Geospatial assessment of active tectonics using SRTM DEM-based morphometric approach for Meghalaya, India

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ABSTRACT
Meghalaya, situated over the Shillong Plateau in the northeastern region of India, is considered a seismo-tectonically active region because of the Indian-Eurasian convergence and rising since the Cenozoic era. The present study aims to identify active deformation zones due to tectonic activity following a morphometric approach. Based on DEM data and GIS techniques, morphometric parameters along with geomorphic indices are obtained which allows the analysis of geomorphic processes responsible for the region’s landscape evolution, and indices of relative active tectonics (IRAT) are calculated by combining them. High drainage density, larger ruggedness number, intermediate to high hypsometric integral values with S/convex-type hypsometric curve, lower valley floor width-to-height ratio and stream sinuosity index values suggesting the region is tectonically active and according to IRAT, the Khasi and Jaintia Hills region (the central and eastern part) of the Meghalaya possesses relatively higher tectonic levels. The variation of tectonic activity is not uniform in the same structural feature and is found to be lower in the western portion and higher towards the east along the same Dauki Fault.

1. Introduction

The tectonic and surficial processes govern landscape evolution in the active deformation region. The endogenic geomorphic processes deform the lithosphere as a deeply incised valley, whereas exogenic processes shape the topography by erosional and depositional mechanisms (Keller & Printer, 2002). Tectonic geomorphology quantifies landscape geomorphic responses resulting from the interaction of active tectonics and geomorphological processes. The emergence of high-quality remotely sensed data, and geomorphological and geodetic tools with GIS have facilitated the tectonic geomorphological studies (Pérez-Peña et al., 2010), which helps in identifying active tectonic deformations, natural-hazard-prone regions and land use planning (Mahmood & Gloaguen, 2012).

The quantitative measurements of landscape shape facilitate the comparison of different landforms and the calculation of elementary parameters using topographic maps (Chen et al., 2003). The morphometric parameters are significant in understanding the structural control of the basin by assessing its areal or relief characteristics (Thomas et al., 2010). In contrast, geomorphic indices detect basin anomalies due to tectonic activities, corresponding to endogenic geomorphic processes (El Hamdouni et al., 2008). These parameters are sensitive to active faulting and tectonic uplift, resulting in river deflection, basin asymmetry and drainage geometry (Keller & Printer, 2002). Morphometric analysis observes the silent changes in a river in the form of channel incision, river length profile, gradient change and accelerated erosion in response to faulting, folding and differential uplift at the variable timescale of thousands to millions of years (since Neogene and Quaternary times; Sharma & Sarma, 2017). Several geomorphic indices and morphometric parameters are successfully used to analyse the tectonically active areas (Amine et al., 2020a; Argiriou et al., 2017; Baruah et al., 2022; Bull & McFadden, 1977; Cox, 1994; El Hamdouni et al., 2008; Hare & Gardner, 1985; Mishra, 2019; Ramirez-Herrera, 1998). Chen et al. (2003) evaluated the relative activities of tectonic features in Taiwan’s western foothills and identified five morphotectonic provinces based on stream-gradient and hypsometric analysis. El Hamdouni et al. (2008) assessed the relative tectonic activity of southern Spain by quantifying the IRAT using different geomorphic indices. A similar set of geomorphic indices are also adopted in other studies (e.g. Ayaz & Dhali, 2020; Mahmood & Gloaguen, 2012; Sarma et al., 2015; Softa et al., 2018; Taesiri et al., 2020; Zhang et al., 2019). Font et al. (2010) emphasised the application of stream length index using DEM and GIS to study the fluvial system with active tectonics. Dar et al. (2014) used morphometric and morphotectonic parameters to identify the tectono-geomorphic evolution of the Karewa basin of Kashmir valley, India, and observed the significant role of late Quaternary climate...
changes and tectonic upliftment in the valley landscape evolution. Similarly, Shukla et al. (2014), Sharma and Sarma (2017), Argyriou et al. (2017), Anand and Pradhan (2019) and Bhat et al. (2020) also adopted both morphometric parameters and geomorphic indices. Nevertheless, all these studies have shown no standard set of parameters/indices that can alone be employed to evaluate regional relative active tectonics in orogenic areas.

Meghalaya possesses a complex seismotectonic setting (Figure 1a,b) and falls under seismic zone V (zone factor of 0.36 g; high-risk zone) as per the Indian building design code (IS1893, 2016). The NER of India in the Eastern Himalayas is one of the most critical orogenic belts and seismically active regions due to collision tectonics of Indian-Eurasian Plates in the north and active subduction beneath the Indo-Burman ranges along the eastern part of the region (Catherine, 2004). The Shillong-Mikir plateau results from such interaction and is actively deforming (Duarah & Phukan, 2011). The present structural alignment of Meghalaya was attained during the Cenozoic Era (Baruah et al., 2022), and continuous tectonic movement has influenced the region’s geomorphology (Devi, 2008). The study aims to analyse the drainage basins and stream networks of Meghalaya to identify the ongoing tectonic activity and consequent geomorphic response using morphometric parameters and geomorphic indices (Figure 1c; Table 1; Anand & Pradhan, 2019; Argyriou et al., 2017). IRAT is obtained to understand the degree of relative active tectonics of the region.

2. Geological setting and tectonic framework

Meghalaya, extending from 25.03° to 26.11°N and 89.82° to 92.80°E, is mainly characterised by Shillong Plateau. It covers ~22,500 km² having elevations ranging from 7 m to 1962 m above mean sea level (Figure 1a). It is one of the rainiest places in the country, with an average annual rainfall varying from 1234

![Figure 1](image-url)
Table 1. Summary of morphometric and geomorphic indices along with adopted classification scheme.

| Group                  | Morphometric Indices | Formula                                                                 | Inference                                                                 | Class | References |
|------------------------|----------------------|-------------------------------------------------------------------------|---------------------------------------------------------------------------|-------|------------|
| Areal Parameters       | Drainage Density ($D_a$) | $D_a = \left(\sum\frac{1}{L}\right) / A$, defined as the total length of streams of all orders in the basin per unit area. $L = \text{total length of each stream order and } A = \text{area of the basin}$ | High values are indicative of impermeable rock with higher relief and resistance to erosion | >1.4  | 1.2–1.4    | <1.2       | (Horton, 1945; A. N. Strahler, 1964; Shukla et al., 2014) |
|                        | Form Factor ($F_f$)   | $F_f = A / L_b^2$, the ratio of the basin area ($A$) to the square of the basin length ($L_b$) | Low values suggest the elongated basins and dominance of exogenous processes, whereas high values indicate circular basins with high peak flow in a shorter duration | <0.3  | 0.3–0.6    | >0.6       | (Horton, 1945; Argyriou et al., 2017; Anand & Pradhan, 2019) |
|                        | Basin Elongation Ratio ($Re$) | $Re = D / L_b = 1.128 A^{0.5} / L_b$, where $D$ is the diameter of an equivalent circle, $A$ is the area of the basin, $L_b$ is basin length | Low values indicate high tectonically active region and vice-versa | <0.5  | 0.5–0.75   | >0.75      | (Schumm, 1956; Bull & McFadden, 1997; Sarma et al., 2015) |
|                        | Circulatory Ratio ($R_c$) | $R_c = 4 A / P^2$, the ratio of the basin area ($A$) to the area of the circle having the same perimeter as of the drainage basin ($P$) | Low values imply the dominance of tectonic activities as it tends to create elongated basins, while high values show severe erosion, which tends to create a circular basin | <0.2  | 0.2–0.3    | >0.3       | (Miller, 1953; Shukla et al., 2014; Argyriou et al., 2017; Bhat et al., 2020) |
| Relief Parameters      | Relief ($R$)          | $R = E_{\text{max}} - E_{\text{min}}$, defined as the difference in the elevations of the highest ($E_{\text{max}}$) and lowest points ($E_{\text{min}}$) of the drainage basin | High relief value indicates ($R > 1.5 \text{ km}$) low infiltration and high physiographic structure, and vice versa | >1.5  | 1.0–1.5    | <1.0       | (A. N. Strahler, 1952; Argyriou et al., 2017; Anand & Pradhan, 2019) |
|                        | Relief Ratio ($R_r$)  | $R_r = R / L_b$, where $R$ is the relief, $L_b$ is the basin length | It represents the degree of rock resistance. High values are indicative of hilly regions with resistant rock, while low values represent less resistive rocks and flat region | >0.05 | 0.02–0.05  | <0.02      | (Schumm, 1956; Vittala et al., 2004; Shukla et al., 2014) |
|                        | Ruggnedness Number ($R_n$) | $R_n = R \times D_a$, where $R$ is the relief in km and $D_a$ is the drainage density | High values show the region is more susceptible to degradation processes and represents the presence of dissected hills with intrinsic structural complexity | >1.5  | 0.75–1.5   | <0.75      | (Schumm, 1956; Shukla et al., 2014; Anand & Pradhan, 2019) |

