitudinal profile of a river. In mountain ranges, recent and active tectonics can be viewed as the main factor contributing to rock uplift, their present-day topography being the result of the competition between tectonic and erosional processes (Andermann and Gloaguen, 2009; Perez- Pena et al., 2009; Guedes, 2008; Fujita, 2009), tectonic activity (Etchebehere, 2000).

Many researches in previous decades employed numerical modeling to characterize longitudinal river profiles and quantitatively used geomorphic indices to evaluate landscape evolution (Keller and Pinter 1996; Douglas and Robert 2001). Regression including factors linear, exponential, logarithmic and power, and the quantifying approximation relationship between internal and river longitudinal profile can be established. Long profile anomalies have been quantified using the SL/k index. Also, it is important to recognize that within the fluvial slope-area scaling regime, knickpoints may separate channel reaches with distinct steepness and concavity indices, depending on the spatial distribution of substrate properties, spatial and temporal rock uplift and climatic patterns, and transitions from bedrock to

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alluvial channel types (VanLaningham 2003, Wobus et al. 2003). Still, given the present uncertainty, landscape evolution models (Tucker & Bras 1998) and Roe et al. (2002) that use fluvial process in tectonically active regions, the bedrock channel network dictates critical relationships among relief and elevation, (Howard et al., 1994). Consequently, analysis of the longitudinal profiles of channels provides a promising avenue of exploration of these relationships (Hack, 1957), and much recent research has focused on the quantitative description of bedrock channel forms and processes. For both the basin-wide and main-channel slope-area data sets, the technique of averaging the slopes in logarithmic bins of drainage area was used, similar to other studies (Tarboton et al., 1991; Montgomery and Foufoula-Georgiou, 1993).

2. Study area

Thoppaiyar sub-basin located in Dharmapuri and Salem districts respectively northern and southern part of the basin and the river act as boundary for both districts (Fig.1). The sub basin area is bounded between northern latitudes 11°51′47″ - 11°59′56″ and eastern longitudes 77°53′5″ - 78°18′2″. The highest elevation in the sub-basin is 1600m above mean sea level (amsl) in upstream at near muluvi and lowest elevation 240m amsl in downstream at vellar. The area is well connected by north-south NH-7 National highways and railway line. The total aerial coverage of the sub basin is 462 Sq.km. The average annual rainfall of Thoppaiyar sub-basin is 708 mm. The climate in the sub-basin is generally warm. The sub-basin is mostly covered by Precambrian crystalline rocks and recent alluvium along the river course

3. Methodology

Due to the plate movement is considerably slow; the human history record is too short to register landscape change for such a long time scale. However, longitudinal river profile can display watershed landscape characteristics (Lee and Tsai, 2010). The present study, an attempt has been made the quantitative analysis of geomorphic indices coupled with some mathematical models for the Thoppiayar sub-basin and its 16 micro basins, including the gradient index (SL), normalized gradient index (SL/k) and slope–area relationship (Slr). Based on quantitative results of these geomorphology indices, this study suggests that the important factor influencing landscape typeset of the Thoppaiyar sub-basin.

The survey of India (SOI) toposheet, IRS P6 LISS III satellite data, 10m contour interval, SRTM data and ArcGIS 9.3 software were utilized. Based on the micro watershed and drainage pattern the 16 micro basins are digitized as control points. The work obtained elevation of each contour (vertical data) and distance from the source (horizontal data) to draw a longitudinal river profile (Fig.1).

