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Tectonic Interferences in the Evolution of a Tropical River Basin, South Western Ghats, India: Evidences from Hierarchical Drainage Network Anomalies

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Abstract

Drainage networks act as surface expressions that reflect the lithologic, structural, atmospheric factors and geologic process of a terrain. The sequence of the hierarchical progressions of the drainage network development is obliterated in response to variation in these factors. In this article, we evaluate the extent of anomalies in the hierarchical organization of the Minachil River in South Western Ghats, India from hierarchical anomaly index and hierarchical anomaly density. An attempt is also made to infer the erosional status of the river basin from the denudation index. The drainage network exhibit high hierarchical anomaly indices in three tributary sub-basins and the denudation index value range from 0.28 - 0.44 tons/km^2/year. The tributary sub-basins of the Minachil River at the head part of the basin, exhibits high hierarchical anomaly index, basin asymmetry revealing the tectonic imprints in the drainage basin evolution.

Keywords: Drainage Morphometry, Hierarchical Anomaly, Tectonic Geomorphology, Rivers of Kerala, Western Ghats.

Introduction

River basins have unique geomorphologic features that have developed and evolved over a span of time in response to the interactions between matter, energy, structure, and processes (Davis, 1909). The progressive evolution of drainage system is influenced by lithology, stratigraphy and tectonic characteristics of a terrain (Miller *et al.,* 1990). In addition to this, the slope of the drainage basin and atmospheric factors plays vital roles in the development of the drainage network, which is often modified by the structural/tectonic processes operated in the drainage basin. Thus drainage network act as surface expressions of the variables influencing river dynamics and terrain evolution (Vijith *et al.,* 2016).

Drainage network develops a sequential hierarchical organization in response to the equilibrium condition exists between lithology, structure and process. The lower order streams join the higher order streams to form a perfect hierarchical sequence. Imbalances in the equilibrium state may create anomalies in the hierarchical progression of the drainage network. Diffusive processes, structural deformation and tectonics can alter the hierarchical progression of the drainage network (Avena *et al.,* 1967; Bahrami, 2013; Ghosh and Sivakumar, 2019). Drainage morphometric studies with the aid of GIS software provide precise data on the linear, aerial, and relief aspects of the drainage basin and mathematical analysis of the surface configuration of the terrain elements (Biswas *et al.,* 2014). The hierarchical geometric progression and the anomalies in the drainage network can be easily inferred from the GIS based drainage morphometric analysis which serves as inputs for tectonic geomorphologic studies.

An investigation to the hierarchical drainage network progression of the Minachil River Basin (MRB), a tropical river in the south Western Ghats (WG) is discussed in this research article. Earthquake history shows that the MRB is a seismically active zone. Earthquakes in Melukavu and Erattupetta regions of MRB occurred on December 12, 2000, and January 7, 2001 (magnitude: 4.0–4.9) and were linked to the activation of NNW-SSE and WSW-ENE lineaments, affecting the drainage course (Bhattacharya and Dattatrayam, 2002; Rastogu, 2001). Valdiya and Narayana (2007) reported the ponding of the Minachil River at Tikovil Ar and Chittar tributary sub-basins. NNE–SSW trending lineament cuts the Minachil River and its tributary stream, the Minadum Ar, in their lower reaches. Kumar *et al.* (2014) analyzed channel variations in the Minachil River and its tributaries and identified structurally controlled domains in the river basin for three different sections of the river. These zones exhibit a NNW-SSE trend and are clustered in the Pannagon (lower catchment), Pala (middle catchment), and Erattupetta (upper catchment), and are well correlated with identified faults in the river basin.

The NNW-SSE lineaments cut through the E-W trending course of the Minachil River (Rajendran *et al.,* 2009).The drainage course is changed southward near Erattupeta and that it is pushed northward before reaching Pala, suggests that its original east-west orientation has been disrupted, likely by NNW-SSE trending faults developed later in the process. It is worth noting that, the earthquakes in 2000-2001 and historical seismicity both correlate with distinct sections of these faults. These observations hint to the tectonic response of the terrain.

Although it is challenging to delineate whether drainage network anomalies are caused by exogenic geologic processes/anthropogenic interference or regional tectonics; hierarchical morphometric parameters, in conjunction with shape, asymmetric characteristics and degree of dissection of drainage basin, are essential in understanding the tectonic response of a drainage basin.