(Continued)
| Group                  | Morphometric Parameters            | Formula                                                                 | Inference                                                                                                                        | Class       | References                                      |
|-----------------------|-----------------------------------|-------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------|-------------|-------------------------------------------------|
| Morphotectonic        | Hypsometric Integral (HI)          | $HI = \frac{EH_{\text{max}} - EH_{\text{min}}}{EH_{\text{max}}}$, where $EH_{\text{max}}$ is the mean elevation of the basin above m.s.l., $EH_{\text{min}}$ is the elevation of the lowest point of the basin, $EH_{\text{max}}$ is the elevation of the highest point the basin                                                                                     | High values ($HI > 0.5$) represent a basin with a deep incised valley and minimal plateau erosion, whereas moderate values ($0.4$–$0.5$) show basins with equilibrium between tectonic and erosional processes. A low value indicates severe erosion | 0.5         | (A.N. Strahler, 1952; Dehbozorgi et al., 2010; Zhang et al., 2019) |
|                      | Valley Floor Width to Height Ratio (VF) | $VF = \frac{W_{n}}{L_{n}}$, where $W_{n}$ is the width of the valley floor, $E_{L}$ and $E_{R}$ are the elevations of the left and right valley divides and $E_{n}$ is the elevation of the valley floor                                                                                     | Low values are associated with rapid upliftment and a high rate of the incision, while high values represent a flat-floored wide valley with a low uplift rate | 0.5–1.0     | (Bull & McFadden, 1997; Keller & Printer, 2002; Sarma et al., 2015) |
|                      | Basin Asymmetric Factor (AF)       | $AF = \frac{A_{L}}{A_{R}}$, where $A_{L}$ is the area of the basin to the right of the main river, $A_{R}$ is the total area of the basin and $AF = |AF - 50|$                                                                                                                     | $|AF - 50|$ close to zero indicate stable setting and no tilting with low active tectonics and vice versa                                      | 0.7–15      | (Cox, 1994; Keller & Printer, 2002; Sarma et al., 2015; Zhang et al., 2019) |
|                      | Transverse Topography Symmetry Index (TTSI) | $TTSI = Da/Dd$, where $Da$ is the distance between river channel to basin midline, $Dd$ is the distance between basin midline and basin divide (boundary)                                                                                           | Low values imply approximate symmetrical basins, and as increases from 0 to 1, the asymmetry increases                                                                                     | 0.2–0.4     | (Keller & Printer, 2002; Sarma et al., 2015; Baruah et al., 2022) |
|                      | Basin Shape Index (BSI)            | $BSI = B_{L}/B_{R}$ defined as the ratio of length measured from the mouth of the river to the most distant point on the drainage divide ($B_{L}$), to the maximum width of the basin ($B_{R}$)                                                                                   | High values imply elongated basins with rapid uplifting due to active tectonics. Low values suggest circular basins with stable settings                                                                 | 2.0–3.5     | (Bull & McFadden, 1977; Argyriou et al., 2017; Zhang et al., 2019) |
|                      | Stream Length Gradient Index (SLGI) | $SLGI = \frac{SH}{SLG_{L}}$, $SH$ is the change in elevation, $SLG_{L}$ is the length of the reach and $L$ is the total length from the midpoint of the reach to the drainage divide upstream                                                                 | High values of SLGI imply basins with high relief, hard rock and active uplift. The lower values are suggestive of lower active tectonics and softer underlying rock                                             | 300–500     | (Hack, 1973; Keller & Printer, 2002; Dar et al., 2014; Zhang et al., 2019) |
|                      | Stream Sinuosity Index (SSI)       | $SSI = C/V$, the ratio of channel length ($C$) to the valley length ($V$)                                                                                                             | Low values indicate the region is tectonically active and vice versa                                                                                                                        | <1.5        | (Bull & McFadden, 1977; Gomez & Marron, 1991)   |

Table 1. (Continued.)
rain-fed, and forms tributaries of the Brahmaputra and Meghna rivers. The important rivers in the Garo Hills region are Daring, Digaru and Someshwari, and in the Khasi and Jaintia Hills regions are Kopilli, Myntdu, Umina and Umkhri.

Several studies such as Biswas et al. (2007) estimated the Indian–Eurasian crustal movement accommodated across the Shillong Plateau varies from 0.7 to 7 mm/year. Vernant et al. (2014) recorded an increase in velocity from ~3 mm/year to ~6 mm/year at the west of the Dauki Fault to the east, suggesting the rotation of the Shillong Plateau. The Dauki Fault, responsible for plateau upliftment, acts as a north-dipping seismogenic thrust forming the southern escarpment along the southern plateau margin (Bilham & England, 2001). In the west (Garo Hills), N-S trending Dhubri Fault and Dapsi Thrust (Chen & Molnar, 1990; Kayal & De, 1991), and in the central and the northeastern portion, Barapani shear zone, Umrago and NW-SE trending Kopili Faults are the major tectonic features (Biswas et al., 2007). The region has also experienced significant earthquakes, including the 1897 Great Assam Earthquake (Mw = ~8.3).

Meghalaya is lithologically diverse and covered by late Cenozoic era alluvial fills to the unclassified gneissic complex of Archaean to Paleoproterozoic aeons (Strong et al., 2019). Approximately 44% of the areas belong to the unclassified gneissic complex (Figure 2a), overlain by sediments and greenstones of the Shillong group (Mishra, 2019). The portion along the southern escarpment is of the late Mesozoic to the Cenozoic era. The inner upland region of the plateau and highly dissected plateau margins in the northeast consists of Granitoid of Neoproterozoic to an early Palaeozoic era (Figure 2a), and the plateau basement experienced erosion to a penep lain till Jurassic. Due to lithological diversification, different erosional rock strengths are produced. Following Selby (1980), the erosional resistance of geological units of Meghalaya is grouped into gneiss, quartzite and granite are

Figure 2. (a) Geological setting of the study area. (AP: Accretionary Prism of middle to late Cenozoic era; ES: Epeiric sea/Marginal overlap cover in Pericratonic Sag of late Mesozoic to early Cenozoic era; GS: Greenstone and allied Supracrustal Belts Proterozoic era; Gr: Granitoid of Neoproterozoic to early Palaeozoic era; IS: Shelf facies cover in Intracratic Sag of Palaeo- to Mesoproterozoic and early to middle Cenozoic era; LG: Terrestrial facies cover in linear Graben of the late Palaeozoic era; Gn: Unclassified Gneissic Complex of Archaean to the Paleoproterozoic era (“Bhukosh-GSI,” 2021); (b) Geomorphological map of the Meghalaya.

To 7467 mm per year (Indian Meteorological Department; Prokop, 2014). Physiographically, the Shillong plateau is a northeastern extension of the Indian Peninsular shield (Figure 1a; Raghukanth et al., 2011). The area has a rich network of streams, mostly

