Active tectonics deduced from geomorphic indices and its implication on economic development of water resources in South-Eastern part of Mikir massif, Assam, India

Manash Protim Baruah, D. Bezbaruah and T. K. Goswami

Department of Applied Geology, Dibrugarh University, Dibrugarh, India

ABSTRACT

The geomorphic analysis of mountain fronts and related drainage networks can provide valuable insights about the recorded tectonic history of any given region especially when the area shows higher seismic activity in recent times. Therefore, such studies at a regional scale have been frequently undertaken using morphotectonic analysis to delineate areas having higher tectonic activity. Also, study of active tectonics in an area is very important for any development activity especially hydropower projects as it has a direct implication on the stability and life of that project. The area along the South-East part of the Mikir massif is considered as one of the deformed zones of the northeastern region of India which is demonstrated by its seismicity. In the present study, an attempt has been made to study the active tectonic in the study area with the help of eight geomorphic indices and to correlate the results with the recent seismic activity and other ground evidence and finally an assessment of the potential for irrigation and hydropower development project in that area. The results of the study show that the area is tectonically more active along the Kaliyani shear zone and close to the Naga orogenic front. This has also been confirmed by the soft sediments deformation in Quaternary deposits. Despite this higher tectonic activeness, the area is having good potential for the development of small-scale hydropower and irrigation projects.

1. Introduction

The Shillong–Mikir Plateau (SMP) is a part of the Indian shield, which is separated out from the peninsular shield, and moved to the east by about 300 km along the Dauki fault (Evans, 1964). Geologically the entire SMP has evolved during the Mesozoic to Tertiary time; mainly consist of crystalline rocks, which are partly covered by gently dipping Tertiary and younger sediments (Evans, 1964). This twin plateau is considered as one of the deformed zones of the northeastern region (NER) of India (Duarah & Phukan, 2011) which is demonstrated by its seismicity. The northwest–southeast trending long Kopili fault in the Assam valley separates the Shillong plateau and the Mikir massif by transverse tectonics (Kayal et al., 2012), which generates intense seismicity. Wide separation of Mikir massif and Shillong Plateau to the southeast as compared to the northwestern part appears to be developed due to either clockwise rotation of the Shillong plateau or counterclockwise movement of the Mikir massif to its east (Dutta, 1967). But, whether the Kopili Fault is responsible for the present disposition of Mikir massif that lies much North of Shillong plateau (Figure 1) or this may be the effect of Naga orogenic front present nearby, these questions have not been addressed in any literature till date.

The structural alignment of the Assam–Meghalaya Plateau and the surrounding region as they have seen today was achieved during the Cenozoic Era (Bhattacharjee, 1987). The upliftment was principally related to the orogenic movement of the Himalaya in the North and Naga orogene to the South and South-East of it. Only a couple of literature are available on the regional and tectonics of the Mikir Hills. A comprehensive study on the lineament fabric analysis of the Mikir Hills based on remote sensing and GIS application has been suggested that the Mikir Hills plateau can be divided into three parts, separated by ENE–WSW trending mega lineaments, roughly demarcated by Kaliyani River and Daigurung River (Dotiwala, 2000). The lineament fabric of all three zones is broadly similar; except a more easterly trend is dominant in Kaliyani lineament while the NE-SW trend is dominant in lineament adjacent to the Dhansiri Valley. Moreover, the observed general trend of foliation, fold axis in Gneissic Complex and mineral lineation in intrusive in the Mikir Hills have NE-SW to E-W orientation.

India’s Northeastern states, with their mountainous topography and perennial streams, have the largest hydropower potential in India. Together, Sikkim, Arunachal Pradesh, Assam, Meghalaya, Manipur, Mizoram, Nagaland, and Tripura account for almost
40% of the total hydropower potential of the country. According to data of North East Electric Power Cooperation Ltd (NEEPCO), the NE Region is blessed with the huge hydro potential of about 58971 MW, out of which 1427 MW (about 2.4%) has so far been harnessed as on February 2019 and another 2600 MW of hydropower is under construction (Power Potential of North East by NEEPCO 2019). The hilly areas of the State of Assam also have good hydro potential particularly in two hill districts – Karbi Anglong and North Cachar Hills (Baruwa, 2006). Despite this huge resource, the area has not been developed yet due to its geographical challenges and higher tectonic activity in the recent past. So to harness its vast potential, the area falls in Karbi Anglong district has been studied for small-scale irrigation and hydropower projects.