Study Area

The Minachil River having a main stream length of 78 km and drainage basin area of 1269 km^2, originates from the south-eastern part (1097m above mean sea level) of the WG. MRB is located between 9° 37' 00" to 9°52' 00" North latitudes and 76 °4' 00" to 76°56' 00" East longitudes. The river is replenished by 16 tributary sub-basins (Fig. 1). Generally, rivers originating from the WG have a relatively small drainage basin area and short flow lengths. Even in such a short course, these rivers show diverse geomorphology before joining Arabian Sea. The broad landforms include isolated hillocks at the upper region, narrow valleys, lateritic mounds and laterites at the middle region, and swamps, marshes, reclaimed lands at the lower regions. The MRB is covered with vegetation including natural forests, different types of plantations and paddy fields. The river basin experiences a tropical humid climate with temperature ranging between 19^{0}C - 35^0 C and average rainfall of 300cm per year. More than 70% of the river basin is covered with rubber plantation, followed by paddy cultivation and mixed agricultural crops such as tapioca, banana and pineapple.

The geologic studies of the MRB were carried out by several researchers. Several researchers have studied the drainage characteristics of Kalathukkadavu and Poonjar sub watersheds with the aid of GIS (Vijith and Satheesh, 2006), river sinuosity of the Pannagon River of the Minachil River (Aswathy *et al.,* 2008) and groundwater potential and quality of Koduvan sub watershed of the MRB (Rekha *et al.*, 2011). In

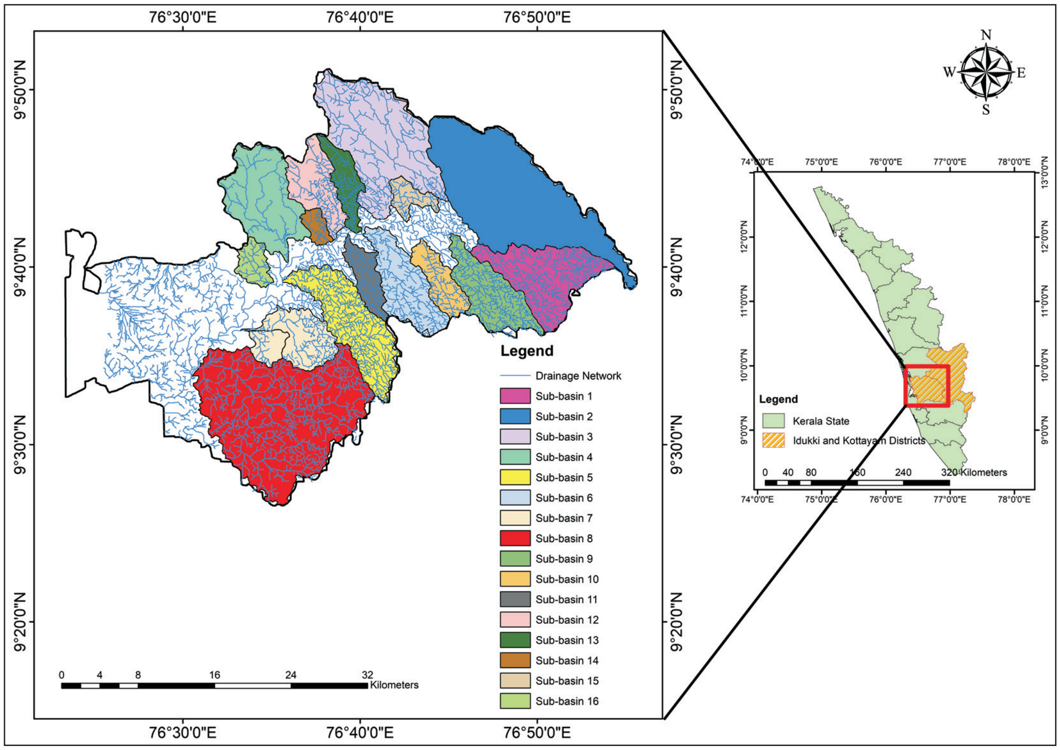


Fig.1. Location map of the study area

Table 1: Equations for determining the drainage network anomaly parameters, denudation index and drainage basin shape parameters.