### Table 2. Drainage basin characteristics of the Meghalaya.

| Basin ID | Area (km²) | Perimeter (km) | Basin length (l_b) km | Stream order |
|----------|------------|----------------|-----------------------|--------------|
| 1        | 2484.39    | 398.65         | 59.86                 | 7            |
| 2        | 523.55     | 196.66         | 48.12                 | 6            |
| 3        | 125.39     | 57.44          | 12.47                 | 6            |
| 4        | 508.63     | 172.95         | 51.14                 | 6            |
| 5        | 341.75     | 105.74         | 31.01                 | 6            |
| 6        | 924.86     | 192.51         | 38.90                 | 7            |
| 7        | 827.64     | 202.28         | 40.88                 | 6            |
| 8        | 582.02     | 160.62         | 31.08                 | 7            |
| 9        | 164.23     | 77.38          | 20.92                 | 5            |
| 10       | 144.57     | 62.72          | 18.57                 | 5            |
| 11       | 512.43     | 156.82         | 21.60                 | 6            |
| 12       | 115.18     | 71.36          | 20.59                 | 5            |
| 13       | 328.82     | 158.44         | 43.84                 | 5            |
| 14       | 210.74     | 91.91          | 25.42                 | 6            |
| 15       | 520.99     | 168.07         | 31.88                 | 7            |
| 16       | 406.17     | 179.68         | 56.22                 | 6            |
| 17       | 375.70     | 136.54         | 36.81                 | 7            |
| 18       | 1030.56    | 241.27         | 48.13                 | 7            |
| 19       | 1264.09    | 278.68         | 52.13                 | 7            |
| 20       | 154.92     | 104.39         | 29.19                 | 6            |
| 21       | 158.05     | 101.98         | 22.57                 | 6            |
| 22       | 90.52      | 56.21          | 15.44                 | 5            |
| 23       | 168.86     | 91.28          | 19.20                 | 5            |
| 24       | 412.25     | 143.78         | 24.91                 | 6            |
| 25       | 858.16     | 214.17         | 44.28                 | 7            |
| 26       | 270.65     | 111.22         | 26.14                 | 6            |
| 27       | 203.55     | 110.57         | 27.77                 | 6            |
| 28       | 261.68     | 160.21         | 45.57                 | 5            |
| 29       | 423.70     | 171.76         | 46.18                 | 6            |
| 30       | 344.53     | 127.68         | 27.15                 | 6            |
| 31       | 521.77     | 151.40         | 32.54                 | 7            |
| 32       | 80.20      | 69.93          | 19.76                 | 5            |
| 33       | 100.16     | 60.96          | 17.97                 | 5            |
| 34       | 97.97      | 57.33          | 18.39                 | 6            |
| 35       | 95.77      | 61.13          | 18.80                 | 5            |
| 36       | 159.07     | 84.99          | 20.51                 | 6            |
| 37       | 96.52      | 64.23          | 20.74                 | 5            |
| 38       | 394.38     | 115.69         | 29.59                 | 6            |
| 39       | 342.62     | 120.38         | 33.24                 | 6            |
| 40       | 2290.45    | 400.30         | 71.88                 | 7            |
| 41       | 113.21     | 58.06          | 14.62                 | 5            |
| 42       | 89.59      | 51.46          | 14.91                 | 5            |
| 43       | 91.97      | 51.60          | 13.86                 | 5            |
Table 3. Calculated morphometric indices (areal parameters) and assigned active tectonic classes for different basins of the Meghalaya region.

| Basin ID | \(D_a\) | \(FF\) | \(Re\) | \(Rc\) | Average of Classes |
|---------|---------|--------|--------|--------|-----------------|
| 1       | 1.34    | 0.69   | 0.94   | 0.20   | 2.50            |
| 2       | 1.14    | 0.23   | 0.54   | 0.17   | 1.75            |
| 3       | 1.26    | 0.81   | 1.01   | 0.48   | 2.75            |
| 4       | 1.22    | 0.19   | 0.50   | 0.21   | 2.17            |
| 5       | 1.04    | 0.36   | 0.67   | 0.38   | 2.50            |
| 6       | 1.18    | 0.61   | 0.88   | 0.31   | 3.00            |
| 7       | 1.30    | 0.50   | 0.25   | 1.22   |
| 8       | 1.16    | 0.60   | 0.88   | 0.28   | 2.50            |
| 9       | 1.01    | 0.38   | 0.69   | 0.34   | 2.50            |
| 10      | 1.07    | 0.42   | 0.73   | 0.46   | 2.50            |
| 11      | 1.33    | 1.10   | 1.18   | 0.26   | 2.50            |
| 12      | 1.42    | 1.27   | 1.59   | 0.29   | 2.50            |
| 13      | 1.33    | 0.17   | 0.47   | 0.16   | 1.25            |
| 14      | 1.40    | 0.33   | 0.64   | 0.31   | 2.00            |
| 15      | 1.26    | 0.51   | 0.81   | 0.23   | 2.25            |
| 16      | 1.21    | 0.13   | 0.40   | 0.16   | 1.25            |
| 17      | 1.24    | 0.28   | 0.79   | 0.30   | 2.25            |
| 18      | 1.24    | 0.44   | 0.75   | 0.27   | 2.00            |
| 19      | 1.23    | 0.47   | 0.77   | 0.28   | 2.25            |
| 20      | 1.31    | 0.21   | 0.48   | 0.18   | 1.25            |
| 21      | 1.19    | 0.31   | 0.63   | 0.19   | 2.00            |
| 22      | 1.21    | 0.38   | 0.69   | 0.36   | 2.25            |
| 23      | 1.19    | 0.46   | 0.76   | 0.28   | 2.00            |
| 24      | 1.26    | 0.66   | 0.92   | 0.25   | 2.50            |
| 25      | 1.35    | 0.44   | 0.75   | 0.23   | 2.50            |
| 26      | 1.34    | 0.40   | 0.57   | 0.22   | 2.00            |
| 27      | 1.28    | 0.26   | 0.58   | 0.27   | 1.50            |
| 28      | 1.38    | 0.13   | 0.40   | 0.13   | 1.25            |
| 29      | 1.46    | 0.20   | 0.50   | 0.18   | 1.25            |
| 30      | 1.37    | 0.47   | 0.77   | 0.30   | 2.25            |
| 31      | 1.32    | 0.49   | 0.79   | 0.31   | 2.25            |
| 32      | 1.41    | 0.21   | 0.51   | 0.21   | 2.50            |
| 33      | 1.43    | 0.31   | 0.63   | 0.34   | 3.00            |
| 34      | 1.39    | 0.29   | 0.61   | 0.37   | 3.00            |
| 35      | 1.56    | 0.27   | 0.59   | 0.32   | 3.15            |
| 36      | 1.36    | 0.38   | 0.69   | 0.28   | 2.00            |
| 37      | 1.42    | 0.22   | 0.53   | 0.29   | 2.50            |
| 38      | 1.31    | 0.45   | 0.76   | 0.33   | 2.50            |
| 39      | 1.30    | 0.31   | 0.63   | 0.30   | 2.00            |
| 40      | 1.31    | 0.44   | 0.75   | 0.18   | 1.25            |
| 41      | 1.14    | 0.53   | 0.82   | 0.42   | 2.75            |
| 42      | 1.11    | 0.4    | 0.72   | 0.43   | 2.50            |
| 43      | 1.21    | 0.48   | 0.78   | 0.43   | 2.50            |

classified as very strong to strong; sandstone, schist, conglomerate are of typically medium to low strength and classified as strong to moderately weak, whereas the alluvial deposits and debris flow have weak erosional strength. A significant portion of the study area is occupied by moderately dissected (~41%) and highly dissected (~30%) structural upper plateau (Figure 2b). The plateau margins, mainly in the study area’s north-western, eastern and southern portions, consist of denuded dissected hills and valleys along the steep to moderate side slopes.

3. Material and methods

3.1. Dataset

Drainage basins are extracted from 1-arcsec (~30 m) Shuttle Radar Topography Mission digital elevation model (SRTM DEM) version 3 (https://earthexplorer.usgs.gov/). The SRTM data offers a better accuracy of about ±16 m (RMSE of 9.73 m) worldwide and is based on C-band radar interferometry data. It showed an absolute horizontal accuracy of ±8.8 m and vertical accuracy of ±6.2 m (90% confidence; Elkhrachy, 2018).

The geological setting and lineament data are obtained from the Bhukosh-Geological Survey of India (GSI) (https://bhukosh.gsi.gov.in/Bhukosh/Public). Using the spatial analyst tool in ArcGIS 10.8, the lineament density is calculated from the lineament dataset as high lineament density regions are more susceptible to erosion than other areas (Taesiri et al., 2020). The earthquake data representing the seismicity of the region are compiled from several sources such as the Bhukosh-GSI, USGS and International Seismological Centre–GEM catalogue (Gupta et al., 2021).

The DEM data is further processed in GIS, and using the Hydrology tools, 43 drainage basins (Table 2) are demarcated. The extraction process involves DEM preprocessing, filling voids, accessing flow direction, quantifying flow accumulation, and stream network and drainage basin extraction. The Strahler stream order of the basins ranges from 5 to 7 (Figure 1c; A.N. Strahler, 1952).

3.2. Areal parameters

The areal parameters identify the degree of erosional activity due to exogenic geomorphic processes and lateral propagation of folds (Keller & Printer, 2002). It mainly includes drainage density \(D_a\), form factor \(FF\), basin elongation ratio \(Re\) and circularity ratio \(Rc\) (Table 1; Horton, 1945). \(D_a\) is influenced by the rainfall intensity, basin’s lithological setup and soil texture, geological setting and vegetation cover (Horton, 1945). \(FF\), \(Re\) and \(Rc\) can describe the basin shape. The basins having lower \(FF\) (<0.3) values represent the elongated basins indicating structural and tectonic control over the drainage basin area (Anand & Pradhan, 2019). The \(Re\) is the ratio of the diameter of a circle of the equivalent area as the basin to the basin length (Schumm, 1956). The lower values of \(Re\) (<0.5) represent a more elongated basin controlled by active tectonics (Sarma et al., 2015). Another significant parameter, \(Rc\), shows the degree of basin circularity (Table 1). It indicates the dendritic stages by reflecting the role of deformation by erosion versus tectonics and is influenced by the topography and geological setting of a basin (Dar et al., 2014).