The study of active tectonics in an area is very important for any development activity especially hydropower projects as it has a direct implication on the stability and life of that project. Since geomorphic indices of active tectonics are useful tools to analyze the influence of active tectonics in areas experiencing rapid deformation (Keller & Pinter, 2002; Zovoili et al., 2004) and the analysis of drainage networks is a powerful tool to detect recent tectonic activity and uplift (Clark et al., 2004). So, to get a preliminary idea about the activeness of the area, an attempt has been made to analyze several geomorphic indices in the six river basins of the South-Eastern part of Mikir massif (Figure 2).

The objective of this paper is to assess active tectonic in the study area with the help of eight geomorphic indices and to correlate the results with the recent seismic activity and other field evidence and finally an assessment of the potential for irrigation and hydropower development project in that area.

2. Geological settings

The Assam–Meghalaya twin plateau, known as “Shillong Plateau” or “Shillong Massif” or “Shillong-Mikir Massif,” is a cratonic shield, the Assam part of which is represented by the Mikir hills. Geologically, Shillong Plateau and Mikir Hills plateau together form a northeastern outlier of the Indian peninsular shield. Like most of the world’s major Precambrian shield areas, the whole Assam–Meghalaya Plateau is encircled by relatively less stable intercratonic linear belt, viz., Naga – Partkai – Lushai (Arakan-Yoma) mobile belt.

Figure 1. Tectonic setting of Northeast India and surrounding regions (adapted from Angelier & Baruah, 2009). Names of main faults and thrusts indicated, with some abbreviations in the western Shillong Plateau (DT, Dapsi Thrust; DuF, Dudhnoi Fault; OF, Oldham Fault; CF, Chedrang Fault; SF, Samin Fault, BS, Barapani Shear Zone), and eastern Mikir Plateau (BL, Bomdila Lineament).
in the south and Himalayan belt in the north (Majumdar & Dutta, 2007). The Mikir Hills are separated from the Meghalaya Plateau by the alluvium tract of the Kopili River and the NE-SW Kopili fault (Nandy & Das Gupta, 1986). The oldest rocks of the Mikir hills Plateau are Archaean-Proterozoic gneiss and schist, overlain unconformably by the Proterozoic Shillong Group (quartzite, phyllite, amphibolite). These rocks have been intruded by late tectonic Proterozoic Khasi greenstone and Proterozoic-early Paleozoic porphyritic granite (Nandy, 2001). Isolated intrusions of ultramafic-carbonatite complex of late Cretaceous age occur along the plateau which is controlled by E-W trending Kaliyani lineament (Kumar et al., 1996). The granitoid within Mikir Hills comprises different sequences of porphyritic and non-porphyritic granites of both grey and pink varieties. The Shillong Group of rocks appear continuously along a linear belt in a NE-SW direction for about 240 km from the north of Mikir Hills in Assam to the Jadukata river section in the southern Meghalaya. Lithologically, this Group is an association of metamorphosed molassic assemblage of clastic sediments of sandstone, siltstone, shale, and conglomerate deposited in miogeosynclinal basin. Post-orogenic basic sills and dykes have been intruded invading the Shillong Group of metasediments. These intrusive bodies have shown weak regional metamorphism (Nandy, 2001).

3. Materials and methods

In the present study, eight geomorphic indices have been used to study the active tectonics prevail in the area. These indices have the advantage of being calculated from GIS over large areas as a reconnaissance tool to identify geomorphic anomalies possibly related to active tectonics. Indices of active tectonics may detect anomalies in the fluvial system or along mountain fronts which can be produced by local changes from tectonic activity resulting from uplift or subsidence (Hamdouni et al., 2007). Fieldwork has been carried out in the study area for evidences of active tectonics in Quaternary sediments.

Geomorphic indices useful for studying active tectonics include the mountain-front sinuosity ($S_{mf}$ index; Bull & McFadden, 1977), valley floor width–valley height ratio ($V_V$ index; Bull, 1978), hypsometric integral (Hi; Strahler, 1952), drainage basin asymmetry (AF index; Keller & Pinter, 2002), transverse
topographic symmetry factor (T index; Cox, 1994), drainage basin shape (Bs index; Bull & McFadden, 1977), stream-gradient index (SL index; Hack, 1973) and steepness index (SI index; Snyder et al. 2000).

3.1. Mountain front sinuosity ($S_{mf}$) was calculated via

$$S_{mf} = \frac{L_{mf}}{L_s}$$

where $S_{mf}$ is the mountain front sinuosity, $L_{mf}$ is the length of the mountain front along the bottom of the mountain and $L_s$ is the straight-line length of the mountain front (Bull & McFadden, 1977; Keller & Pinter, 2002).