Morphometric parameter	Acronym	Formula
Hierarchical anomaly for each stream junction.	($Ha_{i\rightarrow j}$)	$Ha_{i\rightarrow j} = 2^{j-2} - 2^{i-1}$, where, 'j' and 'i' are the order of recipient and tributary streams respectively.
Hierarchical anomaly number of the entire sub-basin.	(Ha_t)	$H_{at} = \sum (Ha_{i\rightarrow j} \times Ns_{i\rightarrow j})$, where ($Ha_{i\rightarrow j}$) is the sum of the hierarchical anomalies of each stream junction and ($Ns_{i\rightarrow j}$) is the number of streams of each stream junction.
Hierarchical anomaly index	(Δa)	Ha_t/N_1 is the hierarchical anomaly number of the whole basin and N_1 is the number of actual first-order streams in the sub-basin.
Hierarchical anomaly density	(g_a)	$g_a = H_{at}/A$ H_{at} is the hierarchical anomaly number of the whole basin and A is the drainage basin area.
Drainage density	(Du)	$Du = \sum Lu/A$, where Lu is the total stream length and A is the drainage basin area.
Denudation index	(log Tu)	$\text{Log Tu} = 1.44780 + 0.32619\ Du + 0.10247 \Delta a$, where Du is the drainage density and Δa is the hierarchical anomaly index.
Basin shape index	(Bs)	Bs = Bl/Bw, Bl is the length of the basin and Bw is the width of the basin
Drainage frequency	(Df)	$Df = \sum Nu/A$, where Nu is the total number of stream segments of all orders in a basin and A is the drainage basin area.
Bifurcation ratio	(R_b)	$R_b = Ni/N(i+1)$, Ni is the number of streams of 'i' order and N(i+1) is the number of streams of 'i+1' order
Bifurcation index	(R)	$R = R_b - R_{bd}$, where R_b is the Bifurcation ratio and Rbd is the direct bifurcation ratio
Asymmetry factor	(Af)	Af = (Ar/At)*100, Ar is the drainage area on the right hand side of the trunk stream and At is the total drainage area of the basin
Percent of basin asymmetry	(PAF)	PAF = (ALS/At)*100, where ALS is the area of the larger side of the trunk stream and At is the total drainage basin area

their study, the GIS analysis techniques were used to evaluate linear, relief and aerial morphometric parameters of the sub-watersheds and groundwater potential with an objective to propose watershed management plans. The GIS was used to analyse drainage morphometric characteristics, which helped to understand many terrain parameters such as nature of bed rock, infiltration capacity, surface runoff etc. Kalathikadavu (154 km^2) and Poonjar (63.45 km^2) watersheds are characterized by their elonagated shape, low infiltration capacity and structural deformation of bedrock (Vijith and Satheesh, 2006). The sinuosity index (s) determined using IRS P6 LISS III data indicates that the river is tortuously meandering, and the basin's asymmetry implies the tectonic response of the basin (Aswathy *et al.,* 2008). Spatial differences in Transverse topographic symmetry factor (T), longitudinal profile, stream length-gradient index (SL index), SL anomaly index throws light on the complexity of the geologic processes in different parts of the sub-basins of Minachil River. Considering the above facts, the present study is an attempt to unravel the relationship between hierarchical anomaly of drainage network and tectonic response of MRB

Materials and Methods

The drainage network are vectorised with the aid of Survey of India (SOI) topo-sheets (scale 1:50,000) downloaded from open source digital map repository website https://soinakshe.uk.gov.in with the aid of ArcGIS 10.4 software. For the evaluation of hierarchical arrangement and calculating denudation index, the MRB is divided into 16 tributary sub-basins. The hierarchical rank of drainage network was determined by Strahler's scheme of stream ordering (Strahler, 1957). The hierarchical anomaly of drainage network is determined following the scheme proposed by Bahrami (2013). The denudation indices of the sub-basins were calculated from drainage density parameter and hierarchical anomaly index. Table 1 summarizes the equations for computing the drainage morphometric parameters. The detailed scheme of the calculation of the parameters is discussed in the following sections.