3.3. Relief parameters

The relief parameters are basin relief \(R\), relief ratio \(Rr\) and ruggedness number \(Rn\) (Table 1; Thomas et al., 2010). \(R\) represents the elevation range of the considered basin and is defined as the topography’s ruggedness (Keller & Printer, 2002). \(Rr\) is the ratio of drainage basin relief \(R\) to the basin length \(L_b\). \(Rr\) is used to
3.4. Geomorphic indices

The geomorphic indices characterise the landscape processes and active tectonics based on the basins’ shape, tilting, relative incision and erosional status (Argyrion et al., 2017). In the present study, the hypsometric curve – hypsometric integral (HI), valley floor width to valley height ratio (VF), basin shape index (BSI), transverse topographic symmetry index (TTSI), asymmetry factor (Af), stream length gradient index (SLGI) and stream sinuosity index (SSI) are considered (Table 1; Dehbozorgi et al., 2010; Rimando & Schoenbohm, 2020). The HI refers to the relative area distribution at different elevations in a drainage basin and represents the area under the hypsometric curve (HC; A.N. Strahler, 1952). The shape of HC is used to infer the geomorphic development stage (Chen et al., 2003). The convex, S-shaped and concave-shaped curves represent the youthful stage (related to weakly eroded basin), mature and old-peneplain stage (highly eroded basin) of basin development, respectively (Amine et al., 2020a). The values of HI close to 1 indicate high incision with negligible plateau erosion and young landforms due to active tectonics, while moderate to low values indicate evenly dissected watersheds (El Hamdouni et al., 2008). The HC for all the basins is calculated using spatial analyst tools in ArcGIS 10.8 (Tebii et al., 2017).

The tectonic influence in a watershed can be inferred by evaluating possible tectonic tilting of the basins (Keller & Printer, 2002). The Af shows the tectonic tilting in the basin in the transverse direction of flow (Hare & Gardner, 1985). For stream in the stable setting, the Af will be close to 50, and if Af is larger or less than 50, it suggests tilt and influence of active tectonics (Pérez-Peña et al., 2010). TTSI also determines the tilt in the drainage basins due to neotectonics and is calculated as per Cox (1994). It is estimated along the mainstream of each basin at multiple locations and averaged (Tsoudoulos et al., 2008). TTSI value approaches 0 for symmetrical basins, and as the stream moves laterally away from the basin centre, the value increases. TTSI close to 1 shows a highly asymmetrical and possibly tilted basin (Keller & Printer, 2002). In tectonically active regions, the basin shape is quantified using BSI (Bull & McFadden, 1977). The high values of BSI reflect elongated basins and low values for more circular basins with stable settings. In tectonically active regions, the drainage basin widths are narrower near the mountain fronts where the high stream energy is primarily involved in downcutting against the continuous upliftment. In contrast, the stable setting permits the widening of drainage basins upstream of the mountain front (Ramirez-Herrera, 1998).
Table 4. Calculated morphometric indices (relief parameters) and assigned active tectonic classes for different basins of the Meghalaya region.

| Basin ID | Relief Parameters |
|----------|-------------------|
|          | \( R (\text{km}) \) | \( \text{Value Class Value Class Value Class Average of Classes} \) |
| 1        | 1.83 1             | 0.030 2 | 2.44 1 | 1.33 |
| 2        | 1.82 1             | 0.038 2 | 2.07 1 | 1.33 |
| 3        | 1.25 2             | 0.100 1 | 1.57 1 | 1.33 |
| 4        | 1.85 1             | 0.036 2 | 2.26 1 | 1.33 |
| 5        | 1.81 1             | 0.058 2 | 1.89 1 | 1.00 |
| 6        | 1.76 1             | 0.045 2 | 2.08 1 | 1.33 |
| 7        | 1.40 2             | 0.034 2 | 1.81 1 | 1.67 |
| 8        | 1.19 2             | 0.038 2 | 1.39 2 | 2.00 |
| 9        | 0.74 3             | 0.035 2 | 0.75 3 | 2.67 |
| 10       | 0.38 3             | 0.020 2 | 0.41 3 | 2.67 |
| 11       | 0.32 3             | 0.015 3 | 0.42 3 | 3.00 |
| 12       | 0.59 3             | 0.028 2 | 0.83 2 | 2.33 |
| 13       | 0.58 3             | 0.013 3 | 0.77 2 | 2.67 |
| 14       | 0.54 3             | 0.021 2 | 0.75 2 | 2.33 |
| 15       | 1.07 2             | 0.034 2 | 1.35 2 | 2.00 |
| 16       | 1.02 2             | 0.018 3 | 1.23 2 | 2.33 |
| 17       | 0.96 3             | 0.026 2 | 1.19 2 | 2.33 |
| 18       | 1.11 2             | 0.023 2 | 1.38 2 | 2.00 |
| 19       | 1.61 1             | 0.031 2 | 1.97 1 | 1.33 |
| 20       | 1.56 1             | 0.051 1 | 2.03 1 | 1.00 |
| 21       | 1.15 2             | 0.051 1 | 1.37 2 | 1.67 |
| 22       | 0.79 3             | 0.051 1 | 0.95 2 | 2.00 |
| 23       | 0.67 3             | 0.035 2 | 0.80 2 | 2.33 |
| 24       | 0.47 3             | 0.019 3 | 0.59 3 | 3.00 |
| 25       | 0.78 3             | 0.018 3 | 1.05 2 | 2.67 |
| 26       | 0.48 3             | 0.018 3 | 0.64 2 | 3.00 |
| 27       | 0.37 3             | 0.013 3 | 0.52 2 | 3.00 |
| 28       | 0.82 3             | 0.018 3 | 1.13 2 | 2.67 |
| 29       | 0.81 3             | 0.018 3 | 1.18 2 | 2.67 |
| 30       | 0.37 3             | 0.014 3 | 0.51 3 | 3.00 |
| 31       | 0.93 3             | 0.029 3 | 1.23 2 | 2.33 |
| 32       | 0.07 3             | 0.004 3 | 0.10 3 | 3.00 |
| 33       | 0.08 3             | 0.005 3 | 0.12 3 | 3.00 |
| 34       | 0.07 3             | 0.004 3 | 0.09 3 | 3.00 |
| 35       | 0.07 3             | 0.004 3 | 0.11 3 | 3.00 |
| 36       | 0.10 3             | 0.005 3 | 0.13 3 | 3.00 |
| 37       | 0.08 3             | 0.004 3 | 0.11 3 | 3.00 |
| 38       | 0.64 3             | 0.022 2 | 0.85 2 | 2.33 |
| 39       | 0.75 3             | 0.022 2 | 0.97 2 | 2.33 |
| 40       | 1.28 3             | 0.018 3 | 1.68 1 | 2.00 |
| 41       | 0.62 3             | 0.043 2 | 0.71 2 | 2.67 |
| 42       | 0.79 3             | 0.053 1 | 0.88 2 | 2.00 |
| 43       | 0.76 3             | 0.055 1 | 0.92 2 | 2.00 |

The \( V_f \) index identifies recent uplift and tectonic quiescence areas and discriminates narrow, U- and V-shaped valleys (El Hamdouni et al., 2008). The low \( V_f \) values (deep V-shaped valleys) are associated with rapid upliftment and higher incision due to active tectonics. The broad U-shaped valleys associated with large \( V_f \) values show attainment of base-level erosion and are subjected to lateral erosion due to relative tectonic quiescence (Keller & Printer, 2002). The intermediate values represent low displacement rates governing moderately active fronts.

The \( SLGI \) is a quantitative geomorphic index that correlates to stream power governing erosional and depositional processes in the specified channel reach and possible active tectonics (Hack, 1973). This index expresses the relation among channel slope, rock resistance and tectonic activity (Keller & Printer, 2002). It is calculated by dividing the stream into multiple segments of equal intervals using the DEM dataset, and the average value is considered. The \( SSi \) is defined as the ratio of the stream channel length and the length of the straight line joining two ends of the channel. It relates to the hydraulic and morphological characteristics of the stream and records tectonic changes (Gomez & Marron, 1991).

After quantification, each index is classified into three classes (Table 1), representing different levels of tectonic activity (Mahmood & Gloguen, 2012), and IRAT is calculated (El Hamdouni et al., 2008). The values of IRAT were divided into four classes, using a natural break classifier (Taesiri et al., 2020): Class 1 – very high (IRAT < 1.851); Class 2 – high (1.851 ≤ IRAT < 2.131); Class 3 – moderate (2.131 ≤ IRAT < 2.330) and Class 4 – low (IRAT > 2.330).