3.2. The ratio of the width of the valley floor to valley height ($V_f$) was calculated using the equation below

$$V_f = 2V_{fw}/[(E_{ld} - E_{rc}) + (E_{rd} - E_{rc})]$$

which $V_{fw}$ is the width of the valley floor, $E_{ld}$ and $E_{rd}$ are the elevations of the left and right valley, respectively, and $E_{rc}$ is the elevation of the valley floor (Figure 3) (Bull & McFadden, 1977).

Both the sinuosity ($S_{mf}$) and valley floor to valley height ($V_f$) values can be calculated from topographic maps or aerial photographs. Lower values of $S_{mf}$ index indicate relatively active mountain fronts, while higher values signify a relatively moderate to less active/inactive mountain fronts (Burbank & Anderson, 2001; Keller & Pinter, 2002). Similar to the $S_{mf}$ index, lower values of the $V_f$ index indicate relatively active mountain fronts and reflect deep valleys with active incision related to uplift, whereas higher $V_f$ index values are associated with relatively moderate to less active mountain fronts that represent low uplift rates (Burbank & Anderson, 2001; Keller & Pinter, 2002; Silva et al., 2003).

In the present study, $S_{mf}$ was calculated for four mountain fronts, viz AA’, BB’, CC’, and DD’ (Figure 4) using $L_{mf}$ and $L_s$ values measured from SRTM images. These fronts are thus chosen that are separated by major dislocation surfaces and abrupt deflections in mountain front orientation. Similarly, $V_f$ is also calculated for all the eight major streams. In the conventional method, this parameter is only used at a set distance from the mountain front, as the erosive power of the stream steeply decreased when it reached the mountain front. Hence, for each drainage basins, $V_f$ is calculated at a prescribed distance upstream from the front (Silva et al., 2003), which is, in this case, is 250 m (Figure 4). Here only the higher order streams (up to 4th order) were considered as higher order streams showing a greater degree of tectonic control on valley development than a lower order stream. The results thus obtained were analyzed segment wise from AA’ to DD’ (as in case of $S_{mf}$).

3.3. Hypsometric integral

The hypsometry (Hi) of drainage basins (Strahler, 1952) has been evaluated in an attempt to simulate the geologic stages of development of drainage basins and to study the influence of varying factors like tectonics, climate, and lithology on watershed evolution. The hypsometric curve is generated by plotting the relative drainage basin height ($h/H$) that is known as the total basin height ratio against the relative drainage basin area ($a/A$) which is the total basin area ratio (Keller & Pinter, 2002; Strahler, 1952). The hypsometric integral is an index that describes the distribution of elevation of a given area of a landscape (Strahler, 1952). Hypsometric integral is generally derived for a particular drainage basin and is independent of the basin area. The area below the hypsometric curve is defined by this index and thus expresses the volume of a basin that has not been eroded. The simple equation that may be used to calculate the index (Keller & Pinter, 2002) is

$$Hi = \frac{\text{Mean Elevation} - \text{Minimum Elevation}}{\text{Maximum Elevation} - \text{Minimum Elevation}}$$

Figure 3. Schematic diagram showing valley floor width to height ratio ($V_f$) (From Keller & Pinter, 2002, figure 4.15, p. 139).
High values of the index generally mean that not much of the uplands has been eroded, and may suggest a younger landscape, perhaps produced by active tectonics (Hamdouni et al., 2007). In this analysis of Hi, we consider whether the curve is convex in its upper portion, convex to concave, or convex in the lower portion, as well as the value of the index itself.

In the present study, all the rivers are originated at a higher elevation in the hilly ranges and flow through the plain up to the confluence at the Dhansiri River. For the computation of the Hypsometric analysis, we consider only that portion of the watershed from the source up to the mountain front (Figure 4). Analysis of the hypsometric integral in the study area was done using digital elevation models utilizing GIS applications. All the river basins are delineated from the DEM in ArcGIS software. The mountain front as marked from the DEM is superimposed above the drainage basin and the required drainage area lies above the front are clipped from the original basin area. The hypsometric analysis is then done based on the modified catchment areas and the results are shown in Table 1.