Hierarchical Anomaly of Drainage Network

Preliminary attempt on the analysis of the hierarchical organization of drainage network in terms of bifurcation ratio is proposed by Horton (1945). The Strahler's scheme (1957) of the hierarchical ranking of the drainage network propose the order relationship between stream segments *i.e.* the confluence of lower order streams produce streams of higher order ranking. Later, Avena *et al*. (1967) introduced the direct bifurcaton ratio (Rbd), Bifurcation index (R), hierarchical anomaly number (Ha), hierarchical anomaly index (Δa), and hierarchical anomaly density (g_a)to describe the anomaly in the drainage network progression.Guanieri and Pirrotta (2008) suggested the application of (Ha) and (Δa) in the interpretation of tectonic response of a drainage basin. An indirect estimation of the sediment yield from denudation index calculated from (Δa) and drainage density is proposed by many workers (Ciccacci *et al.,* 1987; Seta *et al.,* 2006; Grauso *et al.,* 2008). However, one of the simplified schemes for estimating hierarchical anomaly indices of the drainage proposed by Bahrami (2013) reflects a terrain's structural history. The present study makes use of the computational methodology proposed by Bahrami (2013).

Under equilibrium conditions, the hierarchical progression of the drainage network advances when the lower order stream merges the next higher order stream (1→2, 2→3, 3 → 4 etc.). However, drainage network anomaly develops when a lower order stream join to a stream other than its next higher order (1→3, 1→4, 2 →4, 2 →5 *etc.*) This may be due to structural disturbances or diffusive processes operated in a terrain (Avena *et al.,* 1967; Bahrami, 2013). The conceptual model explaining the hierarchical anomaly of a drainage basin and the number of first order streams required make the network with the perfect hierarchical organization (Fig. 2). The extent of hierarchical anomaly in the drainage varies with the evolutionary stage of a drainage basin, provided if there is no significant variation in climate and lithologic and or/structural factors. In the initial stage of drainage network development, the stream network has a very simple structure and is generally constituted by a certain number of channels, and is not very hierarchical in its progression. As the evolution progresses, the streams become more numerous, tend to progressively organize them through an intense erosive activity. In this phase, the hierarchization of the drainage network proceeds hand in hand with evolution. The progressive thinning of the interfluves and the establishment of main channel leads to a further increase in the degree of hierarchization. This increase, however, does not extend indefinitely.

Denudation Index (log Tu)

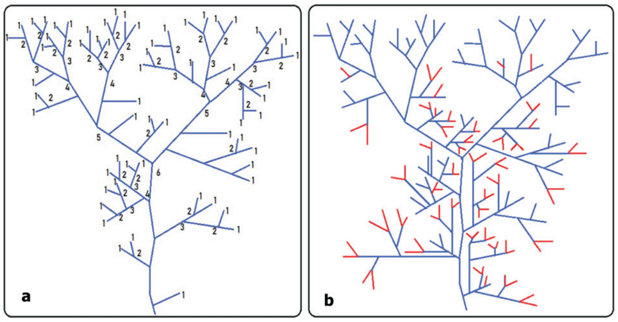
The drainage network extension and organization reflects the denudation power within the drainage basin. Denudation index, expressed by the suspended sediment yield is a rough approximation of the sediment yield of a drainage basin derived from drainage density and hierarchical anomaly index (Ciccacci *et al.,* 1987).

Bifurcation Index (R)

The difference between bifurcation ratio (Rb) and direct bifurcation ratio (Rbd) defines the bifurcation index (R). It is dependent on the presence of hierarchical anomalies in the network and might provide significant information on the typology of active erosive processes and hence the degree of evolution of drainage basin. The extent of dissection in the drainage basin can be interpreted from the degree of branching of the drainage network is expressed by Rb (Horton, 1945; Strahler, 1952). The Rbd parameter expresses the number of streams of a particular stream order (i) that flowed to the next higher order (i+1) divided by the total number of streams in (i+1) order (Avena *et al.,* 1967; Guarnieri and Pirrotta, 2008). Rbd defines the confluence of stream segments and structure of the hydrographic network.

Drainage Shape Index (Bs)

The planimetric shape of a drainage basin can be interpreted from the ratio of the basin length to width ratio or the elongation ratio. It is deduced from the equation Bs=Bl⁄Bw, where Bl and Bw are the basin length and width, respectively. Bl, is the maximum length measured from the mouth of the drainage basin to the farthest point on the drainage divide, whereas Bw is the maximum width of the drainage basin. High Bs value represents elongated drainage basins, and it reveals the extent of tectonic controls in determining the basin shape characteristics (Bull and McFadden, 1977; El Hamdouni *et al.,* 2008).