4. Results and discussion

4.1. Morphometric indices

4.1.1. Areal parameters

In the present study, four areal parameters: \( D_b \), \( F_f \), \( R_e \) and \( R_c \) are considered. The \( D_b \) values range from 1.009/km (basin 9) to 1.560/km (basin 35; Table 3) and are classified into three classes (Shukla et al., 2014; Figure 3a). Higher values (\( D_b > 1.4 \)) are indicative of impermeable lithological setup, high relief, sparse vegetation cover of the basins and high tectonic activity (Nag, 1998; Thomas et al., 2010). The majority of basins (except basins 2, 5, 6, 8–10, 21, 23, 41 and 42) show moderate to the high value of \( D_b \) (≥1.2), generally associated with impermeable lithology (Gneiss complex/Granitoid, Figure 2a), covering most of the study area (71.40%; Figure 3a).

Other parameters such as \( F_f \) vary from 0.13 (basin 28) to 1.10 (basin 11), the \( R_e \) ranges from 0.40 (basin 28) to 1.18 (basin 11) and \( R_c \) ranges from 0.13 (basin 28) to 0.48 (basin 3; Table 3). The basins are classified into three different active tectonic classes based on the values of these parameters (\( F_f \), \( R_e \) and \( R_c \)) (Figure 3b-d; Anand & Pradhan, 2019; Argyriou et al., 2017). The high, moderate and low tectonic activity classes are represented by Classes 1, 2 and 3, respectively. For \( F_f \), except for basins 1, 3, 6, 11 and 24, all other basins (covering ~66% area) have values equal to or less than 0.6, indicating moderate to highly elongated basins and fall under moderate to a high class of active tectonics (Figure 3b). Whereas in the case of \( R_c \), the basins in the Jaintia and Khasi Hills region generally have larger values \( R_c \) values (>0.75), signifying slightly active or inactive tectonic settings (Sarma et al., 2015). The spatial distribution of \( R_c \) shows 21 basins, covering ~52% area, consisting of an intermediate class of active tectonics (0.2–0.3; Figure 3d). Numerically, \( R_c \) values reflect stages of evolution of drainage basins wherein
low (e.g. basins 2, 13, 16, 23, 28 and 29) and high (e.g. basins 3, 5–6, 9–10, 14, 22, 33–35, 38 and 41–43) values correspond to young and mature stage of basin development, respectively (Thomas et al., 2010).

4.1.2. Relief parameters
Relief parameters influence flood patterns and sediment-carrying capacity of the stream and help understand the basin’s denudational characteristics as low basin relief and \( R_r \) are distinctive attributes of low resistant rocks with high erosional tendencies (Schumm, 1956). The basin relief (km) varies from 0.065 (basin 34) to 1.847 (basin 4), and \( R_r \) varies from 0.00353 (basin 34) to 0.10007 (basin 3; Table 4). The basins in the Khadi Hills region (Basins 1, 2, 4–6, 19 and 20) mostly show high relief values (\( R > 1.5 \)), signifying high active tectonics (Figure 4a). The larger relief values result from the nectontic regime of the region (Thomas et al., 2010). In the case of \( R_r \), 19 basins, covering \( \sim 50\% \) area, have moderate values (0.02–0.05; Table 1, Figure 4b). Basins 2, 5, 20–22 and 42–43 show higher \( R_r \) values (\( R_r > 0.05 \)), indicating areas of significant relief and steeper slopes underlain by resistant rocks (Vittal et al., 2004). The \( R_n \) values range between 0.090 (basin 34) and 2.438 (basin 1; Table 4). Ten basins (basins 1–7, 19, 20 and 40) covering \( \sim 42\% \) area, show higher \( R_n \) values (\( R_n > 1.5 \)) and classified under high active tectonic class (Figure 4c). The high \( R_n \) values suggest that these basin patches are more susceptible to soil erosion and have inherent structural complexity in relation to relief and drainage density (Anand & Pradhan, 2019).

4.2. Geomorphic indices
4.2.1. Hypsometric curve and hypsometric integral (HI)
The hypsometric analysis explains the different landscape evolution stages and erosional landforms (A.N. Strahler, 1952). The calculated HI values for the study area vary from 0.16 (basin 38) to 0.72 (basin 1; Table 5) and are classified into different active tectonic classes (Figure 5d; Amine et al., 2020b). To compare the spatial distribution of the HI value, the hypsometric curve is also plotted for each basin (Figure 5a-c). The basin with a high HI value (>0.5), e.g., basins 2, 4, 6 and 7, shows a convex curve (Figure 5a). The basin with an intermediate HI value (0.4–0.5), with complex S-shaped curves (Figure 5b), is found to be randomly distributed over the study area (Figure 4d) and located in moderately dissected hills and valleys. Most of the basins (basins 25 to 43, covering \( \sim 39\% \) area), in the western portion (Garo Hills region), between Dauki, Dhubri and Dudhnai Faults, are found to have low HI values (<0.4), suggesting old stage of the development process (Figure 4d). These tracts are mostly eroded and least affected by active tectonics. A similar inference is also evident from the hypsometric curve (concave-shaped curve) and subdued relief of those basins (Figure 4a and 5c).

4.2.2. Asymmetry factor (Af) and transverse topographic symmetry factor (TTSI)
The Af is calculated for all 43 basins, and the difference between the observed Af and 50 (\( AF = |AF-50| \)) is obtained in absolute terms (Table 5) and plotted in
Table 5. Calculated geomorphic indices for the Meghalaya.

| Basin ID | HI | AF | TTSI | BSI | VP | SLGI | SSI |
|----------|----|----|------|-----|----|------|-----|
| 1        | 0.53 | 17.61 | 0.16 | 1.44 | 0.33 | 1027.53 | 1.63 |
| 2        | 0.61 | 4.41 | 0.44 | 6.42 | 0.29 | 737.78 | 1.36 |
| 3        | 0.31 | 5.67 | 0.29 | 1.24 | 0.98 | 272.50 | 1.44 |
| 4        | 0.68 | 7.23 | 0.29 | 5.14 | 0.19 | 975.68 | 1.34 |
| 5        | 0.50 | 16.25 | 0.47 | 2.81 | 0.39 | 553.46 | 1.26 |
| 6        | 0.56 | 17.04 | 0.51 | 1.64 | 0.25 | 798.71 | 1.33 |
| 7        | 0.60 | 16.10 | 0.35 | 2.02 | 1.10 | 830.66 | 1.35 |
| 8        | 0.40 | 16.39 | 0.45 | 1.66 | 0.97 | 214.15 | 1.19 |
| 9        | 0.55 | 6.43 | 0.20 | 2.66 | 0.63 | 272.99 | 1.60 |
| 10       | 0.37 | 9.52 | 0.40 | 2.38 | 0.93 | 183.39 | 1.43 |
| 11       | 0.72 | 30.55 | 0.51 | 0.91 | 0.55 | 157.22 | 1.30 |
| 12       | 0.52 | 26.04 | 0.59 | 3.68 | 0.28 | 281.34 | 1.28 |
| 13       | 0.60 | 1.97 | 0.53 | 5.84 | 1.53 | 316.82 | 1.40 |
| 14       | 0.51 | 6.14 | 0.22 | 3.06 | 0.74 | 263.31 | 1.47 |
| 15       | 0.28 | 8.20 | 0.35 | 1.95 | 0.31 | 306.40 | 1.46 |
| 16       | 0.65 | 6.25 | 0.37 | 7.78 | 0.38 | 236.28 | 1.36 |
| 17       | 0.53 | 22.35 | 0.39 | 3.61 | 0.44 | 467.99 | 1.33 |
| 18       | 0.33 | 22.38 | 0.47 | 2.25 | 0.50 | 396.33 | 1.30 |
| 19       | 0.52 | 21.17 | 0.49 | 2.15 | 0.30 | 648.87 | 1.45 |
| 20       | 0.60 | 0.05 | 0.31 | 5.30 | 0.82 | 899.62 | 1.32 |
| 21       | 0.52 | 7.03 | 0.34 | 2.22 | 0.30 | 561.31 | 1.41 |
| 22       | 0.57 | 18.55 | 0.46 | 2.63 | 0.49 | 399.36 | 1.27 |
| 23       | 0.53 | 16.82 | 0.40 | 2.18 | 0.37 | 298.26 | 1.22 |
| 24       | 0.42 | 12.54 | 0.14 | 5.07 | 0.37 | 161.44 | 1.37 |
| 25       | 0.27 | 16.80 | 0.41 | 2.28 | 0.43 | 207.30 | 1.34 |
| 26       | 0.61 | 16.41 | 0.44 | 2.52 | 0.25 | 91.24 | 1.28 |
| 27       | 0.31 | 24.32 | 0.45 | 3.79 | 0.56 | 107.21 | 1.34 |
| 28       | 0.22 | 7.07 | 0.32 | 7.94 | 1.03 | 229.85 | 1.45 |
| 29       | 0.22 | 20.16 | 0.40 | 5.03 | 0.70 | 218.81 | 1.63 |
| 30       | 0.22 | 22.58 | 0.36 | 2.14 | 0.71 | 106.25 | 1.34 |
| 31       | 0.21 | 15.85 | 0.35 | 2.03 | 0.89 | 209.97 | 1.60 |
| 32       | 0.30 | 24.16 | 0.44 | 4.87 | 2.43 | 21.77 | 1.39 |
| 33       | 0.33 | 8.85 | 0.29 | 3.22 | 2.42 | 21.26 | 1.37 |
| 34       | 0.36 | 6.84 | 0.24 | 3.45 | 1.54 | 19.44 | 1.39 |
| 35       | 0.38 | 9.96 | 0.27 | 3.69 | 1.50 | 22.23 | 1.29 |
| 36       | 0.32 | 18.02 | 0.28 | 2.64 | 0.83 | 28.21 | 1.35 |
| 37       | 0.31 | 11.16 | 0.33 | 4.46 | 1.53 | 27.06 | 1.55 |
| 38       | 0.16 | 27.85 | 0.53 | 2.22 | 0.98 | 86.35 | 1.65 |
| 39       | 0.17 | 2.64 | 0.24 | 3.23 | 0.65 | 153.10 | 1.51 |
| 40       | 0.31 | 12.72 | 0.31 | 2.26 | 0.36 | 232.35 | 1.63 |
| 41       | 0.23 | 0.71 | 0.21 | 1.89 | 1.07 | 123.80 | 1.25 |
| 42       | 0.38 | 11.26 | 0.32 | 2.48 | 0.92 | 140.52 | 1.46 |
| 43       | 0.32 | 9.90 | 0.34 | 2.09 | 3.31 | 154.21 | 1.20 |