### 3.4. The asymmetry factor (AF)

AF was developed to detect tectonic tilting transverse to flow at the drainage basin on larger scales (Keller & Pinter, 2002). The asymmetry factor is determined by the formula:

$$AF = 100 \left( \frac{A_r}{A_t} \right)$$

where $A_r$ is the area of the basin to the right of the trunk stream that is facing downstream and $A_t$ is the total area of the drainage basin. The asymmetry factor (AF) for most stream network that formed and maintained flow in steady settings is 50. Since the asymmetry factor is susceptible to any tilting perpendicular at

---

**Figure 4.** Digital elevation model (DEM) with the drainage network and the calculated geomorphic indexes in the South-Eastern part of Mikir massif. The arrows show the direction of basin asymmetry. The mountain fronts AA', BB', CC', and DD' that are considered for the present study are depicted. $S_{rot}$ values indicate that CC' and DD' fronts are tectonically active whereas AA' and BB' fronts are relatively inactive. Location of sections for the $V_f$ calculations for all the four segments are shown. The inset show the hypsometric curves for the eight river basins present in the study area.
the trunk of the stream, any AF values greater or less than 50 indicate the possibility of tilting.

3.5. The transverse topographic symmetry factor (T) was calculated via

\[ T = \frac{D_s}{D_d} \]  

(5)

where \( D_s \) is the space from the midline of the drainage basin to the midline of the active belt and \( D_d \) is the space from the midline to the basin limit (Cox, 1994). In a completely symmetric basin \( T = 0 \) and as asymmetry increases \( T \) approaches to value of 1.0.

In the study area, both Asymmetry Factor and Transverse Symmetry Factor are calculated for all the eight river basin present and the values are shown in Table 1. For each river basin, \( T \) is calculated for different segments and the average value of \( T \) is interpreted in terms of tectonic activeness. Along with the AF values, other information such as the direction of the tilting of each drainage basin and the highest order of stream for each basin were also incorporated. The maximum order of the stream is considered to be an important factor in the interpretation, as it will indicate the stage of development or the maturity of that particular river basin. As a thumb rule, a higher order basin should be a mature one and the values of AF thus should better indicate the existing tectonic tilting in that region.

3.6. Drainage basin shape (\( B_s \))

\( B_s \) is a another quantitative index which was calculated from the equation

\[ B_s = \frac{B_l}{B_w} \]  

(6)

where \( B_l \) is the length of the basin, measured from its outline to the most distal point in the drainage divide, and \( B_w \) is the width of the basin. \( B_s \) was calculated for eight basins in the study areas (Table 1).

3.7. The stream length gradient index was calculated via

\[ SL = \frac{\Delta H}{\Delta L}L \]  

(7)

which SL is the stream length gradient index, \( \Delta H/\Delta L \) is the stream gradient at a distinct point in the channel and \( L \) is the total channel length (Hack, 1973; Keller & Pinter, 2002). \( SL \) is used to identify recent tectonic activities. Uplift zones are indicated by anomalously high SL values with a specific rock type and within a particular drainage segment (Azor et al., 2002; Chen et al., 2003; Keller & Pinter, 2002; Troiani & Della Seta, 2008). Commonly, high SL index values are present where rivers cross hard rocks and reflect relatively high tectonic activity, while low SL index values indicate relatively low tectonic activity and suggest less-resistant and softer rock types (Hack, 1973; Keller & Pinter, 2002).

Values of the SL index over the study area, determined from digital elevation models using ArcGIS software. In the present study, we calculate the S. L. values at the points where two lower order streams meet to form a higher order and for points where a major sub-tributary meets the main channel. A GIS-based interpolation map has been prepared using ArcGIS software for the SL values that are calculated using Equation (7) and the results are shown in Figure 5. Different color coding is used to show the variation of SL index throughout the area.

3.8. Steepness index (SI)

Evolution of landscape in the tectonically active mountain region is intrinsically related to the combination of endogenic (crustal deformation) and exogenic (surface) processes (Synder et al., 2002). In such areas, rivers play an important role due to their ability to incise, which ultimately sets the rate of lowering of a landscape and therefore mass removal in actively rising mountainous regions (Synder et al., 2002). The bedrock incision rate is mainly controled by two factors, climate and tectonics. When climate and erosion
are balanced by uplifts, the longitudinal profile of a river would be graded and can be represented by a power law function in which the local channel slope \( S \) of a stream is a function of the stream drainage area \( A \) and can be represented as

\[
S = K_s A^{-\theta} \tag{8}
\]

Here \( K_s \) is the steepness index, \( \theta \) is the concavity.

The value of \( K_s \) should remain constant if there is no differential uplift for a given stream. However, if within the river basin, differential uplift took place \( K_s \) may change from one segment to another. The areas where differential uplift is higher, oversteepening of the river profile should occur and can be ascertained by the change in \( K_s \). However, in this equation, it is assumed that the role of lithology, channel geometry, and sediments variability has limited influence. This is reasonable considering that in the study area there is no significant lithological variation, rivers flow dominantly on the bedrock, and hence variable sediment supply may not have much influence on erosion coefficient. Therefore, in order to ascertain the variation in the uplift, changes in \( K_s \) can be used.

