Longitudinal profiles and geomorphic indices analysis on tectonic evidence of fluvial form, process and landform deformation of Eastern Himalayan Rivers, India

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ABSTRACT
The drainage pattern and the morphology of the piedmont zone of the Himalayas are clear indicators of the active orogenic belt of most recent origin formed by the collision of Indian and Eurasian plate. The foothills of the Himalayas in West Bengal are zones of active tectonics drained by the rivers belonging to the Brahmaputra system. The present study is conducted for the left bank tributaries and sub-tributaries of Tista which bear the imprint of active tectonics of the region as they lie in the zone of Himalayan Frontal Fault, the most active thrust belt of Himalayas. Data and subsequent field experiences which showed that the region is constantly acted upon by recent diastrophism. Various tectonic indices were calculated to evaluate the evidence of tectonism. This include hypsometric integral (HI), fractal dimension (FD), basin asymmetry factor (AF), basin shape index (Bs), stream-length gradient (SL), mountain front sinuosity (Smf) and valley-floor width to valley height ratio (Vf). The results of these indices are used to prepare an index of active tectonics with three classes which is represented in a map. Then the field evidences of deformed landscape are matched with the areas showing high tectonic index values.

1. Introduction
The Himalayas is the most important orogenic belt in the world. The collision of the Eurasian and Indian Plates in the late Pleistocene caused subsidence of the lithosphere and thereby formed the current Himalayan foreland basin (Burbank & Anderson, 2001; Malik & Nakata, 2003; Nakata, 1989; Singh, Parkash, Mohindra, Thomas, & Singhvi, 2001; Singh & Tandon, 2010; Suresh, Bagati, Kumar, & Thakur, 2007). This foreland basin contains Main Frontal Thrust (Nakata, 1989). This Thrust was named the HFF (Himalayan Frontal Fault) by Nakata (1989). Thus the presence of this active fault has made the region unstable after the formation of HFF. The region is characterised by the presence of many substantial rivers and their innumerous branch of rivers. Tectonically imposed changes are noticed by the responses made in the adjoining morphology and morphometry of this fluvial system. The rise and fall in the base profile of the river can alter the course of the river, changes in channel geometry, the river valleys may get constricted or widen, there can be increase in the rate of deposition or changes in the stream energy which may cause formation of fluvial landforms like alluvial fans, terraces, and bars. The changes in the base profiles of the rivers could be in response to tectonics or climate. Due to tectonics the relief of the source area could be altered. This influences the gradient of the fan and sediment production. Local base level changes can also modify this relationship, influencing the erosional and depositional regime in the distal fan zone.

However, the focus of this study is on the neotectonic imprints on the morphology and morphometry of the rivers using different profiles, indices, and the surrounding landscape in the Quaternary alluvial belt along the North Bengal mountain front. The dissection by the younger streams altered the original morphology of coalescing alluvial fan in this piedmont zone. Forms, process and related fluvial landforms of Indian system and sub system of rivers are quite different. Many of Plateau rivers in India developed river bed potholes (Dhali & Biswas, 2017a, 2017b) by response to geological control, their seasonal hydraulic behaviour and erosion zone are different (Dhali & Sahana, 2017). Rivers Gish, Lish, Chel, Mal, Neora, and Murti drain the present sub-Himalayan piedmont zone of North Bengal (Ayaz, Biswas, & Dhali, 2018) and their form-processes are directly related to tectonic control. The present morphology of the region is that of terraced landscape with secondary alluvial fans at the debouching point of these rivers. These rivers have formed their own micro fans which are being modified and their morphology is being changed due to neotectonic activities in the region (Ayaz et al., 2018; Mandal and Sarkar, 2016). All this change in the channel pattern and river...
diversions has been clearly observed in the Gish and Lethi channels which are the feeder channels of the Gish alluvial fan. The presence of the terraces along the river banks is an indicator of the active tectonism and the deformation of the fan surface (Mandal and Sarkar, 2016). Evidence of tectonic activities could be understood from the modifications in the drainage patterns, formation of the east-west scarps and also folding of the fan surface and the sediment strata making up the fan. The formation of Matiali and Chalsa scarp is attributed to the movements of two north dipping blind thrusts. Thus the present study gives the evidence that morphology of the region is tectonically controlled and there is still the presence of active faults which is the reason behind the dynamic nature of the landscape. The morphology of the present landscape is reflecting the effects of these tectonic forces. Many modifications in the course of the rivers and the expansion of the alluvial fans have been noticed for the past 100 years. Thus this paper focuses on mapping such modifications and understanding the neotectonic imprints by the use of various morphotectonic and morphometric indices.