(a) Hypsometry curve of the extracted drainage basins in the study area for HI > 0.5: convex shape curve in the upper portions (young stage of development); (b) for 0.4 ≤ HI ≤ 0.5: S-shaped curve (mature stage); (c) for HI < 0.4: concave shape in the upper portion (old stage of development).

4.2.3. Basin shape index (BSI)

In tectonically active places, the young basins tend to have an elongated shape, normal to the topographic gradient (Ramírez-Herrera, 1998). Most of the basins (except basins 1, 3, 6, 8, 11, 15, 24 and 41) show moderate to high value of BSI, referring to elongated nature and intermediate to high active tectonic class (Figure 6d). The BSI value larger than 3.5 indicates an elongated basin, while the value between 2.0 and 3.5 indicates a moderately elongated shape (Zhang et al., 2019). A maximum elongation is observed in the northwestern part of basin 28 between Dhubri Faults, followed by basins 16 and 13 (Table 5). The lowest value of 0.91 for basin 11 (Table 5) in the eastern portion (in the Jaintia Hill region) is observed, suggesting a stable, mature stage (Figure 6d).
4.2.4. Valley floor width to height ratio (Vf)

The Vf is calculated in basins at more than one location (Figure 7a) and averaged using the DEM data. The Vf ranges between 0.19 (basin 4) to 7.41 (basin 14; Table 5), where low values (Vf < 0.5) indicate V-shaped, deeply incised valleys with higher upliftment rates (Mahmood & Gloaguen, 2012). Basins with a low Vf value, signifying a high active tectonic class, are distributed in the central portion of the study area (Figure 7b). It mainly consists of higher relief
Table 6. Assigned active tectonic classes of geomorphic indices and obtained indices of relative active tectonics (IRAT) based on average of classes of the areal parameter (AP), relief parameter (RP) and geomorphic indices (GI).

| Basin ID | BSI | Vf | Ht | SLLR | AF | SSI | TTSI | GI | AP | RP | Value | Class |
|----------|-----|----|----|------|----|-----|------|----|----|----|-------|-------|
| 1        | 3   | 1  | 1  | 1    | 1  | 2   | 3    | 1.71| 2.50| 1.33| 1.85  | 1     |
| 2        | 1   | 1  | 1  | 1    | 1  | 1   | 1.29| 1.75| 1.33| 1.46  | 1     |
| 3        | 3   | 2  | 3  | 3    | 3  | 1   | 2.43| 2.75| 1.33| 2.17  | 3     |
| 4        | 1   | 1  | 1  | 1    | 2  | 1   | 1.29| 1.75| 1.33| 1.46  | 1     |
| 5        | 2   | 1  | 2  | 1    | 1  | 1   | 1.29| 2.50| 1.00| 1.60  | 1     |
| 6        | 3   | 1  | 1  | 1    | 1  | 1   | 1.29| 3.00| 1.33| 1.87  | 2     |
| 7        | 2   | 3  | 1  | 1    | 1  | 2   | 1.57| 2.25| 1.67| 1.83  | 1     |
| 8        | 3   | 2  | 2  | 3    | 1  | 1   | 1.86| 2.50| 2.00| 2.12  | 2     |
| 9        | 2   | 2  | 1  | 3    | 3  | 2   | 2.14| 2.50| 2.67| 2.44  | 4     |
| 10       | 2   | 2  | 3  | 3    | 2  | 1   | 2.14| 2.50| 2.67| 2.44  | 4     |
| 11       | 3   | 2  | 1  | 3    | 1  | 1   | 1.71| 2.50| 3.00| 2.40  | 4     |
| 12       | 1   | 2  | 1  | 3    | 1  | 1   | 1.43| 1.50| 2.33| 1.75  | 1     |
| 13       | 1   | 3  | 2  | 1    | 1  | 1   | 1.71| 1.25| 2.67| 1.88  | 2     |
| 14       | 1   | 3  | 3  | 1    | 1  | 2   | 2.14| 2.00| 2.33| 2.16  | 3     |
| 15       | 3   | 1  | 3  | 2    | 1  | 1   | 2.00| 2.25| 2.00| 2.08  | 2     |
| 16       | 1   | 1  | 1  | 3    | 3  | 1   | 1.71| 1.25| 2.33| 1.77  | 1     |
| 17       | 1   | 1  | 3  | 2    | 1  | 1   | 1.29| 1.75| 2.67| 1.79  | 1     |
| 18       | 2   | 2  | 2  | 3    | 1  | 1   | 1.71| 2.00| 2.00| 1.90  | 2     |
| 19       | 2   | 1  | 1  | 1    | 1  | 1   | 1.14| 2.25| 1.33| 1.58  | 1     |
| 20       | 1   | 2  | 1  | 3    | 1  | 1   | 1.57| 1.25| 1.00| 1.27  | 1     |
| 21       | 2   | 1  | 1  | 1    | 2  | 1   | 1.43| 2.00| 1.67| 1.70  | 1     |
| 22       | 2   | 1  | 1  | 2    | 1  | 1   | 1.29| 2.25| 2.00| 1.85  | 1     |
| 23       | 2   | 1  | 1  | 3    | 1  | 1   | 1.57| 2.50| 2.33| 2.13  | 2     |
| 24       | 3   | 1  | 2  | 3    | 2  | 1   | 3.00| 3.00| 3.00| 2.55  | 4     |
| 25       | 1   | 3  | 3  | 3    | 1  | 1   | 1.71| 2.00| 2.67| 2.13  | 2     |
| 26       | 2   | 2  | 2  | 3    | 1  | 1   | 2.00| 2.00| 3.00| 2.33  | 3     |
| 27       | 1   | 2  | 3  | 3    | 1  | 1   | 1.71| 1.50| 3.00| 2.07  | 2     |
| 28       | 1   | 3  | 3  | 3    | 2  | 1   | 2.14| 1.25| 2.67| 2.02  | 2     |
| 29       | 1   | 3  | 3  | 3    | 1  | 2   | 2.00| 1.25| 2.67| 1.97  | 2     |
| 30       | 2   | 2  | 3  | 3    | 1  | 1   | 2.00| 2.25| 3.00| 2.42  | 4     |
| 31       | 2   | 2  | 3  | 3    | 1  | 2   | 2.14| 2.25| 2.33| 2.24  | 3     |
| 32       | 1   | 3  | 3  | 3    | 1  | 1   | 1.86| 1.50| 3.00| 2.12  | 2     |
| 33       | 2   | 3  | 3  | 3    | 2  | 1   | 2.29| 2.00| 3.00| 2.43  | 4     |
| 34       | 2   | 3  | 3  | 3    | 3  | 1   | 2.43| 2.00| 3.00| 2.48  | 4     |
| 35       | 1   | 3  | 3  | 3    | 2  | 1   | 2.14| 1.75| 3.00| 2.30  | 3     |
| 36       | 2   | 2  | 3  | 3    | 1  | 1   | 2.00| 2.00| 3.00| 2.33  | 3     |
| 37       | 1   | 3  | 3  | 3    | 2  | 2   | 2.29| 1.50| 3.00| 2.26  | 3     |
| 38       | 2   | 2  | 3  | 3    | 1  | 2   | 2.00| 2.50| 2.33| 2.28  | 3     |
| 39       | 2   | 2  | 3  | 3    | 3  | 2   | 2.43| 2.00| 2.33| 2.25  | 3     |
| 40       | 2   | 1  | 3  | 3    | 2  | 2   | 2.14| 1.75| 2.00| 1.96  | 2     |
| 41       | 3   | 3  | 3  | 3    | 1  | 2   | 2.57| 2.75| 2.67| 2.66  | 4     |
| 42       | 2   | 2  | 3  | 3    | 2  | 1   | 2.14| 2.50| 2.00| 2.21  | 3     |
| 43       | 2   | 3  | 3  | 3    | 2  | 1   | 2.29| 2.50| 2.00| 2.26  | 3     |