Survey of India topographic map [1:50,000] is used for delineating the catchment area for all the rivers in the area. For all the eight rivers, the longitudinal profile is constructed using the distance from the source and elevation data. For the present study, the lower order streams are excluded as in the case of stream length gradient index. The catchment area and slope for individual segments were calculated. Using the SPSS software, a regression analysis of \( \log(S) \) vs. \( \log(A) \) is done, which provides the values for concavity \( \theta \) and steepness index \( K_s \) for all the segments in each basin (Figure 6). In order to estimate the values of \( K_s \), we calculated the value of \( \theta \) which was obtained from the \( \log(S) \) vs. \( \log(A) \) regression analysis for all the segments. Different values of \( K_s \) for all the basins when plotted against the longitudinal river profile (Figure 7) it is observed that the similarities exist between the anomalous zones which are identified in the case of stream length gradient index with that of steepness index.

4. Result and discussion

In this section result of quantitative geomorphological indices along with qualitative geomorphological analyses is presented. Inferences here were drawn based on the results shown in Table 1.

Mountain front sinuosity (Smf) values lower than 1.4 indicate tectonically active fronts (Keller, 1986) while higher Smf values (>3) are normally associated
with inactive fronts. In the study area apart from the front DD’, all the other three fronts are relatively less active. From the extreme higher value of Smf for the front AA’, we can consider it as an inactive one. The front BB’ and CC’ showing inactive to moderately active front. The lower value of Smf associated with the front DD’ may be due to its position near the Naga orogene front, which might play an active role in the upliftment of the frontal part of the massif, in this segment.

Valley floor width to height ratio for the segment AA’, showing the mean value of $V_f$ 2.49 at a distance of 250 m from the front. This higher value of $V_f$ indicates major lateral erosion either due to stability of the base level or to tectonic quiescence. This can also evident from the irregular mountain-front and also from the higher value of $Smf$. For the segment BB’ the general trend of the mean value of $V_f$ decreases from NNW to SSE thus increases the activeness in the lower reach. The presence of a major lineament along the course of the Daigurung river largely governs the shape of the valley profile by providing the weak zone through which the river actively undertakes lateral erosion leads to U-shape valley development and hence higher $V_f$. Here, in this segment, the $Smf$ values also indicate a moderately active front.

**Figure 6.** Graphs showing regression analysis of the eight river basins for the calculation of concavity ($\theta$).
Activeness is gradually increasing towards SSE of the front where valleys were V-shape and the front also appears nearly straight.

In the segment CC', most of the valleys are V-shape, showing lower $V_f$ except one or two in Deopani River. The front appears more or less straight except at the middle where the course of the Deopani River is governed by a major lineament or a cross fault along which relative movement took place within the front. All the adjacent valleys showing lower values of $V_f$ up to the order 0.14 to 0.25 indicating higher tectonic activity along this front. In the segment DD', only two river basins, namely, Neperpatti and Harihajan, which are considered in this present study falls. All the nine valley profile taken in this segment has shown V-shaped valley development with much lower values of $V_f$ up to the order 0.05. Again the mountain front in this segment appears nearly straight in comparison to the other segment and has lower values of $S_{mf}$ as well. Thus, as a whole, we can infer that this DD’ segment is the most active front in the study area. DD’ segment lies very close to the Naga orogenic front. The compressional tectonic domain and also the counter-clockwise rotation of the Mikir block from near EW to NNE-SSW direction (Dutta, 1967) lead to higher tectonic activity in this segment.

The hypsometric curves show distinct convex-up shapes in basins like Daigurung, Nambar, and Deopani River (Figure 4). The convex parts correspond to the younger stage of erosion, related to neotectonic rejuvenation (Strahler, 1952). Small drainage basins would be dominated by hillslope processes and hence has convex hypsometric curves and hypsometric integrals close to 1, the curve would become concave with hypsometric integrals approaching 0 with increasing drainage area (Hurtrez et al., 1999).
Hence, from the concave shape of the hypsometric curve of Kaliyani River having \( H_i = 0.34 \), we can infer that this basin attains the late mature or monadnock stage and here the drainage area may exert a stronger influence on hypsometry than the uplift rate. The sigmoidal shape of hypsometric curves for basins like Jabrajan and Harihajan suggests a moderately eroded landscape and an early mature stage of erosion.

