An assessment of geomorphometric anomalies and their significance on the seismotectonic activity through geoinformatics

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The natural system of the drainage basin is interrupted by sub-surface faults and active tectonic processes. The anomalous nature of the drainage network and its basic morphological characteristics produce significant geomorphometric anomalies of the drainage basins which are an indicator of seismotectonic activity. In recent years, the increasing frequency of earthquakes and the subsequent damage in the Indian sub-continent necessitates a study of the seismotectonic significance with special reference to morphometric analysis. Hence, the present research is focused on studying the geomorphometric anomalies at a micro basin level and their impact on seismotectonic activity using geoinformatics. The study area is the lower Tista sub-basin which belongs to the Himalayan mountain in the northern part, whereas the southern part represents a peneplain surface. The quantitative databases of various morphometric parameters have been generated using digital elevation model data and satellite images to identify the geomorphic anomalies at the micro basin level which have been compared with past seismological databases to understand the impact on seismotectonic activity. The result shows that the drainage bifurcation, anomalous drainage network, drainage compression along the mountain front, narrow steep valleys in the high resistance surface, neotectonic deformation and the asymmetric valley shape are probable geomorphometric anomalies which coincide with past seismic activity in the study region. The present study also shows that the tectonic tilt, compressed meanders in the uplifted surface and the linear valley in the alluvial surface are also equivalently significant for past earthquake occurrences in the foothill zone. It is also observed that the elongated and linear micro basins and the presence of a strike-slip fault with major lineaments in the Quaternary surface are great indicators of geomorphometric anomalies which have no resemblance with any significant earthquake in the past and are equally important signatures of seismotectonic activity. The study concludes that the geomorphometric anomaly is an important parameter of seismotectonic activity which can be used for studying seismic hazards in the future.

Keywords. Geomorphometric anomaly; active tectonics; seismotectonic activity; geoinformatics.

1. Introduction

Morphometry is a fundamental element of fluvial geomorphology which studies the interaction

between fluvial processes and landform dynamics by analysing the form and function of streams (Chorley 1969; Prabu and Baskaran 2013). Drainage morphometry is defined as the mathematical

analysis and quantitative measurement of length, area, perimeter, shape, volume and altitude of a drainage basin for evaluating the geomorphic landforms (Clarke 1970; Keller and Pinter 2002). It explains the morphological changes which occur during the long-term evolution process of a drainage basin that can significantly impact landscape dynamics (Bali *et al.* 2012). Fluvial morphometry involves studying the drainage basin properties and the stream evolution process by estimating the morphometric parameters (Ozdemir and Bird 2009; Prabu and Baskaran 2013). Drainage networks and its basin configurations are the key elements of morphometric analysis (Abrahams 1984). The analysis of morphometric parameters recognises the geomorphic characteristics and landscape evolution processes in a drainage basin (Singh 2005). The evolution of landscape in a drainage basin depends on the erosional power of streams and the resistance capacity of the topographic surface which depends on the sub-surface geology and lithological characteristics (Zavoianu 1985). The surface drainage and its morphometric properties are determined by the sub-surface structural, tectonic and geological characteristics (Cox 1994; Perez-Pena *et al.* 2010). The analysis of morphometric parameters evaluates the relationship between tectonic geomorphology and the landscape dynamic process (Reddy *et al.* 2004).

Active tectonics is a significant parameter of tectonic geomorphology for the investigation of the fluvial geomorphic process in a river basin (Tsodulos *et al.* 2008). The anomaly in the fluvial geomorphic process indicates the tectonic deformation and the structural influence of landscape evolution on the Earth's crust which can be analysed using drainage morphometric parameters (Keller and Pinter 2002). Several research studies have been carried out to investigate the geomorphic anomaly by analysing the morphometric parameters. Viveen *et al.* (2012) evaluated the geomorphic anomaly in the lower Mino catchment in NW Iberia and concluded that the asymmetric nature of the basin, incised river valley, upliftment process and basin subsidence indicates recent tectonic movement. Cuong and Zuchiewicz (2001) analysed morphotectonic parameters to study the geomorphic anomaly in the Lo river basin in North Vietnam and identified that the presence of resistance rocks, a narrow valley and an elongated basin are the indicators of tectonic activity. The estimation of morphometric parameters of the Ramganga drainage basin in Uttarakhand indicated that the

morphological characteristics of drainage basins and the structural control of the drainage network are influenced by tectonic activity (Asthana *et al.* 2015). Musumeci *et al.* (2003) discussed the effects of tectonics on the drainage morphological anomaly in Argentera Massif Western Alps, Italy and suggested that the differential denudation process, anomalous drainage network, etc. are responsible for long-term changes of the landscape and uplift processes. Altin (2012) analysed various morphometric indices in the southern Bolkar mountain region and concluded that a stream length gradient anomaly, a steeped narrow valley, an elongated basin and a primary stage in a drainage network indicate greater tectonic activity. Mahmood and Gloaguen (2012) analysed geomorphic indices and drainage patterns to identify the geomorphic anomaly in the Hindu Kush region and observed that the high rate of upliftments, deformed landforms and anomalous drainage patterns are responsible for active tectonics. The analysis of various morphometric parameters in the south-west border of the Sierra Nevada (southern Spain) suggested that the tilted basin, lithological resistance and young geomorphic landforms are indicators of tectonic activity and geomorphic anomalies (El Hamdouni *et al.* 2008). Venkatesan *et al.* (2015) quantified various geomorphic parameters in the Thoppaiyar sub-basin to study the significance of drainage morphological parameters of geomorphic anomalies and the study confirmed that the high resistance surface in the elevated region, young topography, tectonic tilt and river migration are indicators of high tectonic activity. The evaluation of linear areal and relief morphotectonic parameters in the Alaknanda river basin identified that drainage bifurcation, relief dissection and structural anomalies are significant evidences of tectonic activity (Shukla *et al.* 2014). The analysis of stream length gradient anomaly and sinuosity index in North Canterbury, New Zealand reveals that the fold, fault and lineaments have greater control on the development of the channel pattern in high- and low-resistance surfaces (Litchfield *et al.* 2003). Hassen *et al.* (2014) discussed relevant morphometric parameters to study the recent geomorphic anomalies along the Gafsa fault in the Southern Atlas of Tunisia which suggest that the heterogeneous land surface, drainage anomalies, vertical curvature and undulating rough topography signify long-term morphodynamic changes in the landscape. The drainage morphometric analysis of linear, areal and relief parameters of drainage

basins identifies that the drainage anomaly, asymmetric basin, structural control of the drainage network, high rate of denudation and weathering process, resistance topography and young geomorphic features are indicators of seismotectonic activity in a particular region (Mahmood and Gloaguen 2012; Bahrami 2013; Venkatesan *et al.* 2015).

Active seismotectonic zones are recognised along the active fault which is marked as frequent earthquake occurrences with significant magnitude. It is formed due to the displacements of structural features and deformation of rock masses (Kuk *et al.* 2000). The analysis of drainage morphometric parameters and identification of geomorphic anomaly are key to seismotectonic studies (John and Rajendran 2008; Singh *et al.* 2016). Silva *et al.* (2003) studied the geomorphic indices for the assessment of tectonic and seismic activities in Spain which showed that the variation of geomorphic anomalies such as upliftment, discrete surface rupture, etc., determine the active tectonic process and seismic activity. John and Rajendran (2008) discussed about the various geomorphic indicators of neotectonism in peninsular India and suggested that the abandoned river channels, geomorphic anomalies and seismotectonic fault are associated with earthquakes and active tectonics. A comparative study of the morphometric parameters with seismic activity showed that the tectonic tilt, high deformation activity produces folded structures which are responsible for earthquakes and seismotectonic activity in the Jia Bhareli river catchment in the eastern Himalaya (Duarah and Phukan 2011). A study of the geomorphic observations and their tectonic implications reveals that the anomalies in the morphometric parameters correspond to lineaments, faults and micro seismic activities of the Palghat gap in south India (Singh *et al.* 2016). Bhat-tacharya *et al.* (2013) investigated the morphometric evidences of seismic activity in the Wagad and Gedi faults, Eastern Kachchh, Gujarat by analysing various morphometric parameters which reveal that the asymmetric nature of basin and stream migration suggests lateral displacements of faults, tectonic instability and seismic activity. Also, drainage morphometric study and its integration with seismic data show that basin tilt and channel incision are responsible for the seismotectonic activity in the Brahmaputra river basin (Sarma *et al.* 2015).

Geoinformatics plays a significant role in drainage morphological studies because it maintains a

large volume of databases and has the capability to integrate several geospatial databases (Lo and Yeung 2007; Bhatta 2008). The quantification of morphometric parameters can be derived from topographic maps, digital elevation model (DEM) data, aerial photographs, satellite imagery and fieldwork (Keller and Pinter 2002; Venkatesan *et al.* 2015). The morphometric parameters have been extracted from the topographical map and field observation data as a traditional method in Acambay graben, Mexico (Ramírez-Herrera 1998). Similarly, an aerial photograph was used with the incorporation of field observation data in south-east Spain for a drainage morphometric study (Silva *et al.* 2003). Furthermore, DEM and multispectral satellite images have been used for the morphometric analysis in the inter-fluvial tract of Punjab, NW India (Bhatt *et al.* 2008), the Hindu Kush region (Mahmood and Gloaguen 2012), the Alaknanda river basin (Shukla *et al.* 2014) and the Thamirabarani sub-basin in Kanyakumari district (Kaliraj *et al.* 2015).

The Himalayan region and the Quaternary geological surface of the Indian sub-continent had experienced several earthquakes in recent geological periods due to tectonic activity (Verma and Bansal 2013). Since then, scientists have studied seismic hazards by developing several models with special reference to seismic waves, site investigation, attenuation characteristics and geophysical properties, whereas less attention has been given to active tectonics and drainage morphological parameters (Bansal and Vandana 2007; Nath *et al.* 2007; Anbazhagan and Sitharam 2008; Pal *et al.* 2008). The above literature studies depict that the drainage pattern and its segmentation, basin geometric form, intensity of drainage dissection, symmetric and asymmetric nature of the drainage basin and influence of relief characteristics have a greater impact on tectonics and seismic activity. Thus, it requires a study of the morphometric parameters for identifying the geomorphometric anomaly. Hence, the present research focuses on the quantification of various morphometric parameters for the assessment of geomorphometric anomaly and its significance on seismotectonic activity using geoinformatics.