Anomalous stream junctions (i→j)	$Ha_{i\to j}=2^{(j-2)}-2^{(i-1)}$	$Ns_{i\to j}$	($Ha_{i\to j}$* $Ns_{i\to j}$)
1→3	1	3	3
1→4	3	1	3
1→5	7	2	14
1→6	15	1	15
2→4	2	1	2
2→5	6	1	6
2→6	14	1	14
3→5	4	1	4
3→6	12	1	12
4→6	8	1	8
		Σ =	81
		Ha_t	81
		N_1	61
		$\Delta a= Ha_t/ N_1$	1.33

Legend : 1,2,3,4,5 and 6 are stream orders

Fig.2. Conceptual model explaining the hierarchical anomaly of MRB (a) represents drainage network with poor hierarchical organization (b) depicts the first order streams added (red lines) to drainage network to make it in the perfect hierarchical organization. Calculation of Ha – the minimum number of first order streams required to make the drainage network in perfect hierarchical organization is summarized in the inset.

Percent of Basin Asymmetry (PAF)

Asymmetry of the drainage basin area on either side of the main stream in a drainage basin is indicative of terrain tilting under the influence of regional or local tectonics. Asymmetry factor (Af) is defined as 100 (Ar/At), where Ar is the drainage area on the right hand (facing the downstream direction) of the main stream and At is the drainage basin's total area (El Hamdouni *et al.,* 2008). Tilting may be indicated by Af values that are significantly larger or less than 50. The main channel located to the left side of the basin when Af is greater than 50. (tilting of basin towards the left). If the value is less than 50, the main channel has migrated to the right side of the basin (tilting of basin towards the right).

Bahrami (2013) revised Af to an index known as Percent of basin Asymmetry Factor (PAF). The PAF number does not indicate whether basins are tilted to the right or left side. It defines the percentage or degree of basin tilting. PAF values greater than 50 (around 100) indicate a high degree of asymmetry in the drainage basin.

Drainage Density (Du) and Drainage Frequency (Df)

Drainage density (Du) is the total length of streams per unit area, whereas drainage frequency (Df) is the total stream number per unit area (Horton, 1945). These parameters reveal the degree of dissection and lithologic characteristics of the drainage basin. Keller and Pinter (1996) suggested that drainage density and frequency parameters can be used as criteria for evaluating the rate of uplift and interpreting regional tectonics.

Results and Discussion

The hierarchical anomalies can be used as a proxy to determine the degree of evolution and tectonic response of a drainage basin. The influence of tectonic or diffusive /mass wasting geological processes results in poor hierarchical development of drainage basin and is reflected in the values of hierarchical parameters which is high. The hierarchical indices of the drainage network are calculated and is summarised in Table 2.

Denudation index is represented in Table 3. The drainage basin shape index (Bs), drainage frequency (Df), Bifurcation ratio (Rb), Direct Bifurcation ratio (Rbd), Bifurcation index (R), asymmetry factor (Af) and Percentage of basin Asymmetry factor (PAF) of the MRB are computed and summarized in Table 4.

The hierarchical anomaly number of the whole basin suggests that drainage network of sub-basin 1 must have a minimum of 644 first-order stream segments to be in perfect hierarchical organization. Similarly, for sub-basins 2, 3, 4, 5, 6, 7, 8, 9, 10,11,12,13,14,15 and 16; the number of first order stream segments required to make the drainage network in the ideal hierarchical organization are 1132, 352, 15, 393, 116, 62, 602, 327, 50, 57, 57, 66, 9, 30 and 34, respectively (Table 2).

The total basin show, Δa in a range of 0.41 to 2.27, in which the sub-basin 3 (2.27), sub-basin 1 (1.96), sub-basin 2 (1.76), sub-basin 9 (1.29) and sub-basin 5 (1.23) show higher values (Table 2) implying to intense erosion and /or tectonic response (especially for sub- basin3). Sub-basin 3 is tilted towards the right side (NW) and it is evident from the PAF value (57.48) and Af (45.51).