Hypsometric integral was positively correlated to uplift rate (Lifton & Chase, 1992). The highest \( H_i \) value (0.41) for Deopani River for segment CC’ is associated with convex hypsometric curves that confirms a higher level of tectonic activity (Figure 4). Other watersheds like Barneuria, Neperpatti, and Harihajan which shows Monadnock or Old stage are either due to their smaller dimension or due to their occurrence near the mountain front which intern affects the area that is exposed to erosion in upper reach from the front.

By observing the lower values of AF from the normal (AF = 50) for Kaliyani and Daigurung River basin and also considering the fact that these streams show the highest development of stream order 7th and 6th, respectively, we can infer that the whole area is tectonically active. Also, the location of these two basins near the Kaliyani Shear Zone also affects their direction of tilting. On the contrary, near-normal values of AF for Nambar River basin, indicate the area is tectonically quite stable as compared to the areas lies above and below. Anomalously higher values of AF for Deopani River basin undoubtedly indicate the activeness of that region. This might be due to its position near the Naga orogenic front, which supposed to be the tectonically most active zone in the entire study area. Much higher values for drainage basins of Barneuria, Jabrajan and normal values for Neperpatti and Harihajan are considered to be insignificant as these basins are relatively in a younger stage of development indicated by their lower stream order. Thus, the asymmetry shown by these basins might be due to local lithological or structural control existed in those areas.

For all the eight river basins Transverse topographic symmetry factor (T) varies from 0.33 to 0.94. Maximum values are shown by Neperpatti and Nambar River followed by Barneuria, Daigurung, Deopani, and Kaliyani River. By observing the general trends of the active meanders belt for all the river basins we can say that in a majority of the basins shifting of the trunk stream is towards SE or E-SE direction indicates that the regional tilting of the area is towards that particular direction. A prominent SE trend is also observed in Kaliyani and Daigurung River trunk stream which may be the effect of Kaliyani Shear zone present near to these two river basins.

In the study area most of the higher order mature drainage basins showing higher values of Basin Shape Index \( (B_s) \) or elongated in nature indicating active tectonics throughout the study area. Maximum elongation is observed for the Nambar river basin, followed by Daigurung and Deopani. Kaliyani, on the other hand, shows the lower value of \( B_s (B_s = 2.17) \) as it is the highest order stream present in the study area and also in the mature stage, thus adjust to the existing tectonic condition in order to attain the more evolved form.

From the GIS-based interpolation map of Stream length gradient index (SL) and Steepness index (SI), it has been noticed that areas having higher or anomalous values of S.L. index have also showing anomalous S.I. values and vice versa. Both the parameters have their common genetic relationship between the surface uplift and response of any channel gradient to it. Therefore, a common interpretation will serve the purpose of this study. In the study area, some interesting findings were observed. Firstly, the area lies close to the Kaliyani Shear Zone showing a higher surface uplift rate mainly in the upper reach of the Kaliyani River thus shown by the higher value of S.L. and S.I. Higher values of both S.L. and S.I. index concentrate towards the South-East corner of the study area; hence, the effect of Naga orogenic front near those areas cannot be denied. Finally, smaller pockets of anomalous values may be due to some structural control like joints, faults, and other discontinuities.

**Potential for irrigation and hydropower development projects in the area:**

The study of eight river basins of the Southeastern part of Mikir massif indicates that most of the higher order basins have good potential for the development of irrigation and small-scale hydropower plants. Higher order basins like Kaliyani, Daigurung, Nambar, and Deopani River have steeper gradient which provides required head and is very favorable for any hydropower projects. These higher order basins also attain mature to late mature or monadnock stage as indicated by the Hypsometric Integral \( (H_i) \). The youthful or young stage watersheds could release more sediments than the watersheds which have attained the mature stage. Hence, from the above observation, we can infer that quantity of sediment flux releases due to erosion at the upper reach for these watersheds will be minimum which is favorable for any hydropower projects constructed on these basins.

Anomalously higher uplift areas shown by the convex graded profile for some of the rivers like Nambar River (Location: 26°15’ 35.669’ N & 93°37’ 6.777’ E) and Deopani River (Location: 26°9’ 0.025’ N & 93°37’ 38.986’ E and 26°12’ 31.226’ N & 93°41’ 2.493’ E) also correlated with higher values of SL and SI indices. These
identified areas having a steeper gradient of the longitudinal river profile may be the favorable location for small hydroelectric power projects as they provide the required head. But, on the other hand, these areas are tectonically more active. Hence, for future earthquake, risk evaluation detailed geomorphological and seismotectonic studies should be undertaken in these areas.