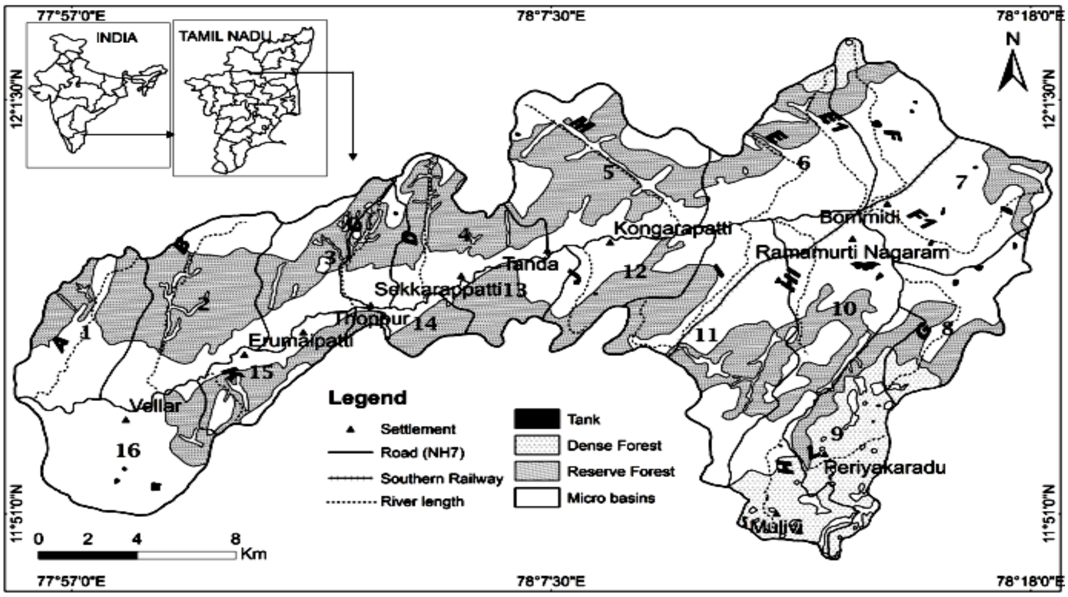


Figure 1. *Location map of Thoppaiyar sub-basin*

Many previous literatures (Snow and Slingerland 1987; Radoane et al. 2003; Chen et al. 2006) indicated that channel sediment grain size is greater and transport-limit, the long profile shows a low degree (below the tangent) of concavity, tending close to a straight line and a better linear function fit. As the transportation and deposition of channel sediment approaches dynamic equilibrium, the long profile better fits the exponential function. The balance of erosion and resistance proposed by Hack (1973), i.e. the so called ‘‘Grade profile’’, and channel sediment grain size decrease downstream, resulting in along profile better fit for the logarithmic function. Channel sediment grain size and shape are similar, and when discharge and load suspension downstream are significantly large, the long profile shows a great degree of concavity and fits better for power function. However, the four mathematic functions above show that the long profile is in strong condition, including active orogenic movement and climate change.

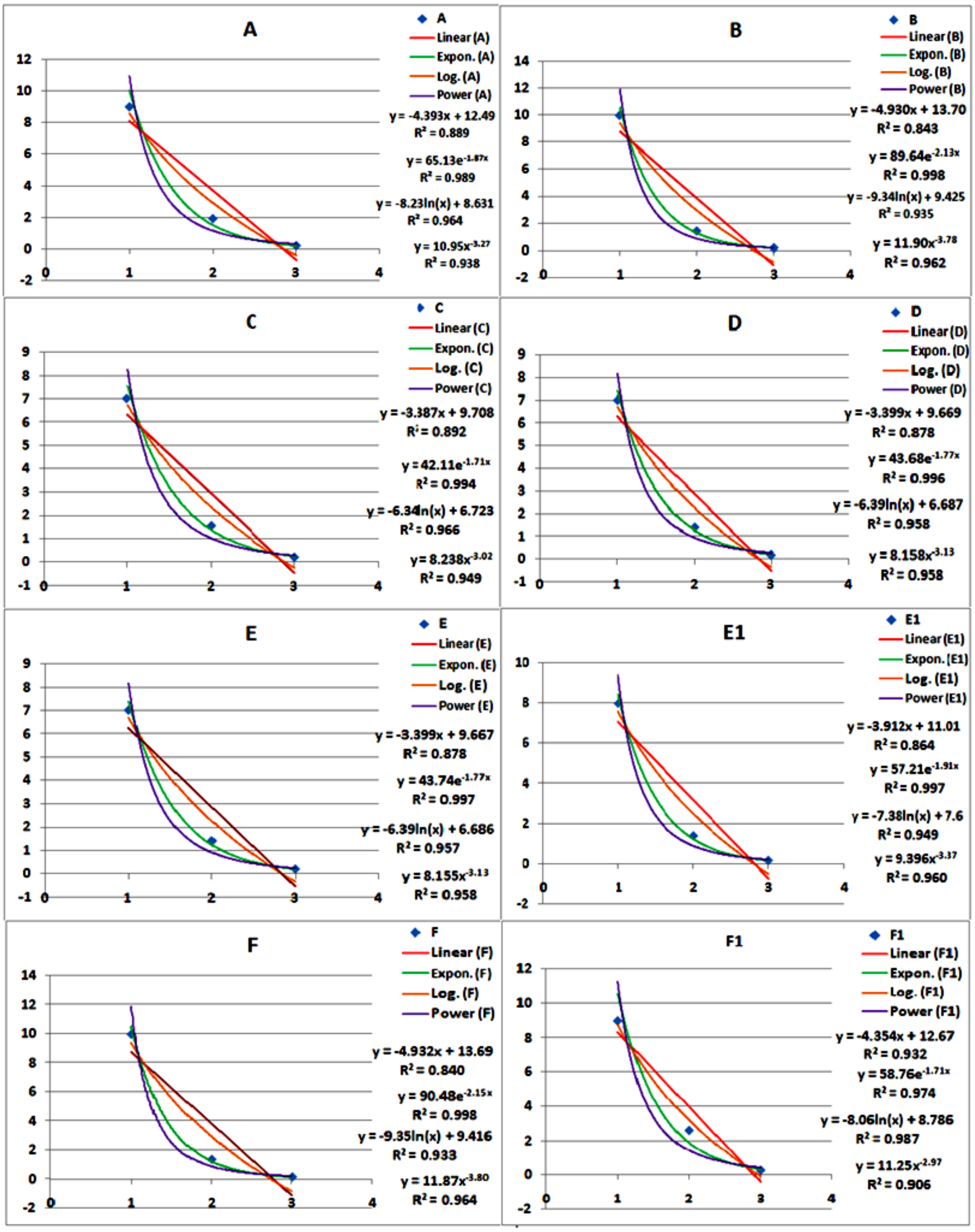
The linear function y=ax+b (1)