The NNW-SSE and NW-SE trending lineaments and its reactivation resulted in the seismic events occurred at Erattupetta and Melukavu (Rastogu, 2001; Bhattacharya and Dattatrayam, 2002; Rajendran *et al.*, 2009). Higher hierarchical anomaly density (10.36) of sub-basin 1 may be due to the presence and reactivation of NNW-SSE and NW-SE trending lineaments. Df value (6.93) is also high for sub-basin 1. However, sub-basin basin 1 is nearly symmetrical (PAF-49.87). The sub-basin 2 also shows high Δa (1.76) and g_a (7.32) value. PAF value is relatively high (63.73) and it is highly titled towards the right side (NW) of the basin and is characterized by high Df (5.69) and Bs (2.55). Vijith *et al.* (2018) reported that Payyappara (sub-basin 3) showed the influence of lineaments trending in the NNW-SSE and NW-SE. Sub-basin 9 shows high Δa and g_a and shows PAF value of 59.86 implying a tilt towards the right side (SE). Bs, Rb, R and Df value is also relatively high for this sub-basin. Sub-basin 5 is asymmetric with tilt towards left side (SW) of the basin. Bs, Rb, R and Df value is also relatively high for this sub-basin. Sub-basin 5 is asymmetric with tilt towards left side (SW) of the basin.

Bs value indicates that 7 sub-basins of MRB are elongated and having values higher than 2.5. The maximum value of Bs is reported from sub-basin 15 and it shows high PAF (72.55), titled towards right side (NW). However, it shows less Δa and g_a value owing to its less drainage basin area. Similarly, sub-basin 13 shows a PAF value of 70.59, high Bs (3.37), Rb (4.73) and R (1.66) and it shows less Δa and g_a value.

Denudation index computed from drainage density and hierarchical anomaly index of Minachil River shows that sub-basin 1 shows has the high maximum value (Table 3).The denudation index acts as an indirect measure of evaluation of the magnitude of erosion from drainage network anomalies of a drainage basin (Ciccacci *et al.,* 1987; Anish *et al.,* 2019). The higher value of denudation index is shown by the sub-basin1 (0.44 tons/km^2/year) whereas the sub-basins 5 and 2 show a high values of 0.43 and 0.41 tons/ km^2/ year, respectively. High value of denudation index of sub-basin 1 is related to the relatively high drainage density which implies that the sub-basin is more susceptible to erosion due to variation in lithology and is characterised by impermeable sub-surface material, sparse vegetation and mountainous relief (Vijith and Satheesh, 2006).

The higher value of Δa also indicates the structural interference *i.e.* presence of lineaments and faults which

Table 2: Hierarchical anomaly parameters of the tributary sub-basins of Minachil River