**Figure 8.** (a) Index of Relative Active Tectonics (IRAT); (b) Lineament density map of the Meghalaya.

(Figure 4a), with deeply incised V-shaped valleys representing the young stage of basin development and active plateau region (Sarma et al., 2015). Moreover, the basin near the southern escarpment (basins 1, 2, 4–6), draining across the Dauki Fault, shows the maximum incision (lowest Vf values). These basins are located in moderately to highly dissected plateau and hills and valley geomorphological units. The basins (7, 13, 14, 28, 32–35, 37, 41 and 43) have large Vf values (>1; signifying low active tectonics), representing flat-floored U-shaped valleys showing the dominance of erosional and depositional processes. These basins generally consist of alluvial deposits in the lower portions near mountain fronts with low erosional resistance and spreading laterally. However, the upper reaches of these basins have a more erosion-resistant
4.2.5. Stream length gradient index (SLGI) and stream sinuosity index (SSI)

The high peaks in SLGI represent an abrupt change in channel slope. The concave longitudinal profile develops in channels that are not tectonically active and have lower SLGI values. The values of averaged SLGI range from 19.44 (basin 34) to 1027.53 (basin 1; Table 5). The SLGI values are classified into three classes (Table 1; Dehbozorgi et al., 2010). The basins with high resistant rocks show high values of SLGI and reflect upliftment due to active tectonics, while low values indicate soft and fragile rocks or when streams are flowing through strike-slip faults (Dar et al., 2014). The basins in the central portion (Khasi Hills region) (basins 1, 2, 4–7, 19–21) are Class 1, indicating a strong tectonic influence (Figure 7c). Despite having more or less similar geological units in the western part than the central portion (Figure 3a), lower SLGI values are observed in the northwestern region, which may be attributed to the subdued topography of these basins (Figure 1). In contrast, the basins dominated by soft sedimentary rocks (ES, Figure 2a) in the southwestern and northeastern parts show consistent results and lower values (Figure 7c).

The SSI ranges from 1.19 (basin 8) to 1.65 (basin 38), showing the sinuous character of the streams and active tectonics. The classified map shows that all the basins have moderate to low value of SSI (≤2.5), signifying moderate to high active tectonics (Figure 7d; Table 5). An inverse relation between channel slope and stream sinuosity is observed. Tectonic uplift and strike-slip movement are recorded in the sinuosity index as variation in stream velocity occurs in response to gradient modification, governing the erosional and depositional character of the stream (Gomez & Marron, 1991). The class numbers associated with different basins of different indices are utilised to produce relative tectonic activity classes (Table 6).

Comparing the spatial distribution of different classes of different parameters with the geological setting of the study area revealed that landscape evolution is mainly influenced by tectonic activity. The basins with the same geological setting fall under the different classes of the same parameters. Basins 4 and 6 have Palaeozoic era formations underneath (Figure 2a) but fall under different indices such as BS1, AF, TTSI and others (Figure 4). As per hypsometric analysis, the convex shape hypsometry curve of basins with high HI values in high topographic regions suggests higher erosional resistance in conjunction with the varying rock strength from moderate to very strong in these tracts (Figure 2a & 4d). Considering the uniformity in climatic conditions in central and western Meghalaya, the HI and SLGI results that reflect both climate and rock strength suggest that local geomorphology and drainage development are affected by the tectonic uplifting (Figure 7c). At the same time, the deformation zone may have been partially impacted by climate, such as the central-southern zone.

4.3. Index of relative active tectonics (IRAT)

The average of measured morphometric parameters and geomorphic indices of 43 basins is calculated through spatial analysis and data integration and utilised for the spatial distribution of IRAT (Table 6; Anand & Pradhan, 2019; Mahmood & Giaoguen, 2012). The basins with high relief generally show high to very high active tectonics (Figure 4a and 8a) and cover ~66.5% of the study area (14,924 km²). The basins of the Khasi Hills region (basins 1, 2, 4, 16 and 19–22), bounding between Dauki Fault in the south and Oldham Fault in the north, are identified with very high (IRAT <1.851) IRAT class (Figure 8a). Similarly, most of the basins in the Jaintia Hills regions (basins 6–8, 12, 13 and 15), associated with Dauki and Tluh Faults, represent high to very high relative active tectonics. The basins possess mixed IRAT classes (classes 2, 3 and 4). The basins of lower reaches with less relief are identified with moderate to low level relative active tectonics (basins 24, 26, 30–39, 41–43; mostly in the southwestern portion), while the basins 25, 27–29 and 40, covering most of the Garo Hills region, are showing high class (1.851–2.130) of IRAT due to presence of structural features such as Dapsi Thrust, Chedrang, Darugiri, Dudhani and Samin Faults. Overall, the basins falling under classes 3 and 4 (moderate to low) of IRAT cover only 4288 km² (Figure 8a). Thus, two-thirds of the study area is classified as class 1 or 2 of very high or high tectonic activity in terms of evident geomorphic response. IRAT tends to increase along Dauki, Kulsi, Tluh, Oldham Faults and Barapani shear zone, showing that tectonic activity is currently high in the region.

Seismic activity is generally linked with rapid tectonic movement and is associated with active deformation zones (Softa et al., 2018). Over the last 230 years, the study region has experienced more than 300 mutually exclusive earthquakes of Mw 3.5 or more. Many events are found in the central and northwestern parts along the diagonal axis (Figure 2a) and are mainly associated with Dhubri, Dauki, Khulsi, Dudhmai, Darungiri, Oldham, Samin Faults and Barapani shear zone. The results are also coherent with this trend, with high IRAT values along the NW-SE (increasing west to east) of Meghalaya. Structural discontinuities are the geomorphological expression of the lineaments that developed due to tectonics representing the structural deformation in a region.
5. Conclusion

The present study aims to identify the tectonic activity of the Meghalaya region, India. Drainage basins and corresponding stream networks are delineated based on the SRTM-DEM (30 m resolution). Morphometric parameters and geomorphic indices for each 43 drainage basins are calculated and analysed further. The values of each index are grouped into Classes 1, 2 and 3, signifying different tectonic activity levels (high, moderate or low). The result shows that rapid uplift and active tectonic deformation have played a significant role in landscape evolution. As evident from morphometry analysis, the high value of SLGI and HI along the southern escarpment and higher river incision indicates rapid uplifting of the Khasi and Jaintia Hills regions. At the same time, smaller values of geomorphic indices in the Garo Hills region reflect relatively slow uplift, which is coherent with the reported differential rate of movement of ~3 mm/year to ~6 mm/year, increasing from west to east along the Dauki Fault. The results obtained from other parameters have also endorsed this finding and confirmed the active tectonic deformation and differential uplift of the Meghalaya.

Further, the integrated spatial analysis of IRAT computed from different morphometric and morphotectonic parameters reveals that most of the basins covering the Khasi and Jaintia Hills region and partially Garo Hills region of the study area (covering ~66.5% of the area) fall under high to very high rate of active tectonic deformation. The majority of the Khasi and Jaintia Hills basins are primarily identified with very high IRATs. These basins show a strong correlation with structural features in the region (such as the Dauki Fault, Barapani shear, Kulsi, Oldham and Dudhani Faults) and have high lineament density confirming the findings of IRAT.

The present study will help in the identification of gradual-temporal changes in the landscape due to endogenic geomorphologic processes and zonation of landslides and seismic-hazard-prone areas.