The exponential function y=ae^bx (2)

The logarithmic function y=a 1n x+b (3)

The power function y=ax^b (4)

Where, y is elevation (H/H0; H: elevation of each point, H0: elevation of source), x is the length of the river (L/L0; L: distance form source, L0: the total length of river), *a* and *b* are coefficients independently determined from each profile. The coefficient of determination (R^2) calculation determines the degree of fit. The number of reach (n) was observed using SRTM and drainage map of the sub-basin.



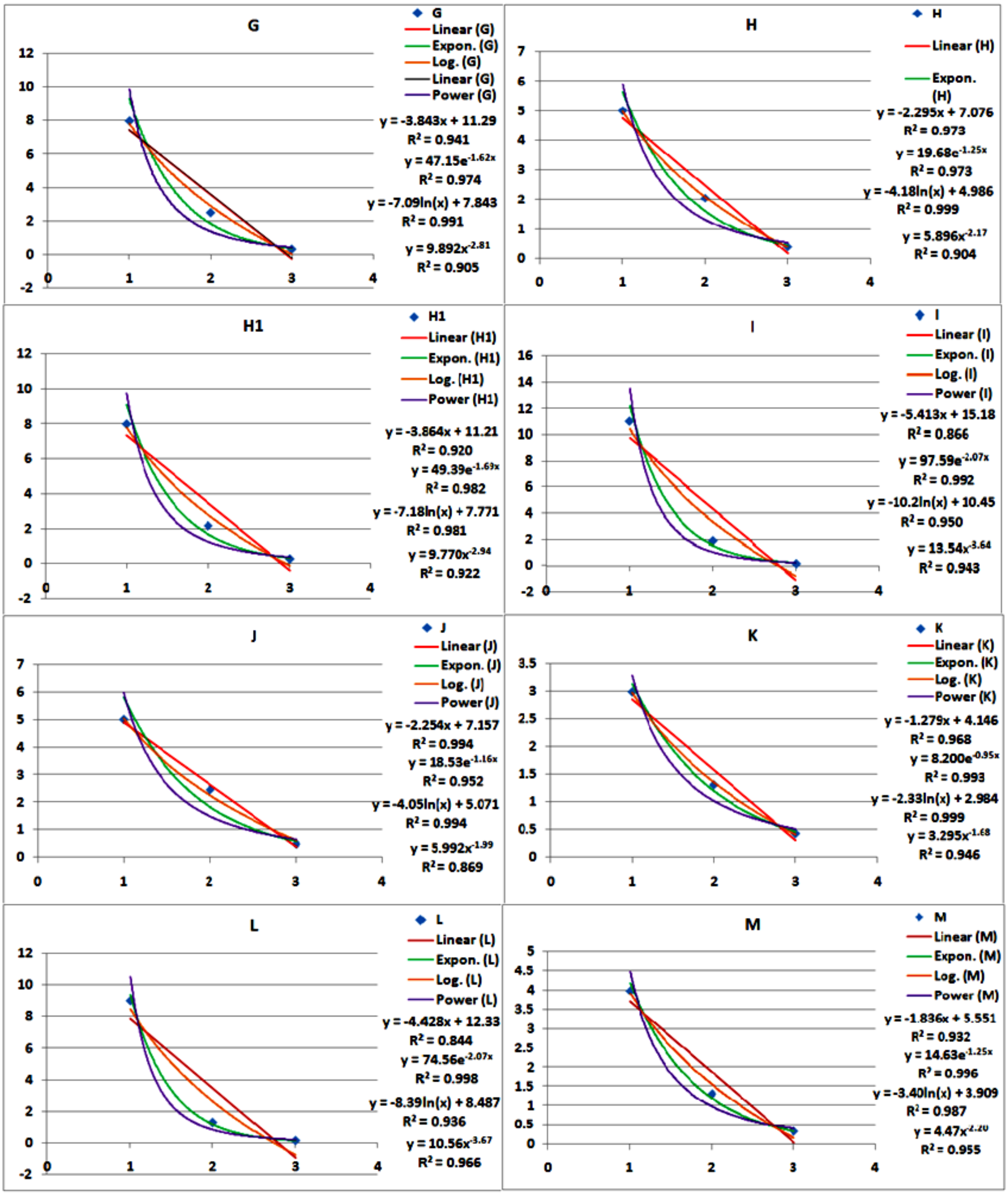


Figure 2. *Longitudinal River profiles modeling of linear, exponential, logarithmic and power function*

The evolution sequence should be linear → exponential → logarithmic. The coefficient of determination (R^2) including linear, exponential, logarithmic and power functions were calculated for 13 micro basins based on length, relief and gradient (Fig.2). The number of reach (n) was observed using SRTM and drainage map of the sub-basin (Table 1).