2. Study area

The study area is the lower Tista sub-basin which is a part of the Brahmaputra basin, with a latitudinal

Figure 1. Location map of study area.

extension from $27^{\circ}20'$ to $27^{\circ}35'N$ and longitudinal extension from $88^{\circ}05'$ to $88^{\circ}20'E$. It has an area of 6043.71 km^2 approximately which is bounded by the upper Tista sub-basin in the north, the Torsa basin in the east, the lower part of the Tista basin in the south and the Mechi basin in the west (figure 1). Tista is the major river in the study area which flows towards the south and the south-west direction and meets various tributaries. It produces a narrow steep valley in the upper course due to the presence of crystalline hard rocks, whereas in the lower part, it shows a much wider valley in the alluvial low resistance surface. The tributaries in the upper course are Rangit, Dik chhu, Rani Khola, and the rill, Rathong chhu while Gish, Lish, Chel and Dharla are the major tributaries in the lower course. The study area has been divided into 24 micro basins on the basis of the major segmentation of the drainage network which have been derived from CARTOSAT DEM and satellite image as shown in figure 2(a and b). From a broad geological point of view, the region is

extended from quaternary sediments to the Greater Himalayan sequence from the south to the north which has been segmented by the fold thrust movement. Physiographically, it belongs to a part of the Himalayan mountain in the northern part which is characterised by very steep slopes with escarpments, narrow valley and ridges, whereas the southern part of the study region represents the peneplain surface with a gentle slope topography. The major places of the study area are Nathang, Gogong, Gezing, Kalimpong, Reshi and Darjeeling in the mountainous region and Bagrakot, Gorubathan, Nipuchhapur and Jalpaiguri are the major locations in the peneplain surface.

3. Methodology

The study has been conducted in five stages as shown in the flow chart (figure 3). In the first stage, spatial as well as non-spatial data have been collected from different sources and have

Figure 2. (a) Extraction of drainage and delineation of micro watershed using Cartosat DEM and (b) drainage map.

Figure 3. Flow chart of methodology.

also been incorporated with field observation data for further analysis. In the second stage, digital image processing techniques have been applied to prepare the image for analysis and geodatabase generation. In the third stage, GIS-based specific thematic databases such as geological formations and seismotectonic features have been prepared using spatial and non-spatial data accompanied by limited field observation. In the fourth stage, quantitative databases have been generated for different drainage morphometric parameters and suitable diagrams have been prepared for a comparative analysis of the parameters. Finally, all morphometric parameters have been integrated with past seismological databases for an assessment of their significance on seismotectonic activity.

3.1 Data acquisition

In the present study, the spatial and non-spatial data have been collected from different governmental and non-governmental sources for the

preparation of geodatabases and drainage morphometric analysis. The Survey of India (SOI) topographical map is used as a database to rectify other spatial databases through the geo-referencing process in GIS. The spatial information on geology has been collected from the Geological Survey of India (GSI) portal map services and updated with limited field observation data. Also, the seismotectonic atlas has been referred to for tectonic feature identification. ASTER GDEM of 2011 has been collected from the United States Geological Survey (USGS) earth explorer to extract elevation information while CARTOSAT DEM of 2011 has been obtained from the National Remote Sensing Centre India (NRSC), Bhuvan, the Indian Geo-portal of ISRO Open data archive to extract surface drainage for morphometric analysis. In addition, Landsat 8-OLI and Resourcesat-1 LISS III satellite images have been acquired from the USGS and the NRSC, respectively, to update the Cartostat DEM-derived drainage network. The attributed data of earthquake epicentres, mainly

Table 1. *Data used and sources.*

Data used	Year/ month	Scale/resolution in metres/pixel (m/p)	Source of data
Topographical map 78A and 78B	1937	1:253,440	Survey of India
Geological map of Sikkim	2012	1:500,000	Geological Survey of India, Miscellaneous Publication No. 30, GSI portal map services/state geology and maps (Mukherjee and Sharma 2013)
Geological map of West Bengal	2010	1:2,000,000	Geological Survey of India, Miscellaneous Publication No. 30, GSI portal map services/state geology and maps (Sarkar <i>et al.</i> 2012)
Seismotectonic atlas of India and its environment SEISAT-13 Map	2000	1:1,000,000	Geological Survey of India (Dasgupta <i>et al.</i> 2000)
Resourcesat 1-LISS-III	2011	23 m/p	NRSC, India, Bhuvan, Indian Geoportal of ISRO, Open data archive
Landsat 8-OLI	2015	30 m/p	USGS Earth explorer
Cartosat DEM	2011	30 m/p	NRSC, India, Bhuvan, Indian Geoportal of ISRO, Open data archive
ASTER GDEM	2011	30 m/p	USGS Earth explorer
Seismological data	1964–2015	–	Earthquake catalogue of India, earthquake catalogue in and around the north-eastern region of India, USGS and IMD, etc.
Field observation data	2016	–	Field visit

the epicentre location and magnitude, have been acquired for the period between 1964 and 2015 from various published seismological catalogues such as the earthquake catalogue of India, earthquake catalogue in and around the north-eastern region of India, the USGS and the Indian Meteorological Department (IMD), National Centre for Seismology, Ministry of Earth Sciences (MOES). The GPS-based location survey and photographic evidences of active tectonics have been collected during the field study (table 1).

3.2 Digital image processing

In the present study, both pre- and post-digital image processing techniques have been applied before geodatabase generation. The pre-processing of the image includes geometric correction, mosaic, image merging and subset which help in preparing the image for analysis. The post-processing process includes band combination, filtering and histogram equalisation which help in enhancing the image for better interpretation. The topographical map has been georeferenced as per existing coordinates and used as a base map for the rectification of satellite images through image-to-image georeferencing

techniques. To delineate the study area boundary, the selected satellite images have been mosaicked and the area of interest has been extracted through the subset option. Also, the image has been merged with PAN data to obtain a better resolution. In the case of post-processing, various false colour composite (FCC) band combination methods have been applied to identify the drainage network and geomorphic landforms. Edge detection filtering techniques (Sobel filtering) are used to extract the structural features. Furthermore, histogram equalisation techniques are applied for nonlinear contrast enhancement to identify the anomalous geomorphometric signatures.

3.3 Thematic database generation

3.3.1 Geological formation

The geodatabase on the geological formation has been prepared using the geological maps of Sikkim and West Bengal (Sarkar *et al.* 2012; Mukherjee and Sharma 2013) and updated with limited field work. The study area is divided into various geological formations on the basis of a broad geological unit and is shown in figure 4(a) and table 2.

Figure 4. (a) Geological formation (modified after geological maps of Sikkim (2012) with limited field observation data); (b) seismotectonic features modified after seismotectonic atlas of India and its environment (2000), geology and stratigraphy of the Tista basin in Sikkim (2007), satellite images and ASTER GDEM; and (c) geomorphology – landform characteristics derived from satellite image and ASTER DEM data.

Table 2. Broad geological units and their various formations.

Broad geological class	Geological formation	Lithological type	Micro basin region
A. Greater Himalayan sequence	1. Kanchenjunga gneiss formation 2. Chungthang formation 3. Kanchenjunga augen gneiss formation 4. Cainozoic formation	Biotite gneiss, Sillimanite Granite gneiss, Magnetite, Kyanite and Mica schist	Kalet khola, Rathong chhu, Rel chhu, Ramman khola Little rangit, Ramman khola, Rangpo chhu
B. Lesser Himalayan sequence	1. Gorubathan formation 2. Buxa formation 3. Damuda formation 4. Reyang formation 5. Ranjit pebble slate group 6. Lingtse gneiss formation 7. Lingtse granite gneiss formation 8. Phuentsholling formation	Chlorite, Schist, Phyllite, Quartzite, Dolomite Sandstone, Shale and Carboniferous shale	Tista upper, middle micro basin, Great rangit micro basin, Dik chhu, Rani khola
C. Siwalik sequence	1. Siwalik group of formations	Sandstone, Conglomerate, Shales	Lower Tista (foothills), Gish and Lish micro basin
D. Quaternary sequence	1. Baikunthapur formation 2. Chalsa formation 3. Matiali formation	Boulders, Gravels, Pebbles, Sands and Silts	Lower chel, Dharla, Lish Gish and Upper chel

The Greater Himalayan sequence is the outermost part of the study area above the main central thrust (MCT) which comprises mainly hard crystalline rocks. The Lesser Himalayan sequence is affected by numerous fold thrust movements which consist of soft sedimentary and metamorphic rocks. In the Greater Himalayan sequence, the Kanchenjunga gneiss and Chungthang are two major formations, whereas in the Lesser Himalayan sequence, the Gorubathan formation is dominant. The Siwalik group of formations is evolved by the sequential erosion and deposition of fluvial action in the area between the frontal and boundary thrusts. The rocks are folded and faulted by lateral compressions to produce the Siwalik foothills. The Baikunthapur formation, Chalsa formation and Matiali formation are the quaternary group of formations which are very recent and a younger formation and are composed of sand, silt and clay (Mukherjee and Sharma 2013).

3.3.2 Seismotectonic characteristics

The origin of the tectonic framework of the Himalaya and the adjacent orogenic belt is the result of different tectonic activation and

reactivation in the geological past. Such activities in the regional extent formed their distinctive tectonic–stratigraphic characters associated with folding, faulting and lineament features (McCann and Saintot 2003). The evolution of the seismotectonic features in different geological ages forms the Himalaya and adjacent orogenic belts, with numerous fragmented rocks (Bansal and Nath 2011).

The seismotectonic database has been prepared using the seismotectonic atlas of India and updated using Landsat Satellite data, ASTER DEM with limited field observation (figure 4b). The structural features have been extracted from the satellite image with the incorporation of digital image processing techniques which include band combination methods, filtering techniques, histogram equalisation, etc. The region is divided into five seismotectonic zones by the separation of the sequential thrust, namely, the main frontal thrust (MFT), main boundary thrust (MBT), main central thrust (MCT) and Ramghar thrust (RT) (Dasgupta *et al.* 2000, 2013; Grujic *et al.* 2002; Mukul *et al.* 2014). A crystalline complex overprinted by a fold thrust movement seismotectonic unit is observed outside the MCT which covers the upper part of the Rathong chhu, Rel chhu, Kalet

khola, Ramman khola, Little rangit, Dik chhu, Rani khola, Upper Rangpo chhu, Rayeng, Resi and Rangali micro basins. An older folded cover sequence overprinted by the Himalayan thrust movement which is surrounded by the MCT zone covers the maximum portion of the Tista upper and the Tista middle micro basins. Also, a significant portion of this unit has been observed in the lower catchment area of Rell chhu, Kilalet khola, Rathong chhu, Dik chhu, Rani khola, Rayeng, the upper part of Lish and the middle portion of the Gish, Chel and Dharla micro basin area. An older cover sequence folded during the thrust movement is observed inside the Ramgarh thrust (RT) zone which has been enclosed in the Great Rangit micro basin. Also, a portion of this tectonic unit has been recognised in the upper part of Lish, Tista lower (foothills) and the middle portion of the Gish micro basin area. Cover rocks of the frontal belt due to the fold thrust movement have been traced between the MFT and the MBT, including the middle portion of the Lish, Tista lower (foothills) and Gish micro basin areas. Alluvial fill along a linear deep tectonic unit is extended below MFT, covering the micro basin of Karala, Tista lower (plainland), lower chel, lower portion of Dharla, Lish Gish and the upper chel. The Tista lineament (TL) is extended along the Tista river where the Gish fault (GF) is present along the Gish river in the alluvial fill surface (Dasgupta *et al.* 2000, 2013; Mukul *et al.* 2014).