Stream Junction (i→j)	A (Fir), (Ha i→j), $2^{(r-2)}-2^{(i-1)}$ r- recipient, i - tributary	Sub-basin 1 (Poonjar)		Sub-basin 2 (Thikovil)		Sub-basin 3 (Paayappara)		Sub-basin 4 (Kattachira)		Sub-basin 5 (Pannagan)		Sub-basin 6 (Mannaani)		Sub-basin 7 (Meenadam)		Sub-basin 8 (KoduvanAr)		Sub-basin 9 (Chittaar)		Sub-basin 10 (Ponnozhukum)		Sub-basin 11 (Mevada)		Sub-basin 12 (Andur)		Sub-basin 13 (Vallichira)		Sub-basin 14 (Mariyidam)		Sub-basin 15 (MinaraThodu)		Sub-basin 16 (Punnathura)	
		B (Nir) (Nsi→j)	A*B	B	A*B	B	A*B	B	A*B	B	A*B	B	A*B	B	A*B	B	A*B	B	A*B	B	A*B	B	A*B	B	A*B	B	A*B	B	A*B	B	A*B	B	A*B
1→2	0	225	0	425	0	113	0	26	0	232	0	97	0	71	0	398	0	173	0	55	0	49	0	66	0	43	0	13	0	23	0	31	0
1→3	1	36	36	88	88	22	22	5	5	42	42	33	33	30	30	72	72	27	27	7	7	15	15	14	14	23	23	9	9	2	2	7	7
1→4	3	21	63	71	213	4	12	2	6	20	60	2	6	6	18	43	129	40	120	11	33	10	30	11	33	11	33	0	0	8	24	7	21
1→5	7	36	252	42	294	1	7	0	0	25	175	5	35	0	0	18	126	14	98	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1→6	15	11	165	17	255	15	225	0	0	0	0	0	0	0	0	5	75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I Order Streams		329		643		155		33		319		137		107		536		254		73		74		91		77		22		33		45	
2→3	0	57	0	102	0	35	0	6	0	50	0	28	0	21	0	96	0	33	0	12	0	10	0	19	0	11	0	5	0	7	0	8	0
2→4	2	5	10	22	44	3	6	2	4	11	22	3	6	7	14	29	58	15	30	5	10	6	12	5	10	5	10	0	0	2	4	3	6
2→5	6	7	42	10	60	0	0	0	0	13	78	4	24	0	0	7	42	8	48	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2→6	14	4	56	7	98	4	56	0	0	0	0	0	0	0	0	2	28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
II Order Streams		73		141		42		8		74		35		28		134		56		17		16		24		16		5		9		11	
3→4	0	12	0	29	0	10	0	3	0	12	0	5	0	5	0	27	0	9	0	3	0	4	0	3	0	3	0	2	0	2	0	3	0
3→5	4	5	20	3	12	0	0	0	0	4	16	3	12	0	0	2	8	1	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3→6	12	0	0	5	60	2	24	0	0	0	0	0	0	0	0	4	48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
III Order Streams		17		37		12		3		16		8		5		33		10		3		4		3		3		2		2		3	
4→5	0	5	0	9	0	5	0	0	0	4	0	2	0	0	0	8	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4→6	8	0	0	1	8	0	0	0	0	0	0	0	0	0	0	2	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
IV Order Streams		5		10		5		0		4		2		0		10		3		0		0		0		0		0		0		0	
5→6	0	2	0	3	0	2	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5→7	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V Order Streams		2		3		2		0		0		0		0		2		0		0		0		0		0		0		0		0	
6→7	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ha of whole basin		644		1132		352		15		393		116		62		602		327		50		57		57		66		9		30		34	
Number of Actual I Order Streams		329		643		155		33		319		137		107		536		254		73		74		91		77		22		33		45	
Hierarchical Anomaly Index (Δa)		1.96		1.76		2.27		0.45		1.23		0.85		0.58		1.12		1.29		0.68		0.77		0.63		0.86		0.41		0.91		0.76	
Basin area		62.16		154.59		107.04		64.42		63.10		44.40		42.73		188.16		43.65		21.87		18.56		33.30		19.94		7.59		11.56		12.58	
Hierarchical Anomaly Density, g_a		10.36		7.32		3.29		0.23		6.23		2.61		1.45		3.20		7.49		2.29		3.07		1.71		3.31		1.19		2.60		2.70	

Table 3: Denudation index of tributary sub-basins of Minachil River

Sub-basin	Drainage Density (Du)	Hierarchical Anomaly Index (Δa)	Denudation Index (log Tu) tons/km^2/year
Sub-basin 1	3.41	1.96	0.44
Sub-basin 2	2.93	1.76	0.41
Sub-basin 3	1.78	2.27	0.35
Sub-basin 4	1.22	0.45	0.28
Sub-basin 5	3.52	1.23	0.43
Sub-basin 6	2.51	0.85	0.37
Sub-basin 7	2.43	0.69	0.36
Sub-basin 8	2.31	1.12	0.36
Sub-basin 9	3.30	1.29	0.42
Sub-basin 10	2.56	0.68	0.37
Sub-basin 11	3.04	0.77	0.40
Sub-basin 12	2.35	0.63	0.36
Sub-basin 13	3.01	0.86	0.40
Sub-basin 14	2.38	0.41	0.36
Sub-basin 15	2.60	0.91	0.38
Sub-basin 16	2.30	0.76	0.36

trending NNW-SSE and NW-SE distributed in the three distinct locations in the elongated drainage basin (Vijith *et al.,* 2018). Valdiya and Narayana (2007) have well documented the effect of this strike-slip fault in the active tectonic response of the basin. They concluded that the above mentioned lineaments are active faults and the ongoing movements of these faults results in the gradational changes and created variously shaped loops in the drainage network at certain locations. Rajendran *et al.* (2009) compiled the earthquake history of Kerala from 1856 -2001 and reported that a series of earthquakes with magnitudes ranging from >1.4 to >5 have struck Kerala. In 12 December 2000 and 7 January 2001, the earthquake doublet struck at with a magnitude of 5 and 4.8 respectively at the Erattupettah-Pala in the MRB causing severe damage. For both of these seismic events, composite fault plane solutions show NW-SE and NE-SW trending nodal planes with a dominant strike slip component (Bhattacharya and Dattatrayam, 2002). They proposed that the northward shift of Minachil River under the influence of these faults (Vijith *et al.,* 2018). The present study proves that hierarchical anomaly characterization serves as significant tool to unravel the tectonic response of a drainage basin.