5. Field evidence of active tectonics

In order to correlate the results of the morphotectonic studies with the active tectonic feature present in the study area fieldwork was carried out in the area. The Southern Mikir massif is supposed to be the more deformed zone as it lies very close to the Naga Orogenic Front. The NW-SE trending Dhansiri Lineament (Nandy, 2001), which governs the course of Dhansiri River is also a major tectonic feature present in the study area. From the satellite imagery, it has been noticed that the course of the river Dhansiri from Doyang-Dhansiri confluence upstream is diverted more towards W-SW and straight course of the stream strongly suggests the presence of an active fault there which marked as F-1 in the satellite imagery (Figure 8). Along that course, steep scarp up to 7 m height was observed in the left bank of Dhansiri facing downstream strongly suggest neotectonic upliftment (Figure 9). Offsetting of Quaternary deposits is the most direct evidence for suggesting reactivation of a fault (Patidar et al., 2008). The ideal preservation of such evidence is in the Quaternary sediments exposed in the scarp sections of bank stratigraphy. Offsetting and deformation of Quaternary deposits observed in the Dhansiri River section suggest structural deformation of the strata in the recent time (Figure 10(a,b)). The presence of boulder beds in the quaternary older alluvium at an elevation of 140 m above msl in one of the road sections suggests that the fluvial environment

Figure 8. Satellite imagery of the area showing the position of different streams along with the structural features like Dhansiri lineament, Naga schupen belt. The presence of the inferred fault F-1 is marked along the course of Dhansiri River. The red dot shows the location where offsetting of the Quaternary deposits were observed.
is dominant at that time which leads to the deposition of thick mid-channel boulder deposits and that got uplifted due to later tectonic disturbances (Figure 11).

6. Conclusion

From the study of geomorphic indices, it has been observed that higher values of $S_{mf}$ and $V_f$ associated with the front DD indicate that it is the most active front present in the area. As this segment lies very close to the Naga orogenic front and this compressional tectonic domain and also the counter-clockwise rotation of the Mikir block from near EW to NNE-SSW direction (Dutta, 1967) leads to higher tectonic activity in this segment. The asymmetry of each drainage basin and the general trends of the active meanders belt for all the river basins indicates regional tilting of the area is towards South–East or E-SE direction. A prominent SE trend is also observed in Kaliyani and Daigurung River basins as shown by

Figure 9. Figure shows a steep scarp along the course of Dhansiri River.

Figure 10. (a), (b) Exposed cliff section along the course of Dhansiri river showing offsetting of Quaternary deposits. Location is shown in Fig 8.

Figure 11. Figure shows exposed boulder bed at an elevation of 140 m above msl along Bokajan-Bogijan road section.
the tilting of these basins and shifting of the active meanders towards SE direction. This may be the effect of Kaliyani Shear zone present near to these two river basins.

Anomalous zones identified for both SL and SI indices are aligned along the Kaliyani shear zone and the South-Eastern part of the study area. Hence, the effect of Naga orogenic front near those areas is evident. The concave shape of the hypsometric curve of Kaliyani River having indicates that it attains the late mature or monadnock stage and hence the drainage area may exert a stronger influence on hypsometry than the uplift rate. The sigmoidal shape of hypsometric curves for basins like Jabrajan and Harihajan suggests a moderately eroded landscape and an early mature stage of erosion. The convex-up shape of the Hypsometric curve for Daigurung, Nambar and Deopani river basin indicates neotectonic rejuvenation. Anomalously higher uplift areas of these river basins also correlated with higher values of both SL and SI. This existing gradient in the river profile can be utilized for the economic construction of small-scale power so that the reservoir capacity will be very less and even in the tectonically active zone, it will not create any adverse effect in the lower reach of the stream. But the location of the project must be fixed in such a way that it will safe even if there is tectonic upliftment in the area.

Field evidence also supplement the active tectonics that is going on in the study area, which is indicated by steep scarp along the course of Dhansiri River, off-setting, and deformation of Quaternary deposits along the river section, fresh scarp in Pleistocene deposits observed near the Bokajan area suggest neotectonic readjustment of the area in recent time. The presence of boulder beds in the quaternary older alluvium at an elevation of 140 m above msl is strongly indicating upliftment of the area due to later tectonic disturbances.

The Southeastern portion of Mikir massif is tectonically active but we have to harness the natural resource present in the area; therefore, study of neotectonic activity and planning any civil engineering projects based on geomorphic indices are very important.