2. Sites, geology, and tectonic setup

This Himalayas could be divided into five tectonic belts (longitudinally) from north to south; The Tibetan Himalayas, Greater Himalayas, Lesser Himalayas, and Siwaliks. These five belts are separated by major thrust belts, i.e., the south Tibetan detachment separates Tibetan and greater Himalayas, the Main Central Thrust (MCT) separating the Greater Himalayas and Lesser Himalayas, the MBT (Main Boundary Thrust) is between the Lesser Himalayas and Siwaliks and the Himalayan Frontal Thrust (HFT) separates Quaternaries from Siwaliks. The three east-west trending south verging thrusts (MCT, MBT, and HFT) gets progressively younger towards the south. The MCT was active during the early Miocene, MBT in the Pliocene, and HFT in the Quaternary (Holocene) (Gansser, 1964; Kumar, 1993). The present day convergence between India and Eurasia is accommodated by the movement on the HFT. Late quaternary movement in the eastern and western Himalayas have been documented in several previous works (Kumar, 1993; Malik & Nakata, 2003; Sarkar, 1999, 2012). The faults present here can be divided into two major groups such as the East-West trending faults along the mountain fronts and the NNE-SSW to NNW-SSE trending faults along the river courses like Chel, Gish river, and Lethi rivers. All the channels like Lish, Gish, Pabriong, Ramthi, Neora, Mal, Murti, and Kurti are part of Eastern Himalayan foothill zone which is eastern part of the river Teesta (Figure 1). The unconsolidated alluvial fan deposits have enveloped the evidences of these faults (Bisaria, 1980). Along these faults two movements have been postulated (Bisaria, 1980). The first phase of movement had taken place in the early Pleistocene that caused the upliftment of the foothill ranges and was responsible for the first phase of deposition of alluvial fans before the Last Glaciation. The second phase of movement had

![Figure 1. Location of Eastern Himalayan foothill rivers, i.e., Lish, Pabriong, Mal, Murti, Lethi, Chel, Naora, Ramthi, Gish which non-perennial tributaries and sub-tributaries of River Teesta.](image-url)
taken place after the deposition of the earliest alluvial fans and followed by the movements along the northerly trending faults. This second phase of movement responsible for the upliftment of some segments of the old piedmont plain terraces. The terrace remnants on top of Gorubathan hill and the Daling Hills are evidence of this event. This second phase of neotectonic activity formed the NNW-SSE and NNE-SSW trending faults. Thus, the geomorphology of this piedmont zone is mainly controlled by the quaternary tectonic activities.

The Gish Traverse Fault (GTF) is present between the Maynabari and Pathorjhora unit. The GTF is one of the famous active faults in this area (Mukul, Jade, Ansari, & Matin, 2014; Mullick, Riguzzi, & Mukhopadhyay, 2009). The activity of this fault has been observed through a network of Global Position System stations. It was seen that the fault in extending in east-west direction at the rate of 10.9 ± 1.6 mm per year (Mullick et al., 2009). This is an indicator that the neotectonic activities are quite significant in this region and thereby influence the rate of sedimentation and thus affect the morphology of the fans in the region. The Chel and Lethi were once guided in the direction of the orientation of this fault (Bisaria, 1980). The presence of this fault is marked by the presence of a scarp along the eastern margin of Bagrakota which is 10–15 m high. Tectonic activities may affect the slope of the river and the local base level to a large extent. Thus changes in the slopes of the rivers, may affect the channel pattern of the river and can also cause diversions in the river (Karsensenberg & Bridge, 2008). Both the Chalsa and Matiali scarps are present across the prime channels such as Murti and Kurti rivers. The MBT is represented by the Matiali Fault and HFT by the Chalsa Fault (Goswami, Mukhopadhyay, & Poddar, 2012; Nakata, 1989). These are the two major lineaments along with Neora and Murti Lineament along which is followed by the two rivers; Murti river and Neora river. The metamorphic rocks of Darjeeling gneiss, the Daling group of rocks (Schist and Quartzites), the Buxa series and also the sedimentary rocks of Gondwanas, and Siwaliks form the different tectonic units of Darjeeling Himalayas (Banerjee, 1955; Acharya, 1971).

3. Data and methods

The previous literatures were done to formulate the research design and the objectives of our research. Required data were also collected by the different topographical maps such as 8B/9, 8B/13, 78 A/12, 78 A/16 from GSI. The satellite images of the study area (Landsat 8) and the SRTM 30 m DEM were downloaded from USGS Earth Explorer.