Data availability statement

The authors confirm that some portion of the data supporting the findings of this study is available within the article and derived data supporting the findings of this study are available upon reasonable request.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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References

Amine, A., El Ouardi, H., Zebari, M., & El Makrini, H. (2020a). Active tectonics in the Moulay Idriss Massif (South Rifian Ridges, NW Morocco): New insights from geomorphic indices and drainage pattern analysis. *Journal of African Earth Sciences*, 167(July), 103833. https://doi.org/10.1016/j.jafrearsci.2020.103833

Amine, A., El Ouardi, H., Zebari, M., El Makrini, H., & Habibi, M. (2020b). Relative landscape maturity in the South Rifian ridges (NW Morocco): Inferences from DEM-based surface indices analysis. *Applied Computing and Geosciences*, 6(June), 100027. https://doi.org/10.1016/j.acage.2020.100027

Anand, A. K., & Pradhan, S. P. (2019). Assessment of active tectonics from geomorphic indices and morphometric parameters in part of Ganga basin. *Journal of Mountain Science*, 16(8), 1943–1961. https://doi.org/10.1007/s11629-018-5172-2

Argyriou, A. V., Teeuw, R. M., Soupios, P., & Sarris, A. (2017). Neotectonic control on drainage systems: GIS-based geomorphometric and morphotectonic assessment for Crete. *Journal of Structural Geology*, 104(November), 93–111. https://doi.org/10.1016/j.jsg.2017.10.002

Ayaz, S., & Dhali, M. K. (2020). Longitudinal profiles and geomorphic indices analysis on tectonic evidence of fluvial form, process and landform deformation of Eastern Himalayan Rivers, India. *Geology, Ecology, and Landscapes*, 4(1), 11–22. https://doi.org/10.1007/24749508.2019.1568130

Baruah, M. P., Bezbbaruah, D., & Goswami, T. K. (2022). Active tectonics deduced from geomorphic indices and its implication on economic development of water resources in South-Eastern part of Mimik massif. *Ecology, Geography, and Landscapes*, 6(2), 1–14 https://doi.org/10.1007/24749508.2020.1754705

Bhat, M. A., Dar, T., & Baj, B. S. (2020). Morphotectonic analysis of Aripal Basin in the North-Western Himalayas (India): An evaluation of tectonics derived from geomorphic indices. *Quaternary International*, 568(December), 103–115. https://doi.org/10.1016/j.quaint.2020.10.032

Bhukosh-Geological Survey India 2021, (narrative: 21 August 2021). https://bhukosh.gsi.gov.in/Bhukosh/MapViewer.aspx

Bilham, R., & England, P. (2001). Plateau ‘pop-up’ in the great 1897 Assam earthquake. *Nature*, 410(6830), 806–809. https://doi.org/10.1038/35071057

Biswas, S., Coutand, I., Grujic, D., Hager, C., Stöckli, D., & Grasemann, B. (2007). Exhumation and uplift of the Shillong plateau and its influence on the eastern Himalayas: New constraints from apatite and zircon (U-Th-Sm)/He and apatite fission track analyses. *Tectonics*, 26(6), 1–22. https://doi.org/10.1029/2007TC002125
(Utica-Mateur region, northeastern Tunisia). Geocarto International, 32(11), 1229–1242. https://doi.org/10.1080/10106049.2016.1195890

Raghukanth, S. T. G., Dixit, J., & Dash, S. K. (2011). Ground motion for scenario earthquakes at Guwahati city. Acta Geodaetica et Geophysis Hungarica, 46(3), 326–346. https://doi.org/10.1556/AGeoed.46.2011.3.5

Ramirez-Herrera, M. T. (1998). Geomorphic assessment of active tectonics in the Acambay Graben, Mexican volcanic belt. Earth Surface Processes and Landforms: The Journal of the British Geomorphological Group, 23(4), 317–332. https://doi.org/10.1002/(SICI)1096-9837(199804)23:4<317::AID-ESP845>3.0.CO;2-V

Rimando, J. M., & Schoenbohm, L. M. (2020). Regional relative tectonic activity of structures in the Pampenan flat slab segment of Argentina from 30 to 325, Geomorphology, 350 (February), 106908. https://doi.org/10.1016/j.geomorph.2019.106908

Sarma, J. N., Acharjee, S., & Murgante, B. (2015). Morphotectonic study of the Brahmaputra basin using geoinformatics. Journal of the Geological Society of India, 86(3), 324–330. https://doi.org/10.1007/s12594-015-0318-0

Schumm, S. A. (1956). Evolution of drainage systems and slopes in badlands at Perth Amboy: New Jersey. Geological Society of America Bulletin, 67(5), 597–646. https://doi.org/10.1130/0016-7606(1956)67<597:EODSSA>2.0.CO;2

Selby, M. J. (1980). A rock mass strength classification for geomorphic purposes: With tests from Antarctica and New Zealand. Zeitschrift für Geomorphologie, 24(1), 31–51. https://doi.org/10.1127/zfg/24/1984/31

Sharma, S., & Sarma, J. N. (2017). Application of drainage basin morphotectonic analysis for assessment of tectonic activities over two regional structures of the northeast India. Journal of the Geological Society of India, 89(3), 271–280. https://doi.org/10.1007/s12594-017-0599-6

Shukla, D. P., Dubey, C. S., Ningreichon, A. S., Singh, R. P., Mishra, B. K., & Singh, S. K. (2014). GIS-based morpho-tectonic studies of Alaknanda river basin: A precursor for hazard zonation. Natural Hazards, 71(3), 1433–1452. https://doi.org/10.1007/s11069-013-0953-y

Softa, M., Emre, T., Sözbilir, H., Spencer, J. Q., & Turan, M. (2018). Geomorphic evidence for active tectonic deformation in the coastal part of Eastern Black Sea, Eastern Pontides, Turkey. Geodinamica Acta, 30(1), 249–264. https://doi.org/10.1080/09853111.2018.1494776

Strahler, A. N. (1952). Hypsometric (area-altitude) analysis of erosional topography. Geographical Society of America Bulletin, 63(11), 1117–1142. https://doi.org/10.1130/0016-7606(1952)63[1117:HAAOT2.0.CO;2

Strahler, A. N. (1964). Part II. Quantitative geomorphology of drainage basins and channel networks. In Chow, V.T. (ed.). Handbook of Applied Hydrology (pp. 4–39). McGraw-Hill.

Strong, C. M., Attal, M., Mudd, S. M., & Sinclair, H. D. (2019). Lithological control on the geomorphic evolution of the Shillong Plateau in Northeast India. Geomorphology, 330 (April), 133–150. https://doi.org/10.1016/j.geomorph.2019.01.016

Taesiri, V., Pourkermani, M., Sorbi, A., Almasian, M., & Arian, M. (2020). Morphotectonics of Alborz Province (Iran): A case study using GIS method. Geotectonics, 54(5), 691–704. https://doi.org/10.1134/S001685212005009X

Thomas, J., Joseph, S., & Thrivikramaji, K. P. (2010). Morphometric aspects of a small tropical mountain river system, the southern Western Ghats, India. International Journal of Digital Earth, 3(2), 135–156. https://doi.org/10.1080/17538940903464370

Tsououlos, I. M., Koukouvelas, I. K., & Pavlides, S. (2008). Tectonic geomorphology of the easternmost extension of the Gulf of Corinth (Boetia, Central Greece). Tectonophysics, 453(1–4), 211–232. https://doi.org/10.1016/j.tecto.2007.06.015

USGS Earth Explorer. (2021). US Geological Survey Earth explorer. https://earthexplorer.usgs.gov/ (narrative: 21 August 2021)

USGS NEIC. (2021). US Geological Survey National Earthquake Information Centre, http://earthquake.usgs.gov/earthquakes (narrative: 21 August 2021)

Vernant, P., Bilham, R., Szélő, W., Drupka, D., Kalita, S., Bhattacharyya, A. K., & Berthet, T. (2014). Clockwise rotation of the Brahmaputra Valley relative to India: Tectonic convergence in the eastern Himalaya, Naga Hills, and Shillong Plateau. Journal of Geophysical Research: Solid Earth, 119(8), 6558–6571. https://doi.org/10.1002/2014JB011196

Vittal, S. S., Govindaiah, S., & Honne Gowda, H. (2004). Morphometric analysis of sub-watersheds in the Pavagada area of Tumkur district, South India using remote sensing and GIS techniques. Journal of the Indian Society of Remote Sensing, 32(4), 351–362. https://doi.org/10.1007/BF03030860

Zhang, T., Fan, S., Chen, S., Li, S., & Lu, Y. (2019). Geomorphic evolution and neotectonics of the Qianhe River Basin on the southwest margin of the Ordos Block, North China. Journal of Asian Earth Sciences, 176(June), 184–195. https://doi.org/10.1016/j.jseaes.2019.02.020