**Disclosure statement**

No potential conflict of interest.

**ORCID**

T. K. Goswami [http://orcid.org/0000-0003-4489-597X](http://orcid.org/0000-0003-4489-597X)

**References**

Angelier, J., & Baruah, S. (2009). Seismotectonics in Northeast India: A stress analysis of focal mechanism solutions of earthquakes and its kinematic implications.

Geophysical Journal International, 178(1), 303–326. [https://doi.org/10.1111/j.1365-246X.2009.04107.x](https://doi.org/10.1111/j.1365-246X.2009.04107.x)

Azor, A., Keller, E. A., & Yeats, R. S. (2002). Geomorphic indicators of active fold growth: South Mountain—Oak Ridge anticline, Ventura basin, southern California. Geological Society of America Bulletin, 114(6), 745–753. [https://doi.org/10.1130/0016-7606(2002)114<0745:GIOAFG>2.0.CO;2](https://doi.org/10.1130/0016-7606(2002)114<0745:GIOAFG>2.0.CO;2)

Baruwa, A. K. (2006). Small hydropower for rural electrification in Assam. Himalayan Small Hydropower Summit.

Bhattacharjee, C. C. (1987). Recent advances in the study of the structures and tectonics of North-East India. Proceedings of the seminar on the recent advances in the study of the Cenozoic Geology of North-Eastern region of India (pp. 44–56).

Bull, W. B., & McFadden, L. (1977). Tectonic geomorphology north and south of the garlock fault, California. In D. O. Dohering (Ed.), Geomorphology in arid regions (pp. 115–128). Publication in Geomorphology, State University of New York.

Bull, W. B., 1978. Geomorphic tectonic activity classes of the south front of the San Gabriel Mountains, California. U. S. Geological Survey Contract Report 14-08-001-G-394, (p. 59). Office of Earthquakes, Volcanoes, and Engineering, Menlo Park.

Burbank, D. W., & Anderson, R. S. (2001). Tectonic geomorphology. Blackwell Science, Inc.

Chen, Y. C., Sung, Q., & Cheng, K. Y. (2003). Along-strike variations of morphotectonic features in the Western Foothills of Taiwan: Tectonic implications based on stream gradient and hypsometric analysis. Geomorphology, 56(1–2), 109–137. [https://doi.org/10.1016/S0169-555X(03)00059-X](https://doi.org/10.1016/S0169-555X(03)00059-X)

Clark, M. K., Schoenbohm, L. M., Royden, L. H., Whipple, K. X., Burchfiel, B. C., Zhang, X., Tang, W., Wang, E., & Chen, L. (2004). Surface uplift, tectonics, and erosion of eastern tibet from large-scale drainage patterns. Tectonics, 23(1). TC1006. [https://doi.org/10.1029/2002TC001402](https://doi.org/10.1029/2002TC001402)

Cox, R. T. (1994). Analysis of drainage basin symmetry as a rapid technique to identify areas of possible Quaternary tectonic activity: An example from the Mississippi Embayment. Geological Society of America Bulletin, 106(5), 571–581. [https://doi.org/10.1130/0016-7606(1994)106<0571:AODBSSA>2.3.CO;2](https://doi.org/10.1130/0016-7606(1994)106<0571:AODBSSA>2.3.CO;2)

Dotiwa, F. (2000). A study of the lineament fabric of the mikir hills using satellite remote sensing data on a GIS system, for inputs to Exploration in the Dhansiri valley, Assam, India. Workshop on remote sensing and GIS for natural resource surveys in NE India. Department of Mathematical Sciences, Tezpur University.

Duarah, B. P., & Phukan, S. (2011). Understanding the tectonic behaviour of the shillong plateau, India using remote sensing data. Journal of the Geological Society of India, 77(2), 105–112. [https://doi.org/10.1007/s12594-011-0013-8](https://doi.org/10.1007/s12594-011-0013-8)

Dutta, T. K. (1967). Seismicity of Assam in relation to geotectonic processes-nature of instability of the Assam Wedge, Bulletin Int. Inst. Seis. And Earth. Eng., 4, 63.

Evans, P. (1964). Tectonic framework of Assam. Geological Society of India, 5, 80–96.

Hack, J. T. (1973). Stream-profile analysis and stream-gradient index. United States Geological Survey Journal of Research, 14(4), 421–429.

HAMDOUNI, R. E., IRIGARAY, C., Fernandez, T., CHACON, J., & KELLER, E. A. (2007). Assessment of relative active tectonics, southwest border of the sierra nevada (southern...