3.1 Stream length gradient index (SL)

Hack (1973) proposed the stream gradient index as a practical resource to determine anomalies in the natural concavity at the longitudinal profile. The index allows the normalization of the gradient values and the identification of anomalous points in each section of the river from headwaters to mouth. The stream gradient index by stretch of river is calculated by the equation:

$$SL = \frac{\Delta H}{\Delta L} . L \quad (5)$$

Where ΔH is the difference of altitude between two points in the watercourse, ΔL is the length of this stretch and L is the total length of the channel. Using equation 5 the SL values were calculated for randomly selected 12 micro basins (Table 2) based on the river length.

Table 1. *Parameters of longitudinal river profile*

River	Length (km)	Relief (km)	Gradient (°)	Coefficient of determination (R^2)				
				Linear	Exponential	Logarithmic	Power	Data(n)
A	9	1.923	0.214	0.889	0.989	0.964	0.938	63
B	10	1.388	0.139	0.843	0.988	0.935	0.962	75
C	7	1.575	0.225	0.892	0.994	0.966	0.949	54
D	7	1.411	0.202	0.878	0.996	0.958	0.958	68
E	7	1.405	0.201	0.878	0.997	0.957	0.958	71
E1	8	1.4	0.175	0.864	0.997	0.949	0.96	71
F	10	1.35	0.135	0.84	0.998	0.933	0.964	76
F1	9	2.619	0.291	0.932	0.974	0.987	0.906	76
G	8	2.5	0.313	0.941	0.974	0.991	0.905	54
H	5	2.047	0.409	0.973	0.973	0.999	0.904	106
H1	8	2.175	0.272	0.92	0.982	0.987	0.922	106
I	11	1.906	0.173	0.866	0.992	0.95	0.943	129
J	5	2.454	0.491	0.944	0.952	0.994	0.869	48
K	3	1.322	0.441	0.968	0.993	0.999	0.946	31
L	4	1.307	0.327	0.932	0.966	0.987	0.955	59
M	9	1.282	0.142	0.844	0.988	0.936	0.966	128

3.2 Normalized gradient index (SL/k)

A straight line on a semi-logarithmic plot of elevation (linear) versus distance (logarithmic) represents an equilibrium or graded long profile (Hack, 1957). This plot is hereinafter called the Hack profile. However, most natural streams do not follow a single logarithmic profile along their entire course, so it is more informative to create a curved Hack profile with the elevation and distance measures for successive reaches. By comparing the curved Hack profile to the straight line of the graded profile, under-steepened and over-steepened reaches become apparent. The SL/k index, which is sensitive to stream slope, provides a measure of the deviation of an individual reach from its graded river profile (Hack, 1973). Long profile anomalies have been quantified using the SL/k index (Table 2) (Perez-Pena et al., 2008) (where S = reach slope, L = distance from reach to source, and k = graded river gradient), the k is computed as

$$k = \frac{(h_s - h_f)}{1n(L_t)} \qquad (6)$$

Where, h_s are the river head elevation (m), h_f is the elevation of the river mouth (m) and Lt is the total length of the river (m). Because Perez-Pena et al. (2008) used the SL/k index to detect anomalies related to tectonic and lithologic features along entire river courses; k was calculated using the river mouth as the downstream point of reference. In this study, the point of interest is the downstream end of each reach rather than an arbitrary stream mouth and the formula for k was adjusted accordingly, so that the SL/k index was computed as follows:

$$\frac{SL}{k} = \frac{Sx_r\, 1n(x_r)}{(h_s - h_r)} \qquad (7)$$

Where, x_r is the distance from the stream source to the middle of the reach (km) and hr is the elevation at the mid-point of the reach (m). It is informative to display the curved Hack profile with height on the primary Y axis and a step curve of the SL/k index using a secondary Y axis, where the SL/k index value is held constant over the length of each reach to create the step-like appearance (Chen et al., 2003). The SL/k index was calculated for 12 micro basins (Table 2).

Table 2. *SL index of the Thoppaiyar sub-basin*

Distance (km)	SL	SL/k	Elevation (km)	MWS	Distance (km)	SL	SL/k	Elevation (km)	MWS
0	0.09	14	0.45	A	0	0.04	0.3	1.04	G
1.9	0.02	0.8	0.39	A	0.2	0.1	0.7	0.92	G
3.3	0.03	2	0.35	A	0.6	0.15	0.6	0.76	G
4	0.04	1.8	0.33	A	1	0.06	0.2	0.65	G
5	0.04	1.5	0.32	A	2	0.03	1.3	0.54	G
6.4	0.06	1	0.37	A	3	0.02	0.9	0.51	G
7.8	0.02	1.7	0.27	A	4.6	0.02	0.8	0.48	G
0	0.03	25	0.47	B	6.7	0.02	0.4	0.45	G
3	0.02	9	0.44	B	0	0.01	2.5	1.19	H
5.2	0.04	8	0.4	B	1.3	0.02	2.4	1.16	H
6	0.03	2	0.37	B	2.4	0.03	1.4	1.11	H
7	0.02	1	0.36	B	3	0.1	0.2	1.08	H
7.6	0.02	2	0.35	B	3.4	0.16	3	0.97	H