3.3.3 Geomorphology

The geomorphology database has been prepared using the Landsat 8-OLI satellite image and ASTER DEM data and updated with limited field observation for a better understanding of the landforms and their significance on active tectonics (figure 4c). By the digital processing of the satellite image, namely, histogram equalisation, band combinations, principal component analysis (PCA) techniques, followed by image interpretation, different landforms have been identified which vary from mountain terrain to peneplain surface. The anomalous geomorphic landforms which are associated with the different morphotectonic features can originate from active tectonic deformations (Howard 1967; Deffontaines and Chorowicz 1991) and are efficient indicators of recent seismotectonic activity (Nakata 1972; Deffontaines and Chorowicz 1991; Ferry *et al.* 2007).

The geomorphic landforms in the northern part of the study area originated by glacial and periglacial action, whereas in the southern part of the study area, landforms developed by fluvial action which have been greatly influenced by active tectonics. The glacial moraines and permafrost are predominant in the Rel chhu and Rathong chhu micro basin region in the north-western part. Also, glacial trough, arete and glacial lakes are also observed around Phedang in the north-eastern and Upper Rangpo chhu micro basin around the Nathang region. The central part of the study area is highly dissected by fluvial action and developed elongated numerous structural ridges, dissected structural mountains and narrow fluvial valleys. The landforms originate by the erosional action of the Tista river and its tributaries and have greater influence on the structural features. Along the mountain foothills, triangular facets with dissected mountains have been recognised which have a great impact on the mountain frontal thrust movement. In the southern part of the study region, mainly the Gish, Lish, Chel, Dharala and the Tista lower micro basin region is occupied by younger and older flood plains. Also, alluvial terraces which have a significant influence on active tectonics have been recognised in the quaternary geological surface.

3.4 Computation of geomorphometric parameters

Different geomorphotectonic parameters have been analysed, namely, linear, geometry of basin shape, areal and relief parameters as listed in table 3.

3.4.1 Linear parameters

The different linear parameters such as bifurcation ratio (BR), stream length ratio (SLR), stream sinuosity indices (SSI), fractural dimension of drainage network (FDDN) and hierarchical anomaly index (HAI) have been measured. Bifurcation ratio has been analysed to identify the relationship of the geological structure and tectonic activity with the branching pattern of the drainage network (Singh 2005; Asthana *et al.* 2015). Similarly, the stream length ratio has been analysed to determine the relative permeability of rock formation in the context of tectonic geomorphology (Shukla *et al.* 2014). The geometric structure of the drainage network can be altered by the influence of sub-surface geological structures which can be identified by stream sinuosity indices (Litchfield *et al.* 2003; Singh 2005). The fractal dimension of drainage

Table 3. Morphometric parameters and its description.

Parameters	Computed	Formula	Application to tectonic activity
Linear parameters			
Bifurcation ratio	Horton (1945)	$BR = \frac{N_u}{T N_{u+1}}$; BR=bifurcation ratio, N_u = number of streams in order u , N_{u+1} = number of streams in next higher order $u + 1$	Asthana <i>et al.</i> (2015) Shukla <i>et al.</i> (2014)
Stream length ratio	Horton (1945)	$SLR = \frac{\bar{L}_u}{\bar{L}_{u-1}}$; SLR = stream length ratio; $\bar{L}_u$ = mean stream length of order u	Asthana <i>et al.</i> (2015) Shukla <i>et al.</i> (2014)
Stream sinuosity indices	Schumm (1956)	$SSI = \frac{AL_o}{EL_o}$; SSI = stream sinuosity indices of main stream, AL_o = actual or observed length of the given stream order from source to junction point of next order stream, EL_o = expected length of the same stream order	Litchfield <i>et al.</i> (2003)
Fractal dimension of drainage network	Barbera and Rosso (1989)	$FDDN = \frac{\ln BR}{\ln SLR}$; FDDN = fractal dimension of drainage network, BR = bifurcation ratio, SLR = stream length ratio	Mahmood and Gloaguen (2012)
Hierarchical anomaly index	Avena <i>et al.</i> (1967)	$HAI = \frac{Ha_n}{\sum N_{so1}}$; Ha_n = hierarchical anomaly number of whole basin, $\sum N_{so1}$ = total number of first order stream	Bahrami (2013)
Geometry of basin shape			
Basin form factor	Horton (1932)	$BFF = \frac{A_b}{L_b^2}$; BFF = basin form factor, A_b = area of the basin, L_b = longest length of the basin	Shukla <i>et al.</i> (2014) Asthana <i>et al.</i> (2015)
Circulatory ratio	Miller (1953)	$CR = \frac{4\pi A_b}{P_b^2}$; CR = circulatory ratio; $\pi = \frac{22}{7}$, A_b = area of the basin, P_b = perimeter of the basin	Shukla <i>et al.</i> (2014) Asthana <i>et al.</i> (2015)
Ellipticity index	Stoddart (1969)	$EI = \frac{\pi L_b^2}{4A_b}$; EI = ellipticity index, A_b = area of the basin, L_b = longest length of the basin	Stoddart (1969)
Elongation ratio	Schumm (1956)	$ER = \frac{2\sqrt{A_b/\pi}}{L_b}$; ER = elongation ratio, $\pi = 3.14$, A_b = area of the basin, L_b = longest length of the basin	Asthana <i>et al.</i> (2015) Altin (2012)
Basin shape index	Bull and McFadden (1977)	$BSI = \frac{L_b}{W_b}$; BSI=basin shape index, L_b = longest length of the basin, W_b = width of the widest part of the basin	Ramírez-Herrera (1998) Mahmood and Gloaguen (2012)
Fitness ratio	Melton 1957	$FR = \frac{C_1}{P_b}$; FR = fitness ratio, C_1 = actual length of main channel, P_b = perimeter of the basin	—
Basin compactness	Panek 2004	$BC = \frac{P_b}{A_b}$; BC = basin compactness, A_b = area of the basin, P_b = perimeter of the basin	Altin (2012)

Table 3. (Continued.)

Parameters	Computed	Formula	Application to tectonic activity
Areal parameters			
Transverse topographic symmetry factor	Cox (1994)	$\text{TTSF} = \frac{D_a}{D_d}; \text{TTSF} = \text{transverse topographic symmetry factor,}$ $D_d = \text{distance of basin midline to basin divide, } D_a = \text{distance of basin midline to drainage midline}$	Shukla <i>et al.</i> (2014) Altin (2012) Viveen <i>et al.</i> (2012)
Asymmetric factor	Hare and Gardner (1985)	$\text{AF} = \frac{A_r}{A_t} \times 100; \text{AF} = \text{asymmetry factor, } A_r = \text{right side area of the basin of a downstream facing river, } A_t = \text{total area of the drainage basin}$	Viveen <i>et al.</i> (2012) Mahmood and Gloaguen (2012)
Stream frequency	Horton (1945)	$\text{SF} = \frac{\sum N_s}{A_b}; \text{SF} = \text{stream frequency, } \sum N_s = \text{total number of streams in all orders for selected basin, } A_b = \text{area of the basin}$	Asthana <i>et al.</i> (2015) Shukla <i>et al.</i> (2014)
Drainage texture	Horton (1945)	$\text{DT} = \text{DD} \times \text{SF}; \text{DT} = \text{drainage texture, DD} = \text{drainage density for selected basin, SF} = \text{stream frequency of the same basin}$	Shukla <i>et al.</i> (2014)
Drainage density	Horton (1945)	$\text{DD} = \frac{\sum L_s}{A_b}; \text{DD} = \text{drainage length density, } \sum L_s = \text{total length of stream in all order in given basin, } A_b = \text{area of the same basin}$	Asthana <i>et al.</i> (2015) Shukla <i>et al.</i> (2014)
Hierarchical anomaly density	Gioia <i>et al.</i> (2011)	$\text{HAI} = \frac{\text{Ha}_n}{A_b}; \text{HAD} = \text{hierarchical anomaly density,}$ $\text{Ha}_n = \text{hierarchical anomaly number of whole basin, } A_b = \text{area of the same basin}$	Gioia <i>et al.</i> (2011)
Denudation rate index	Ciccacci <i>et al.</i> (1980)	$\text{DRI} = 10^{1.44780 + 0.32619\text{DD} + 0.10247\text{HAI}}; \text{DRI} = \text{denudation rate index, } H_a = \text{hierarchical anomaly index, DD} = \text{drainage density}$	Gioia <i>et al.</i> (2011)
Relief			
Local relief	Schumm (1956)	$\text{LR} = E_{\max} - E_{\min}; \text{LR} = \text{local relief, } E_{\max} = \text{maximum elevation of the basin, } E_{\min} = \text{minimum elevation of the basin}$	Panek (2004) Asthana <i>et al.</i> (2015)
Relief ratio	Schumm (1956)	$\text{RR} = \frac{E_{\max} - E_{\min}}{L_b}; \text{RR} = \text{relief ratio, } E_{\max} = \text{maximum elevation of the basin, } E_{\min} = \text{minimum elevation of the basin, } L_b = \text{longest length of the basin}$	Panek (2004) Asthana <i>et al.</i> (2015)
Dissection index	Nir (1957)	$\text{DI} = \frac{E_{\max} - E_{\min}}{E_{\max}}; \text{DI} = \text{dissection index, } E_{\max} = \text{maximum elevation of the basin, } E_{\min} = \text{minimum elevation of the basin}$	Asthana <i>et al.</i> (2015)
Ruggedness index	Schumm (1956)	$\text{RI} = \frac{(E_{\max} - E_{\min}) \times \text{DD}}{1000}; \text{RI} = \text{ruggedness index, } E_{\max} = \text{maximum elevation of the basin, } E_{\min} = \text{minimum elevation of the basin, DD} = \text{drainage density for selected basin}$	Asthana <i>et al.</i> (2015)