Conclusions

This research work elicits the scope of the analysis of drainage network anomalies in unraveling the role of tectonics in the drainage basin evolution. The present study provides an insight on the extent and causative factors of drainage network anomalies of the Minachil River Basin (MRB). The value of hierarchical anomaly index (Δa) for the sub-basins of the Minachil River ranges from 0.41 to 2.27. Three of the sixteen tributary sub-basins of the Minachil River, situated adjacent to the drainage basin's head, exhibits high Δa. The Δa is higher for sub- basin 3, indicates the tectonic response. The hierarchical anomaly density is high for sub-basin 1, indicates the role of lineaments in shaping the drainage network configuration. The sub-basins of MRB are elongated and asymmetric especially towards the head portion of the basin. The high degree of dissection experienced by the sub-basins of the Minachil River is interpreted from the bifurcation ratio and bifurcation index.

However, there are some limitations in the present study, especially in delineating the role played by the denudation process by geologic agents or human beings and/or regional tectonics act as factors for creating drainage network

Table 4: Drainage basin shape index (Bs), drainage frequency (Dt), Bifurcation ratio (Rb), Direct Bifurcation ratio (Rbd), Bifurcation index (R), Asymmetry factor (Af) and Percent of basin Asymmetry factor (PAF) of the MRB.

Length	Width	Basin shape index (Bs)	Nu	Basin Area	Draiange frequency (Df)	Rb	Rbd	R index	Ar	Af	ALS	PAF
0.14	0.08	1.67	431.00	62.16	6.93	3.35	2.67	0.68	31.00	49.87	31.00	49.87
0.25	0.10	2.55	880.00	154.59	5.69	3.72	2.87	0.85	56.08	36.28	98.51	63.73
0.17	0.09	1.86	254.00	107.04	2.37	2.96	2.35	0.61	45.51	42.52	61.53	57.48
0.12	0.07	1.70	45.00	64.42	0.70	3.26	2.75	0.51	19.9	30.96	44.48	69.04
0.15	0.05	2.94	487.00	63.10	7.72	4.42	3.11	1.31	38.62	61.21	38.6	61.21
0.12	0.05	2.33	213.00	44.40	4.80	3.76	2.59	1.17	27.06	60.95	27.06	60.95
0.14	0.09	1.53	168.00	42.73	3.93	5.13	3.55	1.58	17.59	41.16	25.06	58.66
0.17	0.15	1.15	736.00	188.16	3.91	3.79	2.87	0.92	107.30	57.02	107.30	57.02
0.13	0.05	2.50	323.00	43.65	7.40	4.11	3.10	1.01	26.13	59.86	26.13	59.86
0.08	0.03	2.56	112.00	21.87	5.12	4.67	3.25	1.42	11.16	51.00	11.16	51.00
0.09	0.03	2.81	99.00	18.56	5.33	4.29	3.19	1.10	9.41	50.67	9.41	50.67
0.10	0.05	2.02	144.00	33.30	4.32	5.28	4.03	1.25	11.34	34.05	21.96	65.95
0.10	0.03	3.37	115.00	19.94	5.77	4.73	3.07	1.66	5.87	29.41	14.08	70.59
0.04	0.02	1.77	35.00	7.59	4.61	3.30	2.37	0.93	3.61	47.54	3.98	52.46
0.05	0.04	1.50	51.00	11.56	4.41	3.61	2.69	0.92	3.17	27.45	8.38	72.55
0.05	0.03	1.47	60.00	12.58	4.77	3.59	2.83	0.76	5.60	44.52	6.98	55.48

anomalies. These limitations are overwhelmed to a great extent by comparing the drainage network anomaly indices with basin shape, asymmetry characteristics and degree of dissection. Furthermore, seismic history and structural deformation characterization of the MRB revealed by previous studies substantiate the role of tectonics in determining the drainage network progression.

Authors' Contributions

Anish A.U.: Conceptualization, Methodology, Investigation, Writing- Original draft preparation. **Baiju K. R.**: Supervision, Manuscript Reviewing and Editing. **Ajay K.K.**: Manuscript Editing and Data Validation. **Aryapriya M.S.**: Formal Analysis, Software. **Chandana S.** : Formal Analysis. **Parvathy H. S.**: Reviewing and Editing.

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