8.5	0.02	0.6	0.34	B
9.5	0.02	1.5	0.31	B
0	0.06	14	0.5	C
2.1	0.04	3	0.47	C
3.4	0.03	0.5	0.43	C
4.1	0.02	1	0.4	C
4.7	0.03	0.9	0.36	C
5.8	0.02	1.2	0.34	C
0	0.02	4	0.46	D
1.5	0.03	5	0.44	D
2.3	0.06	2	0.42	D
3.1	0.03	2.4	0.4	D
4.3	0.04	1.4	0.38	D
5.1	0.02	2.8	0.36	D
0	0.02	1.2	0.51	E
1	0.02	2	0.48	E
1.5	0.04	3	0.46	E
3.2	0.02	5	0.43	E
4.9	0.02	3	0.41	E
0	0.15	3	1.08	E1
1	0.02	0.6	1.03	E1
1.8	0.05	0.2	0.81	E1
2.4	0.2	0.2	0.65	E1
3.4	0.05	0.1	0.51	E1
4.8	0.04	0.9	0.45	E1
6.4	0.02	1.4	0.43	E1
4.6	0.02	0.6	0.67	H
0	0.04	1.7	1.04	H1
0.2	0.14	0.4	0.92	H1
1.7	0.06	0.7	0.76	H1
2.7	0.03	1.3	0.65	H1
4.3	0.02	2.5	0.54	H1
6.3	0.02	0.9	0.51	H1
0	0.02	0.6	0.53	I
1.8	0.02	7.6	0.52	I
2.7	0.03	17	0.48	I
5.3	0.02	27	0.45	I
9.2	0.04	9.7	0.42	I
0	0.06	0.09	1.21	L
1.5	0.07	0.1	1.17	L
2.3	0.1	0.07	1.13	L
3.5	0.02	0.6	1.09	L
0	0.07	42	0.48	M
2.3	0.04	15	0.47	M
4	0.03	8	0.46	M
4.8	0.02	3	0.4	M
6	0.03	7	0.42	M
7.7	0.01	9	0.4	M

3.3 Profile complexity index (PCI)

Profile complexity index (PCI) means the standard deviation of the SL/k index. In the present study the index were calculated for 12 micro basins for infer tectonic evolution of Thoppaiyar sub-basin (Table 3).

***Table 3**. PCI values of Thoppaiyar sub-basin*

Micro basin	PCI
A	4.76
B	8.28
C	5.25
D	1.34
E	1.42
E1	1.03
G	0.37
H	1.13
H1	0.76
I	10.05
L	0.26
M	14.25

3.4 Slope Area Relation (SAR)

In the present study, the area (A) is calculated for 50m high river reach from the upstream drainage area and the slope (S) are calculated for 5m or 10m river reach (Table 4). This study uses the logarithmic plot linear regression curve of the local channel gradient versus drainage area to find concavity (θ) values and the steepness index (ks).

Some slope–area plots of the uppermost channel were proved applicable to the Debris-Flow region (Fig. 3). The results of the determination coefficient (R^2) of linear regression were >0.5 reveal θ and ks for applicability to the Bedrock–Fluvial region in this study. Findings show that the most slope–area plots of the main river and six tributaries are applicable to the Bedrock–Fluvial region (where stream power law should apply).

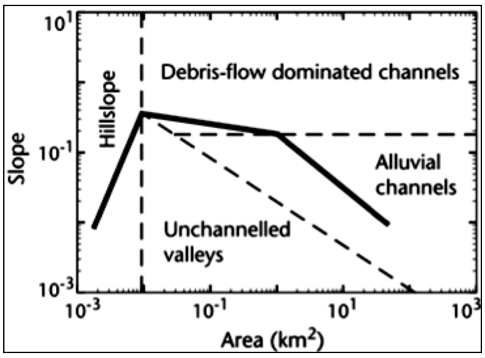


***Figure 3.** Model on slope area relationships (after Hack, 1973)*

***Table 4.** Slope Area Relation of Thoppaiyar sub-basin*

Slope	Area	MWS	Slope	Area	MWS
20	11.74	C	10	16.8	I
10	11.09	C	10	15.38	I
10	9.77	C	10	9.46	I
10	7.31	C	30	5.56	I
20	1.36	C	10	21.85	I
30	1.069	C	10	19.79	I
10	3.32	D	20	15.11	I
10	2.57	D	20	14.11	I
20	2	D	20	13.11	I
30	1.6	D	10	11.95	I
30	1.34	D	20	9.64	I