Stream length gradient index	Hack (1973)	$SLGI = \frac{\Delta h}{\Delta l} \times L_s$; SLGI = stream length gradient index, Δh = changes in elevation of the reach around the selected point A, Δl = length of the channel in between the selected elevation contour, L_s = longest length of the channel from the drainage divide to the selected point of the reach	Viveen <i>et al.</i> (2012) Panek (2004) Altin (2012)
Hypsometric integral	Strahler (1952)	$HI = \frac{E_{\max} - E_{\min}}{E_{\max} - E_{\min}}$; E_{mean} = mean elevation of the selected basin, $E_{\max}$ = maximum elevation of the selected basin, $E_{\min}$ = minimum elevation of the selected basin $E_{\text{mean}} = \frac{\sum E_{pi}}{N_{pi}}$; $\sum E_{pi}$ = total pixel elevation of a selected area, N_{pi} = number of selected pixel	Hassen <i>et al.</i> (2014) Panek (2004) Altin (2012) Mahmood and Gloaguen (2012)
Valley-floor width–height ratio	Bull and McFadden (1977)	$VFWHR = \frac{2W_f}{(E_{ls} - E_{vf}) + (E_{rs} - E_{vf})}$; VFWHR = valley-floor width–height ratio, W_f = width of the valley floor, E_{ls} = left side elevation of the valley divides, E_{rs} = right side elevation of the valley divides, E_{vf} = elevation of the valley floor	Perez-Pena <i>et al.</i> (2010) Ramírez-Herrera (1998) Silva <i>et al.</i> (2003)
Landscape roughness index	Zuchiewicz (1989)	$LRI = \frac{E_{\text{mean}}}{L_r}$; LRI = landscape roughness index, E_{mean} = mean elevation of the selected basin, L_r = local relief	Panek (2004)

network estimates the degree of irregularities in the drainage network which helps to determine the neotectonic deformation in a region (Dombradi *et al.* 2007; Mahmood and Gloaguen 2012) and the perfectness of the drainage network and stream segmentation. Anomalies in stream order occur while the river course breaks the hierarchical order due to the lithological alteration and structural disturbance and produces an anomalous stream junction which is an indicator of tectonic activity and has been analysed by measuring the HAI (Bahrami 2013).

3.4.2 Geometry of the river basin

The geometry of the river basin defines various forms or shapes of the drainage basin which have a relation with its origin. The shape of the basin depends on the length of the main stream, basin perimeter and area which is controlled by relief, slope, geological structures and lithological characteristics of a particular region (Singh 2005). The different basin shapes are circular, elliptical and elongated which help in identifying the degree of tectonic influence. The various geometric parameters have been analysed, namely, circularity ratio (CR), elongation ratio (ER), ellipticity index (EI), basin form factor (BFF), basin shape index (BSI), basin compactness (BC), fitness ratio (FR), etc. which have a great significance with regard to the tectonic geomorphology (Ramírez-Herrera 1998; Shukla *et al.* 2014; Asthana *et al.* 2015). The various dependent parameters of geometric shapes such as basin area and perimeter, the longest and the widest length of the basin and the actual length of the main channel for basins have been measured from DEM (Cartosat DEM) in the GIS platform for understanding the significance of the geometric shape on active tectonics.

3.4.3 Areal parameters

Areal parameters measured the symmetric–asymmetric nature as well as the intensity of topographic dissection for a particular drainage basin. The asymmetric nature estimated by measuring the asymmetric factor and the average transverse topographic symmetry (ATTS) factor while the estimation of drainage density (DD), frequency, texture, hierarchical anomaly density (HAD) and denudational rate have been measured for identifying the intensity of landscape dissection, structural and lithological control of a drainage

network and its tectonic influence (Mahmood and Gloaguen 2012; Bahrami 2013; Shukla *et al.* 2014; Kaliraj *et al.* 2015). To estimate the symmetry factor, the various points have been selected along the main stream of each micro basin. The respective distance has been calculated for each point by drawing a line feature and the estimated values are used to compute the symmetry factor for each point. Similarly, to measure the asymmetric factor, the left and right side areas have been demarcated by the separation of the main stream of each micro basin (Keller and Pinter 2002; Mahmood and Gloaguen 2012). To estimate DD and stream frequency (SF), the total number of streams and stream length has been computed after merging all stream order in one feature class database for the respective drainage micro basin and was extracted from the stream attribute table while the area of the same basin has been measured from the vector feature class in GIS. Drainage textures (DTs) have been computed based on SF and density (Singh 2005; Shukla *et al.* 2014). Furthermore, HAD and denudational rates index have been estimated to measure the degree of perfectness of the drainage hierarchical order and the degree of drainage segmentation and to identify the erosion rate with relation to the tectonic activity in the basin area (Bahrami 2013; Kaliraj *et al.* 2015).

3.4.4 Relief parameters

Different relief parameters, namely, local relief (LR), relief ratio (RR), dissection index (DI), ruggedness index (RI), stream length gradient index (SLGI), valley-floor width–height ratio (VFWHR), landscape roughness index (LRI) and hypsometric integral have been analysed. The LR and relief ratio have been measured for determining the morphological character of a terrain, the degree of dissections, the intensity of the erosion process which has greater significance to tectonic geomorphology (Panek 2004; Asthana *et al.* 2015). To estimate the relief parameters, the elevation value has been extracted from ASTER DEM and compared with the topographical map and field-based GPS observation data. Similarly, the DI and ruggedness index have been analysed for estimating the magnitude of dissection of a terrain and the degree of undulating topography which is highly influenced by the geological structural and tectonic geomorphological features (Singh 2005; Asthana *et al.* 2015). The stream length gradient index quantifies the deviation of a river along

longitudinal profiles from its stable condition due to changes in slope which have a great connection with lithological resistance and neotectonic activity (Keller and Pinter 2002; Perez-Pena *et al.* 2010). To measure the stream length gradient index, the contour has been generated from ASTER DEM and used to compute the elevation difference surrounding the selected point. The hypsometric integral has been measured for studying the landscape dynamics which has a great impact on tectonic geomorphology (Keller and Pinter 2002). Similarly, landscape roughness has been estimated for measuring the vertical sinuosity of the landform on the basis of surface elevation change (Hassen *et al.* 2014) which depends on the variety of morpho-tectonic features at various scales (Panek 2004). The uplift and incision in the particular river basin have been measured by analysing the valley-floor width–height ratio which is influenced by the active tectonic movement (Keller and Pinter 2002; Viveen *et al.* 2012). To measure the valley-floor width–height ratio, the river cross section has been drawn for each and every selected point in such a way that it can connect both sides of the nearest divider. The ASTER DEM has been used to prepare the cross profile along the selected cross section which measures the right and left sides of the divider height along with the valley floor height and width for a particular point.

4. Results and discussion

4.1 Drainage morphometric analyses for the identification of geomorphometric anomalies

The quantification of different morphometric parameters such as linear, areal and relief has been derived for all micro basins and suitable diagrams have been prepared for a comparative analysis of the parameters. The results of the morphometric analysis and its significance to tectono-geomorphometric evolution have been discussed below:

4.1.1 Linear parameters

A comparative study of the average stream length ratio (ASLR), average bifurcation ratio (ABR), average fractal dimension of drainage network (AFDDN), HAI and the average stream sinuosity indices (ASSI) shows some significant geomorphometric anomaly with reference to tectonic activity in the study area (figure 5 and table 4). The

upper Rangpo chhu (MB 13) and Tista middle (MB 22) micro basins show a higher peak of ASLR (1.843 and 2.339, respectively), ABR (3.088 and 3.250, respectively) and a lower value (−1.337 and 0.122, respectively) with significant trough points of AFDDN, implying a tectonically deformed surface with geo-structural control on drainage development. Also, a higher peak of ASLR (3.750) and troughs of AFDDN (0.821) curve are recognised in the Lish micro basin (MB 07), indicating young geomorphic landforms with a high rate of neotectonic deformation where the geometry of the drainage network has been modified from a complex dendritic pattern to a linear stream in the zone of a topographic break due to the presence of an active thrust (Mahmood and Gloaguen 2012). Similarly, the Great Rangit micro basin (MB 17) shows a high peak of ABR (3.724) and a low AFDDN (−1.779) value with an anomalous trough point in the curve signifying the drainages are greatly controlled by the tectonic thrust movement and the regions are neotectonically deformed which represents significant geomorphic anomaly in this micro basin. Furthermore, it is observed that the Great Rangit micro basin (MB 17) and the Tista lower (foothills) micro basin (MB 23) represent higher values of HAI (2.801 and 6.097, respectively) and area of special scientific interest (ASSI) (1.644 and 1.523, respectively) with significant peak in the curve, indicating the presence of a compressed meander in the uplifted surface and the drainage hierarchical order has been crushed due to the higher strain of active thrust. Similarly, the Lish micro basin (MB 07) and Tista lower (plainland) micro basin (MB 24) have a lower value of ASSI (1.111) with the trough zone, indicating the presence of a lineament or fracture in the sub-surface along the river course. Lower Rangpo chhu micro basins (MB 14) show a higher peak of HAI (4.420) and a moderate value of ASSI (1.149), indicating the significant geomorphic anomaly of this micro basin. The compressed meanders in the Lesser Himalayan sequences along the Tista river and the linear valley between the MFT and the MBT are shown in figure 6(a and b).

4.1.2 Geometry of the basin shape

BFF, CR and ER show significant troughs while the EI and the BSI represent higher peaks in Karala (MB 01), Tista lower (plainland) (MB 24), Lish (MB 07), Dharla (MB 05), Upper chel (MB 04), Lower chel (MB 03) and the Tista lower foothills

(MB 23) micro basin region (figure 7 and table 4). The lower BFF, CR and ER values with the trough zone imply a more elongated basin which has been highly influenced by the structural disturbance and tectonic activity, indicating a higher geomorphometric anomaly (Zuchiewicz 1989; Altin 2012; Bali *et al.* 2012; Shukla *et al.* 2014). Similarly, the higher EI and BSI indexes produce a more elliptical and elongated basin due to compression and the uplifted mountain front which indicates high tectonic activity (Ramírez-Herrera 1998; Mahmood and Gloaguen 2012). Furthermore, it is recognised that the Rathong chhu (MB 16), Tista upper (MB 21), Ramman khola (MB 19) and the Rel chhu (MB 10) micro basin (0.222, 0.374, 0.266 and 0.266) shows a lower value of BC and significant trough zone in the curve, while the FR represents the peak value in Rill (MB 02), Gish (MB 06), Little rangit (MB 18) and the Dharala (MB 05) micro basin (0.495, 0.495, 0.467 and 0.441, respectively) where tectonic compression and geomorphic anomaly are significant. The lower value of BC indicates high tectonic activity due to the presence of high resistance rocks influencing less segmentation of the basin ground plan (Panek 2004). Similarly, the higher FR value implies the anomaly in drainage adjustment due to tectonic activity where the long length of drainage has been adjusted in a narrow micro basin where geomorphometric anomalies are recognisable. The Karala (MB 01) and the Lish micro basin (MB 07) show a higher value with significant peak of BC (0.722 and 0.845, respectively) and the Lower chel (MB 04), Dik chhu (MB 03), Rayeng (MB 09) and Kalet Khola micro basin (MB 20) represent a lower value of FR (0.184, 0.312, 0.336 and 0.345, respectively) in association with the trough zone. The higher BC value indicates a less resistant rocky surface which has been considered as an inactive zone (Panek 2004; Altin 2012) while the lower FR value signifies the almost perfect adjustment of drainage network in a micro basin which indicates low geomorphic anomaly.

The geometry of basin shape analysis shows that the widths of the Tista lower (foothills), Lish, Gish, Upper chel and Dharla micro basins are narrower near the mountain front along the MFT while they are much wider in the alluvial surface and more elongated in nature, indicating significant geomorphic anomaly in the micro basin (figure 8a and b). Also, the higher value of the FR in the Rill, Gish, Upper Chel and Lower Tista (foothills) micro basin indicates the anomaly in drainage adjustment and significant geomorphic anomaly. The continuous

Table 4. Computation of morphometric parameters.

Micro basin no.	Linear					Geometry						
	ASLR	ABR	AFDDN	ASSI	HAI	BFF	CR	EI	ER	BC	BSI	FR
MB 01	2.08	1.98	-4.80	1.51	0.43	0.07	0.13	11.17	0.30	0.72	5.62	0.44
MB 02	1.60	2.83	1.55	1.23	0.99	0.31	0.46	2.55	0.63	0.40	2.03	0.50
MB 03	1.32	1.30	1.09	1.41	1.34	0.19	0.34	4.20	0.49	0.50	2.97	0.18
MB 04	2.32	2.96	1.42	1.24	0.53	0.17	0.25	4.54	0.47	0.41	3.33	0.41
MB 05	2.20	3.22	0.61	1.28	0.78	0.15	0.20	5.08	0.44	0.46	4.16	0.44
MB 06	1.74	2.76	2.19	1.25	1.02	0.16	0.25	4.96	0.45	0.48	3.54	0.49
MB 07	3.75	2.18	0.82	1.11	1.74	0.14	0.22	5.72	0.42	0.84	3.17	0.37
MB 08	1.77	3.22	1.72	1.32	1.57	0.30	0.49	2.61	0.62	0.32	2.00	0.44
MB 09	1.46	2.72	1.16	1.24	1.03	0.63	0.63	1.24	0.90	0.39	1.02	0.34
MB 10	1.95	3.29	1.80	1.36	1.44	0.57	0.48	1.38	0.85	0.27	1.30	0.41
MB 11	1.52	2.65	2.42	1.23	1.46	0.54	0.64	1.45	0.83	0.40	1.14	0.38
MB 12	1.43	2.48	2.19	1.19	0.73	0.61	0.52	1.29	0.88	0.48	0.91	0.35
MB 13	1.84	3.09	-1.34	1.28	1.36	0.38	0.40	2.07	0.70	0.36	1.62	0.37
MB 14	0.89	1.52	1.64	1.15	4.42	0.46	0.45	1.72	0.76	0.55	1.30	0.37
MB 15	1.87	2.95	5.22	1.12	1.20	0.33	0.44	2.35	0.65	0.34	2.25	0.31
MB 16	1.97	3.65	1.72	1.21	1.32	0.39	0.44	2.00	0.71	0.22	2.08	0.37
MB 17	1.34	3.72	-1.78	1.64	2.80	0.45	0.37	1.75	0.76	0.28	1.06	0.40
MB 18	2.18	2.65	3.50	1.37	1.22	0.29	0.42	2.75	0.60	0.43	1.93	0.47
MB 19	1.98	3.25	1.88	1.26	1.49	0.46	0.47	1.71	0.77	0.27	1.19	0.43
MB 20	2.06	3.11	1.95	1.20	1.89	0.36	0.42	2.18	0.68	0.38	2.55	0.35
MB 21	0.89	2.61	3.67	1.22	3.08	0.32	0.34	2.48	0.64	0.26	1.94	0.37
MB 22	2.34	3.25	0.12	1.28	6.68	0.40	0.36	1.95	0.72	0.41	1.30	0.36
MB 23	1.19	2.98	2.78	1.52	6.10	0.22	0.33	3.51	0.53	0.45	2.48	0.42
MB 24	1.48	1.51	1.05	1.22	1.91	0.09	0.11	8.78	0.34	0.53	7.99	0.35

Table 4. (Continued.)

Micro basin no.	Areal						Relief								
	AF	ATTSF	SF	DD	DT	HAD	DRI	LR	RR	DI	RI	HI	LRI	AVFWHR	ASLGI
MMB 01	0.26	0.49	0.32	0.81	0.26	0.08	56.9	133	0.003	0.65	0.11	0.32	0.86	21.61	21.1
MMB 02	0.41	0.38	1.01	1.10	1.11	0.76	81.1	2052	0.087	0.91	2.26	0.63	0.73	0.20	270.2
MMB 03	0.83	0.40	0.59	1.06	0.63	0.47	85.5	30	0.001	0.29	0.03	0.29	2.79	28.76	11.6
MMB 04	0.36	0.52	0.67	1.18	0.79	0.26	76.8	2384	0.057	0.97	2.80	0.01	0.05	8.67	161.9
MMB 05	0.45	0.45	0.86	1.26	1.09	0.50	86.8	3090	0.071	0.97	3.89	0.20	0.22	17.46	490.9
MMB 06	0.65	0.50	0.83	1.10	0.91	0.63	81.4	2254	0.061	0.96	2.47	0.30	0.34	39.25	328.5
MMB 07	0.53	0.21	0.94	0.98	0.92	1.12	88.1	1248	0.052	0.92	1.22	0.20	0.28	14.22	356.4
MMB 08	0.53	0.25	1.03	1.13	1.17	1.28	94.9	1862	0.064	0.47	2.11	0.42	1.54	0.08	445.4
MMB 09	0.65	0.47	1.00	1.05	1.05	0.79	78.8	2404	0.165	0.92	2.53	0.56	0.64	0.15	350.6
MMB 10	0.52	0.45	0.96	1.12	1.07	1.07	91.1	5060	0.198	0.89	5.65	0.58	0.70	0.07	1155.0
MMB 11	0.43	0.23	1.14	1.15	1.31	1.22	93.6	1319	0.088	0.45	1.51	0.45	1.69	0.08	186.0
MMB 12	0.27	0.42	1.10	1.08	1.18	0.57	74.8	3217	0.245	0.84	3.46	0.64	0.83	0.07	456.4
MMB 13	0.68	0.46	0.93	1.13	1.05	0.97	90.2	4047	0.157	0.87	4.57	0.67	0.82	0.08	2741.2
MMB 14	0.65	0.43	0.98	1.09	1.06	3.32	179.9	1985	0.140	0.87	2.16	0.51	0.65	0.12	218.7
MMB 15	0.38	0.17	0.95	0.98	0.92	0.85	77.5	4527	0.167	0.89	4.43	0.60	0.73	0.07	1106.6
MMB 16	0.62	0.29	0.95	1.15	1.09	0.97	90.5	5729	0.149	0.90	6.57	0.59	0.70	0.10	1454.3
MMB 17	0.56	0.21	0.94	1.00	0.93	2.05	114.8	2607	0.085	0.91	2.60	0.51	0.61	0.09	236.8
MMB 18	0.59	0.26	0.92	1.04	0.95	0.82	81.5	2514	0.107	0.82	2.61	0.72	0.94	0.12	379.3
MMB 19	0.64	0.52	0.90	1.06	0.96	1.04	88.2	3233	0.112	0.88	3.42	0.67	0.80	0.07	755.2
MMB 20	0.70	0.21	1.07	1.09	1.17	1.53	99.7	3278	0.136	0.86	3.59	0.63	0.80	0.12	519.7
MMB 21	0.65	0.27	0.95	1.14	1.09	2.27	137.0	3334	0.081	0.92	3.81	0.53	0.61	0.07	161.5
MMB 22	0.57	0.22	0.95	0.71	0.67	4.94	230.4	1899	0.084	0.90	1.34	0.57	0.68	0.08	64.7
MMB 23	0.49	0.33	0.76	1.03	0.79	3.70	256.2	1581	0.055	0.94	1.63	0.21	0.28	19.09	88.1
MMB 24	0.40	0.33	0.13	0.36	0.05	0.15	57.7	140	0.002	0.77	0.05	0.26	0.57	1659.5	36.7

Figure 5. Linear parameters – average stream length ratio (ASLR), average bifurcation ratio (ABR), average fractal dimension of drainage network (AFDDN), hierarchical anomaly index (HAI) and average stream sinuosity indices (ASSI).

Figure 6. (a) Compressed meander in Lesser Himalayan sequences and (b) linear valley in between MFT and MBT.

evolution of drainage in the Rayeng and Resi micro basins is due to active tectonic compression of MFT and MBT, resulting in the conversion of the elongated shape to a more circular shape of micro basin, indicating the anomalous geomorphometric nature of the basin shape.

4.1.3 Analysis of areal parameters

The geomorphometric graph of areal parameters (figure 9 and table 4) shows that the Kalet khola micro basin (MB 20) has a higher peak of asymmetry factor (AF) and the troughs of the ATTSE

Figure 7. Geometric form of the basin – basin form factor (BFF), circulatory ratio (CR), elongation ratio (ER), basin compactness (BC), fitness ratio (FR), ellipticity index (EI) and basin shape index (BSI).

Figure 8. (a) Uplifted mountain front along MFT near to Lish river basin – changes of the river basin shape from linear to elongated and (b) elongated basin of the Chel river at the alluvial surface after the frontal thrust.

curve indicate a tectonic tilt in the left side with less drainage migration. Karala micro basin (MB 01) shows troughs of AF and peaks of the ATTSTF curve, indicating a tectonic tilt on the right side of the micro basin with significant drainage migration. Ramman khola (MB 19) and the lower and upper Rangpo chhu micro basins (MB 13 and

MB 14) show a higher peak of AF and ATTSTF, indicating a surface tilt on the left side with a high magnitude of stream migration. Dik chhu (MB 15), Rani khola (MB 08) and Lish micro basin (MB 07) are tectonically stable and the geomorphic anomaly is less as it shows the symmetric curves of ATTSTF (very close to 0) and AF (very close to 0.5). The

Figure 9. Areal parameters – asymmetry factor (AF), average transverse topographic symmetry factor (ATTSF), stream frequency (SF), drainage density (DD), drainage texture (DT), hierarchical anomaly density (HAD) and denudation rate index (DRI).