30	1.02	D	20	9.01	I
30	0.62	D	20	8.21	I
30	0.43	D	10	17.85	L
10	15.13	G	20	17.76	L
10	11.23	G	20	17.68	L
20	8.36	G	10	17.59	L
40	6.16	G	20	17.48	L
20	7.39	H	20	17.38	L
20	6.9	H	20	17.3	L
30	6.41	H	30	17.24	L
30	6.03	H	30	17.18	L
30	5.67	H	20	17.12	L
40	5.33	H	20	17.01	L
30	4.79	H	10	16.56	L
30	4.5	H	20	15.3	L
30	4.27	H	10	13.18	L
30	4.05	H	20	11.47	L
10	3.84	H	20	4.65	M
10	3.42	H	20	4.12	M
			20	3.8	M
			20	3.52	M
			20	3.18	M
			10	2.71	M
			10	24.91	M
			10	22.02	M

4. Results and Discussion

The fitting results of normalized longitudinal profiles of all tributaries indicate that the B and C are better fitted for exponential function; the four tributaries of part A fit better for linear function. The normalized longitudinal profile of the main river is better fitted for logarithmic function. Regarding all tributaries flowing into the main river to mouth, only the E1 fits better for logarithmic function similar with the main river A. All others fit better for exponential function.

4.1 Longitudinal profile with SL index

The analysis of river profile reveals that a pronounced decrease in gradient from origin to confluence (65.5km). The longitudinal profile of the Thoppaiyar sub-basin has shown as overall convexity that reflects a pronounced decrease in stream gradient. The points which the SL index exceeds the threshold coincide with the anomalies observed in the mouth and headwater segments of the longitudinal profile (Fig.4).

Anomalies detected in the upper river coincide with the convexity of the longitudinal profile. Anomalies detected in the lower river comprise one section. It located after the confluence of Thoppaiyar River. This anomaly also coincides with the convexity represented by longitudinal profile.

In this study, the geomorphic indices such as stream length gradient index (SL), normalized gradient index (SL/k), profile complexity index (PCI) and slope-area index were analyzed for fluvial characteristic of Thoppaiyar sub-basin. In order to obtain the stream length gradient index (SL) of any river profile segment, the segment must be fitted using linear regression (R^2 >0.99) in a semi-logarithmic plot that represents similar resistance bedrock.

This study also obtains the SL of a partial river profile between SL values and river profile. Therefore, the partial river profile can obtain from SL value. This investigation finds two abnormally high SL in Hack's profile as follows: The first occurs in upper stream area channels, with distance from their source ranging from a few to 10km. the abnormally high SL values exhibit a decreasing trend from lower to mid-stream areas (Fig.5). Therefore, it is influenced mainly by tectonic movement not lithology.

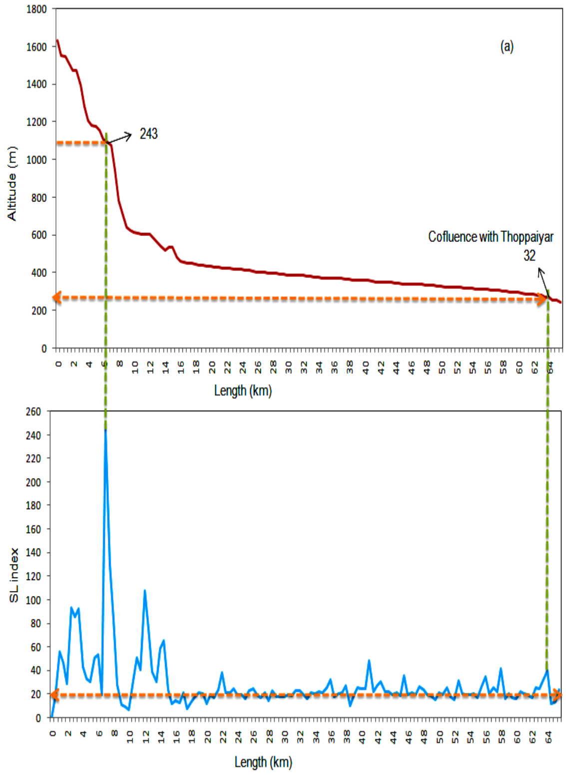


Figure 4. Longitudinal profile (a) and SL index of the Thoppaiyar (b)

Higher SL/k index values are indicative of greater stream power (Fig.6). It is also found that the abnormally high values of SL/k were affected by river and fault intersecting to form a high angle or perpendicular, where the rate of river incision was lower than the movement of the fault. The abnormally low values of SL/k were affected by river along with a fault or form a low angle, where the rate of river incision was greater than the movement of the fault.

Brardinoni et al. (2009) observed such a shift to lower ordered process domain in response to increased profile complexity index in a mountain drainage basin where a fluvial channel shifted. The profile complexity index (PCI) not studied in detail in the present study.