Figure 10. (a) Tectonic tilt of the Gish river in the alluvial surface and (b) high rate of weathering and denudation process in the Lesser Himalayan sequence.

tectonic tilt is also observed in Gish (MB 06) and the Upper Chel river basin (MB 04) and it has also been witnessed in the field (figure 10a).

A comparison of the SF, DD and DT curves shows (figure 9 and table 4) that the Rill (MB 02), Dharla (MB 05), Rani khola (MB 08), Kalet (MB 20) and Tista upper micro basin (MB 21)

represents a higher peak of SF, DD and DT, indicating significant geomorphic anomaly of the micro basin, while the Lower chel (MB 03) and Dik chhu (MB 15) show a relatively lower trough of the SF, DD and DT curves, indicating less geomorphic anomaly. The Rathong chhu micro basin (MB 16) represents a higher peak of DD and DT

Figure 11. Relief parameters – local relief (LR), dissection index (DI), ruggedness index (RI), relief ratio (RR), average stream length gradient index (ASLGI), hypsometric integral (HI), average valley-floor width–height ratio (AVFWHR) and landscape roughness (LRI).

Figure 12. (a) V-shaped narrow valley and (b) relief steepness and high resistance surface in the Lesser Himalayan sequence.

while a higher peak of the SF and DT curve is observed in the Rangli micro basin (MB 12), indicating the presence of a high-resistance lithological surface where an undulating topography has been generated due to the MBT and MCT active thrust movement. Similarly, the Tista middle (MB 22) and the Tista (plainland) (MB 24) show a trough zone of the DD and DT curves,

indicating less resistance surface and have been less influenced by tectonic activity.

Tista middle (MB 22), Tista foothills (MB 23), Lower Rangpo chhu (MB 14), Tista upper (MB 21) and Great rangit (MB 17) have a higher value of HAD (4.943, 3.703, 3.316, 2.272 and 2.047, respectively) and a denudation rate index (DRI) (230.39, 256.23, 179.91, 137.00 and 114.79,

Table 5. Correlation of morphometric parameters.

	ASLR	ABR	FDDN	ASSI	HAI	BFF	CR	EI	ER	BC	BSI	FR	AF
ASLR	1.00												
ABR	0.18	1.00											
FDDN	-0.17	0.07	1.00										
ASSI	-0.22	0.17	-0.50	1.00									
HAI	-0.22	0.04	0.07	0.19	1.00								
BFF	-0.32	0.35	0.21	-0.13	0.08	1.00							
CR	-0.31	0.30	0.40	-0.19	-0.01	0.88	1.00						
EI	0.27	-0.50	-0.50	0.19	-0.22	-0.83	-0.85	1.00					
ER	-0.32	0.40	0.28	-0.14	0.13	0.99	0.90	-0.89	1.00				
BC	0.42	-0.68	-0.36	-0.08	-0.04	-0.53	-0.53	0.68	-0.59	1.00			
BSI	0.17	-0.47	-0.29	0.03	-0.21	-0.81	-0.83	0.92	-0.86	0.50	1.00		
FR	0.16	0.41	-0.09	0.16	-0.11	-0.15	-0.11	0.11	-0.14	-0.05	0.03	1.00	
AF	-0.15	0.00	0.13	0.00	0.23	0.14	0.20	-0.38	0.20	-0.26	-0.32	-0.32	1.00
ATTFSF	-0.14	-0.17	-0.30	0.06	-0.35	-0.04	-0.14	0.21	-0.09	0.08	0.14	0.21	-0.05
SF	0.01	0.53	0.41	-0.29	0.08	0.70	0.77	-0.86	0.76	-0.42	-0.88	0.11	0.24
DD	-0.05	0.40	0.26	-0.08	-0.27	0.30	0.45	-0.53	0.35	-0.34	-0.60	0.18	0.24
DT	-0.07	0.50	0.43	-0.30	-0.11	0.62	0.73	-0.80	0.68	-0.45	-0.79	0.16	0.22
HAD	-0.19	0.18	0.09	0.13	0.96	0.24	0.15	-0.38	0.29	-0.13	-0.41	-0.05	0.26
DRI	-0.24	0.13	0.12	0.21	0.96	0.11	0.06	-0.29	0.16	-0.08	-0.31	-0.03	0.22
LR	0.03	0.69	0.35	-0.25	-0.14	0.49	0.39	-0.60	0.54	-0.67	-0.49	0.10	0.12
RR	-0.11	0.39	0.33	-0.34	-0.10	0.81	0.68	-0.72	0.82	-0.44	-0.67	-0.06	0.00
DI	0.19	0.44	0.12	-0.19	0.18	0.07	-0.15	-0.15	0.09	-0.12	-0.10	0.41	-0.09
RI	0.02	0.67	0.33	-0.25	-0.20	0.45	0.36	-0.56	0.50	-0.66	-0.45	0.13	0.12
HI	-0.21	0.31	0.19	-0.13	0.01	0.69	0.66	-0.63	0.72	-0.51	-0.61	0.00	0.25
LRI	-0.27	-0.35	0.00	0.15	-0.14	0.12	0.33	-0.12	0.13	-0.06	-0.15	-0.53	0.33
AVFWHR	-0.11	-0.42	-0.04	-0.10	-0.01	-0.34	-0.44	0.49	-0.39	0.18	0.74	-0.14	-0.20
ASLGI	0.14	0.41	-0.02	-0.19	-0.24	0.27	0.23	-0.33	0.30	-0.38	-0.27	-0.02	0.19

respectively) with a significant peak in the curve (figure 9 and table 4). The higher value of HAD is associated with the heterogeneous land surface with mass movements of weathered material, indicating high tectonic activity (Bishop 2007; Kaliraj *et al.* 2015) as shown in figure 10(b). Also, a significant higher peak has been observed in the Lower Rangpo chhu, Great rangit (MB 17) and Tista lower (foothills) micro basin (MB 23) in both HAD and DRI curves, indicating significant weathering on the heterogeneous surface. MCT, MFT and MBT have a greater impact of producing a heterogeneous lithological surface where weathering is also high. Karala (MB 01) and Tista lower (plainland) (MB 24) show a lower value of HAD (0.081 and 0.152, respectively) and DRI is 56.88 and 57.68, respectively, indicating less drainage anomaly in a uniform lithology (figure 10a).

4.1.4 Relief parameters

The comparative geomorphometric curve has been prepared based on the relief parameters (figure 11).

The LR curve represents a significant peak in the Rel chhu (MB 10), Upper Rangpo chhu (MB 13), Rathong chhu (MB 16), Dharla (MB 05) and the Rill micro basin (MB 02) region where the highest and lowest elevation differences are more and the lower chel (MB 03), Resi (MB 11), lower Rangpo chhu (MB 14) and great rangit (MB 17) show a trough where the differences between the maximum and the minimum elevation is less. The higher LR is associated with the high and steep mountainous regions where asymmetric drainage distribution is observed and is strongly indicated by geomorphic anomaly. Similarly, the lower LR is observed in a plain flat surface where a gentle slope and least DD is observed while it is associated with low tectonic activity with less disturbance by geostructural features.

The Lower chel (MB 03), Resi (MB 11) and Rani khola micro basin (MB 08) show a lower value of the DI (0.29, 0.45 and 0.47, respectively) with significant trough and a higher value of the LRI (2.79, 1.69 and 1.54) with a significant

Table 5. (Continued.)

ATTSF	SF	DD	DT	HAD	DRI	LR	RR	DI	RI	HI	LRI	AVFWHR	ASLGI
−0.29	1.00												
0.19	0.67	1.00											
−0.14	0.94	0.83	1.00										
−0.37	0.31	−0.10	0.10	1.00									
−0.25	0.19	−0.05	0.04	0.95	1.00								
−0.04	0.55	0.48	0.58	0.00	−0.06	1.00							
0.02	0.67	0.38	0.64	0.05	−0.04	0.77	1.00						
0.12	0.18	0.07	0.13	0.21	0.21	0.50	0.36	1.00					
0.03	0.53	0.55	0.61	−0.07	−0.11	0.99	0.73	0.48	1.00				
−0.22	0.55	0.10	0.44	0.15	−0.02	0.53	0.69	0.08	0.47	1.00			
−0.13	0.02	0.06	0.03	−0.14	−0.16	−0.30	−0.15	−0.92	−0.30	0.18	1.00		
−0.04	−0.69	−0.78	−0.66	−0.21	−0.20	−0.36	−0.35	−0.07	−0.35	−0.24	−0.08	1.00	
0.10	0.28	0.29	0.33	−0.17	−0.20	0.71	0.54	0.20	0.71	0.44	−0.07	−0.17	1.00

peak indicating highly dissected undulating strong erosional potential topography due to the influence of tectonic activity. The Resi micro basin is affected by the MBT and MFT thrusts while the Rani khola micro basin has greater control over MCT. Also, the Lower chel is greatly influenced by lineament and micro fractures in the alluvial surface where significant evidence of neotectonic activities is recognised. Similarly, the lower RI is observed in the Lower chel (MB 03), Tista plainland (MB 24) and Karala (MB 01) micro basin (0.03, 0.05 and 0.11, respectively) while the Upper chel (MB 03), Dharla (MB 05), Tista lower foothills (MB 23) and Lish (MB 07) micro basin show a lower value of LRI 0.05, 0.22, 0.28 and 0.28, respectively, which are located in less resistant alluvial surface and less affected by structural features. It is also observed that the RI curve is very similar to the LR curve, indicating the topography of the region is greatly affected by fluvial erosion and DD and its anomalous nature which has been greatly controlled by tectonic activity.

The comparative study of the RR and HI graph shows that the Rel chhu (MB 10) and Rill (MB 02) micro basin have significant peaks in both HI and RR curves where the MCT and MBT influence is significant (figure 11). Resi (MB 11), Great rangit (MB 17), Tista lower (foothills) (MB 23) and Lower Rangpo chhu (MB 14) show a significant drop in the HI and RR curves, indicating that the transformation of the youthful stage to the mature stage in the drainage development cycle are very active. The Lower chel (MB 03) and the Tista lower plainland (MB 24) micro basin show a significant drop in the RR curve as the micro basin reaches the

old stage of drainage development and represents a peneplain surface with the presence of less resistance rocks.

The significant lower value of average valley-floor height-width ratio (AVFWHR) has been observed in high elevated micro basins, whereas a significant higher value of average stream length gradient index (ASLGI) is recognised in the Dik (MB 15), Rel (MB 10), Rathong (MB 16) and Upper Rangpo chhu (MB 13) micro basin (2741.17, 1454.35, 1154.96 and 1106.64, respectively) (figure 11). The lower AVFWHR produces a 'v'-shaped narrow valley which is actively incised due to a high rate of uplift (Keller and Pinter 2002; Mahmood and Gloaguen 2012), while the higher ASLGI in the high-resistant narrow valley indicates high tectonic activity (Keller and Pinter 2002; Mahmood and Gloaguen 2012). The higher value of AVFWHR and lower value of ASLGI are recognised in the Tista lower (plainland) (MB 24), Lower chel (MB 03) and Karala (MB 01) micro basin which may be crushed by the active fault movement, indicating the presence of a strike-slip fault and produces a much wider valley (Keller and Pinter 2002; Mahmood and Gloaguen 2012). The v-shaped valley is shown in figure 12(a) and the high-resistance surface in the Lesser Himalayan sequence is presented in figure 12(b). A comparison between the AVFWHR and ASLGI curves (figure 11) shows that the Rel chhu (MB 10), Upper Rangpo (MB 13), Rathong (MB 16) and the Raman khola (MB 19) micro basin have a significant peak and trough in the ASLGI and AVFWHR curves, respectively, which produces a steep-sided narrow valley in the resistance surface where the

Figure 13. Relationship of morphometric parameters with earthquake frequency and magnitude.

tectonic influence of MCT and MBT are significant, indicating the high geomorphic anomaly of these micro basins.

The correlation analysis among the parameters has been carried out (table 5) and the interdependence of parameters has been identified with special reference to seismotectonic activity. The analysis shows that ABR is interdependent on BC (-0.68) and RI (0.67), indicating that the evolution of the drainage network depends on the structural control and the resistance of rocks. Similarly, AFDDN have significant correlation with ASSI (-0.50), which implies the relationship of the neotectonic deformation with the channel pattern. Also, it is observed that HAI has a good correlation with DRI (0.96), indicating that stream segmentation is strongly affected by the mass movement of weathered materials. The shape, specifically, CR and BSI have a good relation with SF (0.77), RR (-0.67) and AVFHW (0.74), respectively, by the structural and lithological unit

and the continuous upliftment causes the change in the shape of the basin. DRI has a very good relation with HAD (0.95), indicating that the drainage hierarchical order and degree of drainage segmentation depends on the tectonic movement and structural features. The correlation also shows that ASLGI has a good relation with RR (0.54), RI (0.71) and HI (0.44), respectively, which suggests the relationship of rock resistance with the degree of dissection, landscape dynamics and tectonic activity. DI has a very good relation with LRI (-0.92) and also with BSI, indicating that the evolution of the basin shape modifies the drainage pattern and the dynamic changes of landform.

4.2 Significance of geomorphometric anomalies on seismotectonic activity

The morphometric parameters have been integrated with seismological databases to study their role in seismotectonic activity. The computed

Table 6. Relationship between morphometric parameters and past seismic activity.

Sl. no.	Parameters	Range	No. of earthquakes	Highest magnitude	Lowest magnitude
1	Avg. stream length ratio (ASLR)	>1.98	6	4.7	4.0
		1.59–1.98	24	6.2	3.2
		<1.59	27	5.5	3.0
2	Avg. bifurcation ratio (ABR)	>2.97	36	6.2	3.5
		2.65–2.97	8	5.5	3.2
		<2.65	13	5.3	3.0
3	Avg. stream sinuosity index (ASSI)	>1.32	21	5.4	3.5
		1.24–1.32	5	6.2	4.6
		<1.24	31	5.5	3.0
4	Avg. fractal dimension of drainage network (AFDDN)	>1.95	16	5.0	3.0
		1.16–1.95	24	5.5	3.6
		<1.16	17	6.2	3.5
5	Hierarchical anomaly index (HAI)	>1.90	23	5.3	3.0
		1.36–1.90	12	5.4	3.9
		<1.36	22	6.2	3.2
6	Basin form factor (BFF)	>0.36	36	6.2	3.5
		0.22–0.36	20	5.5	3.0
		<0.22	1	4.3	4.3
7	Circulatory ratio (CR)	>0.42	27	5.5	3.2
		0.34–0.42	21	6.2	3.5
		<0.34	9	5.0	3.0
8	Ellipticity index (EI)	>3.51	0	0.0	0.0
		2.18–3.51	17	5.5	3.0
		<2.18	40	6.2	3.5
9	Elongation ratio (ER)	>0.67	36	6.2	3.5
		0.53–0.67	20	5.5	3.0
		<0.53	1	4.3	4.3
10	Fitness ratio (FR)	>0.37	24	5.5	3.5
		0.35–0.37	22	6.2	3.0
		<0.35	11	5.3	3.2
11	Basin shape index (BSI)	>2.55	0	0.0	0.0
		1.61–2.55	30	5.5	3.0
		<1.61	27	6.2	3.5
12	Basin compactness (BC)	>0.45	3	5.3	4.5
		0.35–0.45	10	5.5	4.0
		<0.35	44	6.2	3.0
13	Asymmetry factor (AF)	>0.59	29	5.5	3.2
		0.45–0.59	22	5.4	3.5
		<0.45	6	6.2	3.0
14	Avg. transverse topographic symmetry factor (ATTSF)	>0.38	15	6.2	3.9
		0.28–0.38	2	5.5	4.3
		<0.28	40	5.5	3.0
15	Stream frequency (SF)	>0.95	11	5.5	4.0
		0.76–0.95	45	6.2	3.0
		<0.76	1	4.3	4.3
16	Drainage texture (DT)	>0.95	37	6.2	3.0
		0.25–0.95	20	5.1	3.2
		<0.25	0	0.0	0.0
17	Drainage density (DD)	>1.07	34	6.2	3.0
		0.80–1.07	23	5.3	3.2
		<0.80	0	0.0	0.0

Table 6. (Continued.)

Sl. no.	Parameters	Range	No. of earthquakes	Highest magnitude	Lowest magnitude
18	Hierarchical anomaly density (HAD)	>1.53	23	5.3	3.0
		0.85–1.53	24	6.2	3.6
		<0.85	10	5.5	3.2
19	Denudation rate index (DRI)	>114.79	11	5.3	3.0
		86.42–114.79	36	6.2	3.5
		<86.42	10	5.5	3.2
20	Local relief (LR)	>2607	36	6.2	3.0
		1899–2607	19	5.5	3.5
		<1899	2	4.6	4.3
21	Relief ratio (RR)	>0.11	31	6.2	3.2
		0.07–0.11	24	5.5	3.0
		<0.07	2	4.6	4.3
22	Dissection index (DI)	>0.83	53	6.2	3.0
		0.68–0.83	3	4.5	4.4
		<0.68	1	4.6	4.6
23	Ruggedness index (RI)	>2.80	36	6.2	3.0
		1.62–2.80	20	5.5	3.5
		<1.62	1	4.3	4.3
24	Avg. stream length gradient index (ASLGI)	>755.22	22	6.2	3.2
		328.52–755.22	11	5.3	4.0
		<328.52	24	5.5	3.0
25	Hypsometric integral (HI)	>0.53	33	6.2	3.2
		0.32–0.53	23	5.3	3.0
		<0.32	1	4.3	4.3
26	Avg. valley-floor width–height ratio (AVFWHR)	>21.61	0	0.0	0.0
		14.21–21.61	1	4.3	4.3
		<14.21	56	6.2	3.0
27	Landscape roughness index (LRI)	>0.72	12	6.2	4.0
		0.34–0.72	44	5.5	3.0
		<0.34	1	4.3	4.3

quantitative indices are grouped into three classes, namely, high, medium and low indexed values which have been intersecting with seismic frequency and magnitude (figure 13 and table 6). Also, the seismotectonic features and earthquake epicentres have been overlaid on the ASTER DEM-derived 3D view and satellite images (figure 14a and b). The result shows that the higher index value of ABR and HAI shows a higher frequency of earthquake (36 and 23) with significant highest (6.2 and 5.3) and lowest (3.5 and 3.0) earthquake magnitudes, respectively. The drainage bifurcation and anomalous drainage network signifies the significant structural control on the drainage network which may be further influenced by fold-thrust movements which are probable factors for past earthquakes in the greater and Lesser Himalayan regions (Bahrami 2013; Shukla *et al.* 2014). A

higher value of FR represents 24 earthquake epicentres where the highest and the lowest magnitudes are 5.5 and 3.5, respectively. The anomaly in drainage adjustment occurs when a higher length of stream has been adjusted in a narrow basin which may be compressed from a wider basin due to active thrust movement which is an important factor for past earthquakes in the Himalayan frontal surface. Also, higher values of DD, HAD and DT shows a higher frequency of the earthquake epicentre (34, 23 and 37) with the highest magnitude of earthquake (6.2, 5.3 and 6.2) in the study area. The narrow steep valley in the high resistance surface and the heterogeneous undulating topography which is produced due to the active thrust movement in the crystalline Greater Himalayan complex and Lesser Himalayan older folded cover sequence are relevant factors for earthquakes in

the study region (Gioia *et al.* 2011; Thomas *et al.* 2012; Shukla *et al.* 2014). A high indexed value of LR, RR, DI, RI and HI also shows a higher frequency of earthquake (more than 30 earthquakes) with significant magnitude (>6.0). The asymmetric drainage distribution in the high resistance steep and the rough topographic surface in the Greater Himalayan terrain is produced due to the active movement of MCT and MBT (Thomas *et al.* 2012). Also, the high rate of relief dissection is associated with the sudden changes of slope in the mountain frontal surface due to the active tectonic movement of the MFT which is responsible for the earthquake occurrences in the past. The youthful topographic surface reflects less erosion in a high-resistance rock, indicating high tectonic activity which is another important factor for the higher frequency with the higher magnitude of earthquakes in the Greater Himalayan sequence (Keller and Pinter 2002; Altin 2012; Mahmood and Gloaguen 2012).