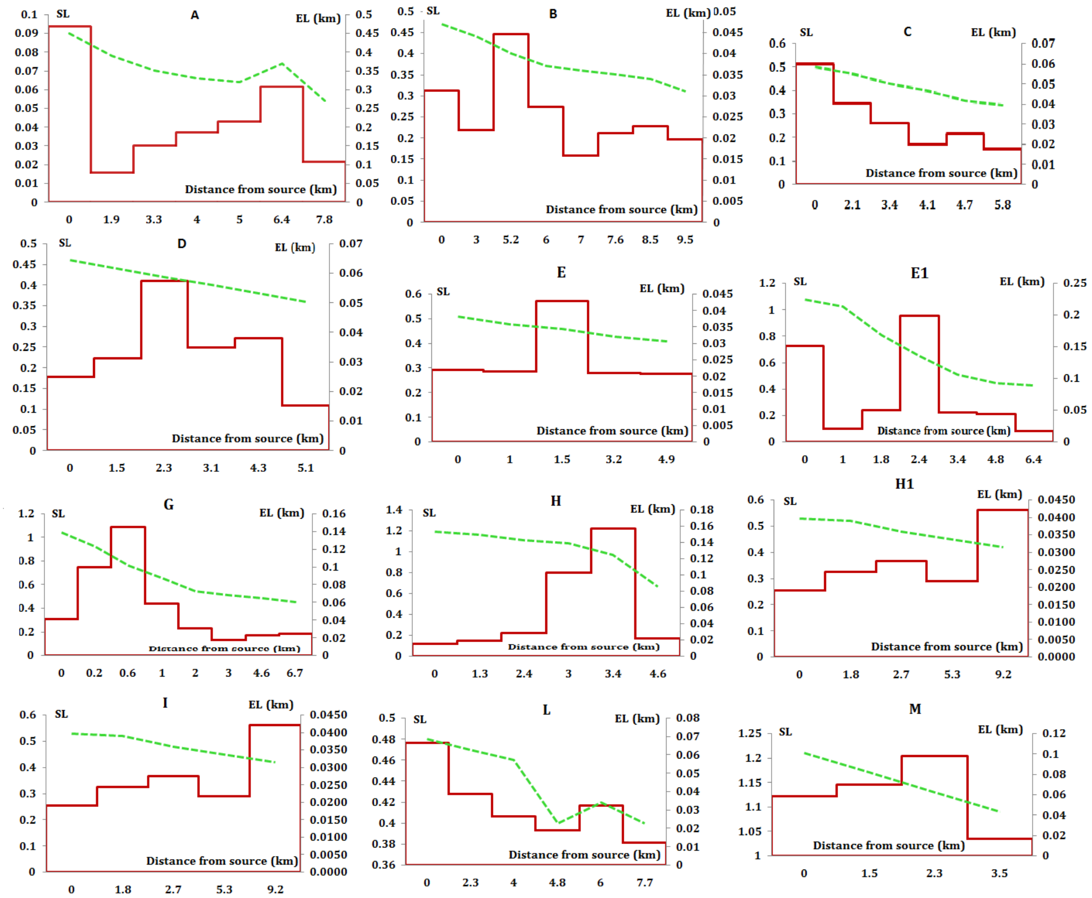


Figure5. *SL index of Thoppaiyar sub-basin*

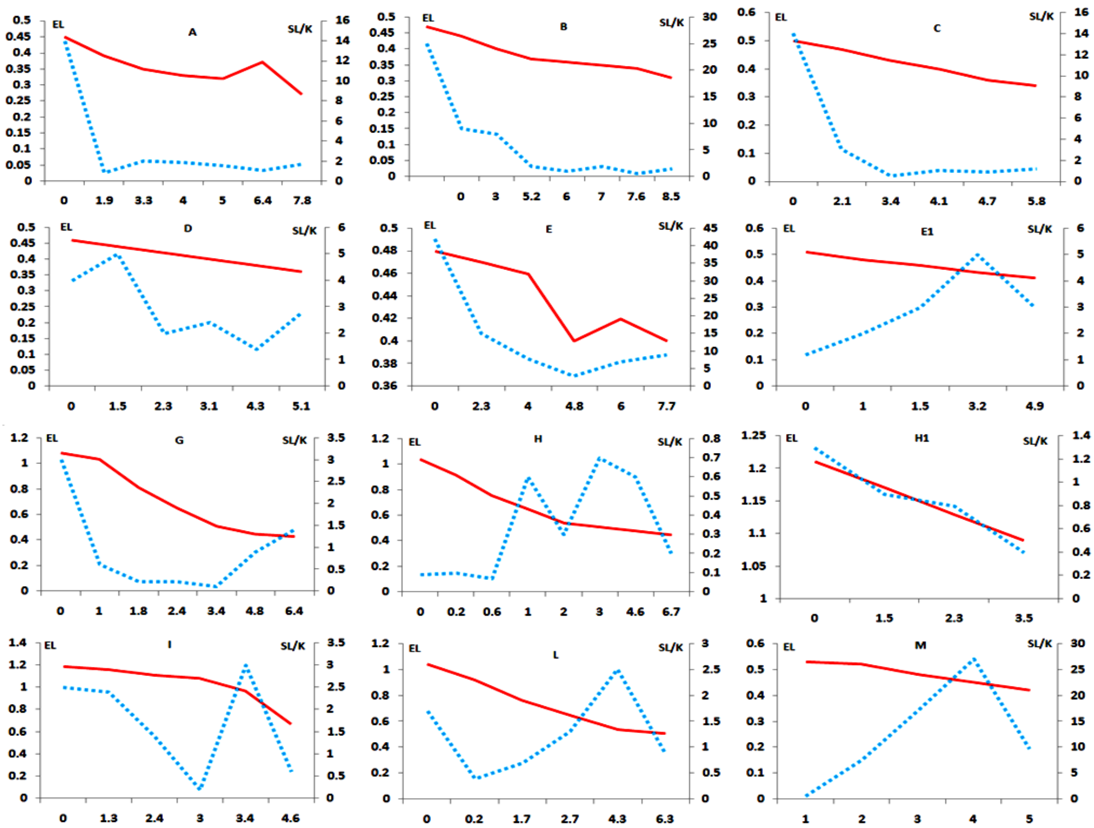


Figure 6*. Hack profiles with step SL/k index curves of Thoppaiyar sub-basin*

This study separates the scatter of slope–area relationship plots to find concavity and steepness for applicability to the Bedrock–Fluvial region. Findings indicate a scatter group of slope–area relationship plots in the uppermost stream of the ranging 0–3km from source. The area should be part of a debris-flow region. However, the scatter of slope–area relationship plots did not exist in the uppermost stream of the Thoppaiyar sub-basin. Moreover, we found a scatter group of slope–area relationship plots near the junction of the four tributaries and Main River. An interesting phenomenon surfaces on the channel above the scatter data or the channel to mouth below the scatter data. The determination coefficient (R^2) of linear regression is 0.01 to 0.81. As shown in the plots of slope–area relationship (Fig.7), regression lines of the upper- and lower stream exhibit an obvious right-shift. In other words, the slope–area plots of upper and lower-stream area of this location exhibit a similar gradient and different intercept.

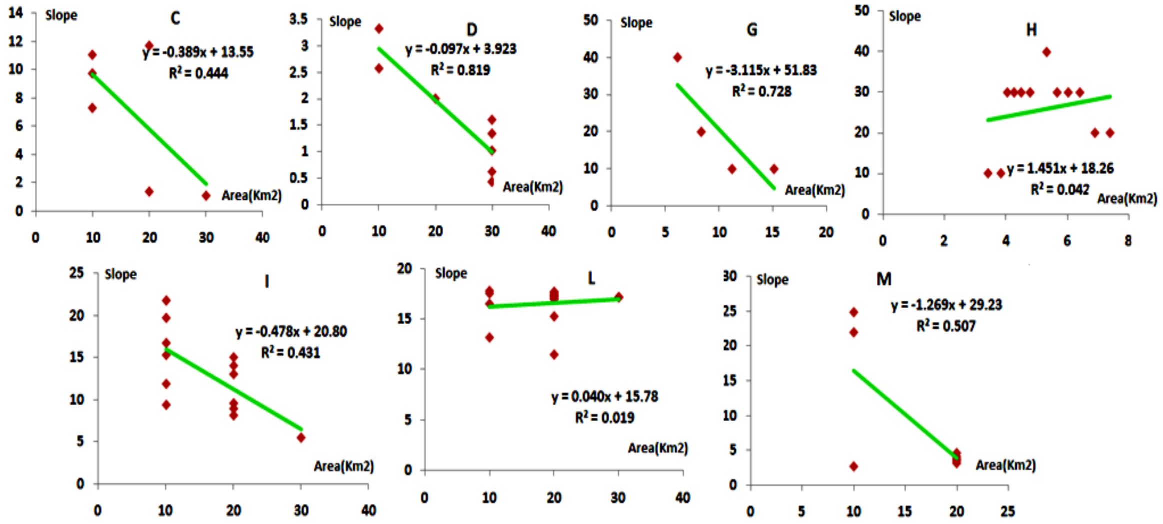


Figure 7. *Plots of slope–area relationship for selected micro basins*

5. Conclusions

The gradient index (SL) and the slope–area relationship indicated that the moderate active movement of northern middle portion of sub-basin. This study also found that the abnormally high values of SL/k were affected by river and fault intersecting to form a high angle. Hack's profile analysis (abnormally high SL and SL/k) is the most informative of the tools applied to the Thoppaiyar sub-basin. Geomorphic indices coupled with some mathematical models reveals that the better understanding of fluvial geomorphological characteristics.

The abnormally high SL and SL/k values indicated that a decreasing trend from lower to mid-stream areas and the result of slope–area relationship also indicated that the regression line of the upper and lower steam exhibit an obvious right-shift could be explained by geodynamic models of active deformation in Thoppaiyar sub-basin. This study also found that the abnormally high values of SL/k were affected by river and fault intersecting to form a high angle or perpendicular and the abnormally low values of SL/k were affected by river along with a fault or form a low angle.

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