Similarly, a lower index value of the specific indices can signify high tectonic potentiality for earthquake occurrences. The lower index value of AVFHWR represents a higher frequency of earthquake (56) with a higher value of earthquake magnitude (6.2) while the AFDDN shows a higher frequency of earthquake (6.2) with less frequency (17). The 'v'-shaped valley in the steep resistance surface is produced due to the active MCT movement which is responsible for the higher frequency and higher magnitude earthquakes in the Greater and Lesser Himalayan sequence while neotectonic deformation on the crystalline surface causes less frequent earthquakes with a higher magnitude. Nakata (1989) and Thakur (2013) showed that the mountain frontal thrusts are marked as the displacement zone where tectonic stress on drainage is reasonable for seismic activity.

Sometimes, higher and lower index values of morphometric indices similarly show a higher tectonic influence on earthquake occurrences. A higher index value of AF shows a higher frequency of earthquake (29) while a lower index value represents a higher earthquake magnitude (6.2), indicating the tectonic tilt to the left and the right sides are both equally significant for past earthquake occurrences. Similarly, higher and lower values of ASSI show a higher frequency of earthquakes (21 and 31, respectively). The higher values of ASSI indicate the presence of compressed meanders in uplifted surfaces due to a higher strain of active thrust, while relatively lower ASSI, indicate the presence of a linear fracture in the

sub-surface which are both responsible for increasing the frequency of earthquakes in the study region (Litchfield *et al.* 2003). The antifoam represents a major folded structure which is formed in the Ranjit window zone along the Great Rangit river and mountain frontal zone along the Tista river where the high-meandering channel pattern of the Rangit river coincides with the frequency of earthquake occurrences (Mrinalinee Devi *et al.* 2016). Even the structural patterns are quite complex within the windows because of the repetition of geological formation and the presence of many fractures/faults due to consequent thrusting (Mitra *et al.* 2010). The seismotectonic study in the Sikkim–Darjeeling Himalaya indicates that the TL which is extended in the central part of the study region around the central thrust zone has a greater influence on earthquake occurrences (Mukul *et al.* 2014). The higher and lower values of the ASLGI represent 22 and 24 earthquake frequencies with significant magnitudes of 6.2 and 5.5, respectively. The presence of high-resistant hard rocks in the Greater and Lesser Himalayan sequences indicates high tectonic activity and produces significant earthquake magnitude (Keller and Pinter 2002; Mahmood and Gloaguen 2012) while the presence of strike-slip fault is also responsible for significant earthquake (Keller and Pinter 2002; Mahmood and Gloaguen 2012). The deep hypocentres of earthquakes with higher magnitudes are reported in the Greater and Lesser Himalayan sequence which is highly responsible for the displacement of the existing fault and the subsequent earthquake. The previous seismotectonic study also showed that the distribution of earthquakes has a deep hypocentral distance and can extend towards the Gangtok lineament (Mukul *et al.* 2014).

The moderate index value of morphometric indices also shows significant frequency and magnitude of earthquakes. The moderate values of ASLR, DRI, AFDDN, SF and LRI show an earthquake frequency of 24, 36, 24, 45 and 44, respectively, with significant highest magnitude ranges between 5.5 and 6.2. The presence of high erosional potential hard resistance rock in the greater crystalline complex, the high rate of weathering in the lesser and Siwalik Himalayan sequence, neotectonic deformation and forms of alluvial terraces in the quaternary surface, undulating rough topography in the Greater and Lesser Himalayan surface and structural features controlling the drainage network are indicators of tectonic activity

Figure 14. Seismotectonic features and earthquake epicentres are shown in (a) ASTER DEM derived a three-dimensional view and (b) Landsat-8 OLI/TIRS satellite image.

Figure 15. Morphostructural evidences: (a) Schistose rock with faulted structure in the Greater Himalayan sequence, (b) thrust fault with a folded structure, (c) thrust fault with a fracture in the Greater Himalayan sequence, (d) a folded structure in the gneissic rock, (e) micro fold in the gneissic rock with a fracture near the rock garden region – Darjeeling, (f) micro fractures in the Lesser Himalayan sequence, (g) crisscross fractures in hard rocks in the Lesser Himalayan sequence, (h) angular and parallel lineament/fractures in the Siwalik group of rocks and (i) nappe/overthrust in the Siwalik sequence near Sevoke.

responsible for past earthquake occurrences in the study region.

The study also indicates that the geometry of the basin shape such as lower values of BFF, CR and ER and higher values of EI and BSI indicate a more elongated basin which has a greater influence on tectonic activity. Also, a lower value of ASLGI and ASSI in the linear micro basins signifies the presence of a strike-slip fault and a linear fracture or lineament which are the significant causes of earthquakes. Dasgupta *et al.* (2013) show that the strike-slip faults are associated with the earthquake epicentres in the foothill zones. TL is the counterpart of the basement fault crossing the MCT, MBT and MFT at various places along the Tista and Rangit river basins (Dasgupta *et al.* 1987). This transverse

lineament produces a seismotectonically active zone in the Himalayan frontal surface where the drainage pattern and the geometric basin shape anomaly are recognised (Dasgupta *et al.* 2013). Mukul (2000) reveals that the terrace upliftment is the result of the reactivation of the MBT in the Siwalik surface and foreland propagation of the frontal thrust along the Tista river valley. The more elongated and linear micro basin is located in the Quaternary surface in the study region that has not even produced any significant earthquake in the past has been observed in figure 14(a and b). Geomorphic and neotectonic deformation indicating faulting along the range and outboard of the range front in the alluvial surface have been recognised by Nakata (1972, 1989). Also, the truncated terrace along

the fault in the alluvial surface indicates tectonic displacement where tectonic tilt, landscape roughness and significant drainage anomaly are recognised by analysing the morphometric parameters (Mukul 2000). The dislocation of the strike-slip Gish transverse fault was recognised by the GPS measurement between the Gish and the Chel river micro basin where the tectonic tilt is significant (Mukul *et al.* 2014).

The morphological parameters have a significant relationship with the morphostructural features. The drainage basins of the Himalayan region have been evolved during different geological periods due to tectonic movements. Such tectonic influence in the regional extent formed their distinctive tectonic-stratigraphic features, namely, folding, faulting and lineament structure (McCann and Saintot 2003). Schistose rock with faulted structures has been observed in the Greater Himalayan sequence (figure 15a). Similarly, thrust fault with a folded structure and thrust fault with a fracture have been recognised in the Greater Himalayan sequence (figure 15b and c). Micro folds in gneissic rock with fractures have been found on the crystalline surface (figure 15d and e). The Lesser and Greater Himalaya is segregated by the MCT thrust. The anomaly in drainage pattern, drainage bifurcation, drainage compression, steepness of relief and resistance surface topography has been evolved with the influence of the MCT thrust. Micro fractures are recognised in the Lesser Himalayan sequence, and Crisscross fractures are observed in hard rocks indicating the release of rock strain due to seismotectonic activity (figure 15f and g). The Ramgarh thrust (RT) included in the Lesser Himalayan sequence (Grujic *et al.* 2002; Mukul *et al.* 2014) has a great influence on drainage morphology. It mostly covers the Rangit river basin, covering the thrust zone named as the Rangit window (Mottram *et al.* 2014). Folded domal structures have been identified in the southern part of the study area around the Rangit window. It is observed that the faulted zone is associated with the rocks of the underlying Lachi formation. The granite-gneiss formation is affected by a series of faults and graphite schists are also observed along the shear or the fault plane. The changes in the drainage hierarchical order, drainage compression, basin shape and drainage basin asymmetry occurred due to the influence of the Ramgarh thrust. The presence of a fault in this region changes the geological succession and a repetition of the same formation has also

been recognised which are both responsible for the evolution of the channel pattern. Angular and parallel lineament/fractures and folded structures in the Siwalik group of rocks are very common which are due to the active tectonic movement along the MBT and the MFT (figure 15h and i). Neotectonic deformation, tilted topography and drainage migration have occurred due to the movement of the frontal thrust and the upliftment of the land surface, also leading to a drainage pattern evaluation which changed from a linear to a wider valley. The quaternary surface also has a resemblance with lineament, fractures and fault scarp which have a greater influence on geomorphometric anomaly and its evolution.

5. Conclusion

Quantitative databases have been generated for various drainage morphometric parameters and a comparative analysis has been carried out between the parameters. Also, the parameters have been integrated with previous seismological databases to assess their significance and impact on seismotectonic activity. The result shows that the higher index value of ABR, HAI, FR, DD, HAD, DT, LR, RR, DI, RI and HI shows a higher frequency earthquake ranging between 23 and 36 with the significantly highest earthquake magnitude varying between 5.3 and 6.2 and the lowest magnitude differing between 3.0 and 3.5. The drainage bifurcation and anomalous drainage network, drainage adjustment anomaly in a micro basin along the mountain front, a narrow steep valley in the high-resistance surface with heterogeneous undulating topography in the crystalline Greater Himalayan complex as well as the Lesser Himalayan older folded cover sequence and the asymmetric drainage distribution due to the effect of an active thrust movement are probable factors for the previous earthquakes in the Himalayan region. The lower indexed values of AVFHW and AFDDN indicate higher magnitude earthquake while the same indexed values of AVFHW and AFDDN represent high and low frequency (56 and 17), respectively. The 'v' shaped valley in the steep resistance surface is produced due to the active MCT movement between the Greater and the Lesser Himalayan sequence where higher earthquake frequencies and magnitudes are recognised. Similarly, it is observed that the neotectonic deformation in the crystalline surface produces less

frequency with a higher earthquake magnitude. Higher and lower indexed values of AF represent a higher earthquake frequency (29) with a high earthquake magnitude (6.2), indicating the tectonic tilt in the left and the right side are both equivalently significant for past earthquake occurrences. Similarly, higher and lower values of ASSI indicate a higher frequency of earthquake (21 and 31), respectively, revealing the presence of compressed meanders in the uplifted surface due to a higher strain of active thrust and the presence of a linear fracture in the sub-surface which are both responsible for increasing the frequency of the earthquake in the study region. The study also indicates that the geometry of the basin shape, with lower values of BFF, CR and ER and higher values of EI and BSI, reveals a more elongated basin which has a greater influence on tectonic activity. Also, a lower value of ASLGI and ASSI in the linear micro basin signifies the presence of a strike-slip fault and a linear fracture or lineament which are significant sources of earthquakes. It can also be observed that the elongated and linear micro basin is located in the Quaternary surface in the study region which has not produced any significant earthquakes in the past. The study concludes that the geomorphometric anomaly is an important parameter for seismotectonic activity. In the context of future work, it can be stated that the parameters will be selected for active tectonic study based on the correlation. The AHP method will be applied for the development of the active tectonic index. Similarly, PCA can also be performed to prioritise the parameters for the estimation of the active tectonic index. This study is a precursor to future seismic hazard assessment studies.

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