3.1. Stream-length gradient index (SLGI)

The instantaneous changes in the river longitudinal profiles are clear evidences of the structural and tectonic influence in the region resulting in changes in the channel dynamics. The SLGI as developed by Hack (1957) help to calculate these changes. This SL index to apprehend the influence of lithology and tectonics in the longitudinal profiles of the river have been used by many researchers (Lee & Tsai, 2009) The formula explained by Hack (1957) is used to calculate the SL Index of a segment of the river between two points which is written as:

$$ SL = (h1 - h2)/[ln(d2) - ln(d1)], $$

where $SL$ = stream gradient index; $h1$ = height of the first point from the source; $h2$ = height of the second point from the source; $d1$ = source to first point distance; $d2$ = distance of the second point from the source; $ln$ = natural log.

3.2. Normalised stream-length gradient index (NSL)

It is very common and useful method for analysis of recent tectonic activity of fluvial system (Seeber & Gornitz, 1983). Mathematically, the statement can be represented as:

$$ NSL = SL/k, $$

where $NSL$ = Normalized Gradient Index for the given part of length, $SL$ = Stream gradient index for the given part of length, $k$ = Slope of the idealized Hack’s graded profile. The Segments having $NSL \geq 2$ are considered as notably steeper while it is $NSL \geq 10$ are identified as immensely steep reaches. The results of $NSL < 2$ imply gentle gradient.

3.3. Analysis of hack profile

For morphometric study the scanned Topographical sheets and the SRTM 30 m DEM were used. The elevation of each contour crossing the six main tributaries of River Tista, i.e Neora, Gish, Chel, Lish, Mal, and Murti along with their sub-tributaries were obtained and the distance from the source were also calculated to obtain the longitudinal profiles of the rivers by using the editor tool in ArcGIS 10.2.2. Rivers that are in equilibrium have a concave shape which represents a decline in the slope of the channel downstream. If the river overflows through an area marked by active tectonism then it displays a convex long profile. For ideal rivers, if the long profiles are plotted in a semi-logarithmic graph paper then they are represented as a straight line (Hack, 1973). This profile is also called the “Hack Profile” (Hack, 1973).
3.4. Long profile length and relief normalisation

The variations in the basin relief and size are reflected in the long profiles of the river. Thus in order to reduce the effects of the basin size and relief the long profile length and relief are normalised. The elevations and distances were divided by the head (maximum basin relief) and the total stream length respectively to normalize the profiles (Lee & Tsai, 2009). Thus the presence of breaks in the river profile is indicative of strong structural influence in the river course. The normalised long profile model is based on four simple mathematical functions;

\[ H = C - K \ln (L). \]  
\[ K = (H_i - H_j) / (\ln L_i - \ln L_j). \]

\( K \) is the average stream length gradient index (SL Index). \( C \) is the regression intercept. As in logarithmic scale, zero cannot be plotted; the source of all the rivers is taken as 0.02 km.

3.5. Valley-floor width to height ratio (Vf)

The present scientific explanation was put forward by Bull (1977). It is expressed as,

\[ Vf = 2Vfw / \left[ (\text{Eld} - \text{Esc}) + (\text{Erd} - \text{Esc}) \right], \]

where \( Vfw \) is showing the valley width, \( \text{Eld} \) is altitude of the left bank of valley, \( \text{Erd} \) is indicated altitude of the right bank of valley, and \( \text{Esc} \) is provided altitude of the channel. High value of Valley-floor width to height ratio (Vf) indicated highly flat and wide valley-floor but low value of “Vf” is very narrow, active tectonic related uplifting results.

3.6. Hypsometric curve and hypsometric integral (HI)

Hypsometric curve and hypsometric integral is a common method for use to explain the stage of landforms in a particular river basin or any types of landforms. Hypsometric curve mainly showing the difference of erosional landforms and stages of evolution of those landforms (Strahler, 1952). Percentage of relief and cumulative percentage of area refer by way of hypsometric integral (Pike & Wilson, 1971) which is varying 0–1 range. When the value of hypsometric integral is closed to 0, it is highly eroded region and near 1 is showing opposite nature of character.

\[ H.I. = \left( \sum (x(i).y(i + 1)) - \sum (x(i + 1).y(i)) \right) / 2. \]

4. Results and discussions

The tectonic deformations are imperceptible to human eye. Deformation of the earth surface due to tectonic activities takes place for thousands of years. Rivers are very sensitive to these deformations even if it takes place very slowly. Thus river system analysis are an important tool for studying the tectonic geomorphology as they are capable of adjusting to the deformations that takes place over periods of centuries to decades (Keller & Pinter, 1996, 2002). Thus the sensitivity of the six left bank tributaries of Teesta and four sub-tributaries in the mountain front of North Bengal has been analysed using the morphometric and Morphotectonic parameters. This has helped to understand the recent tectonics of the region from where passes the MCT of Himalayas.

4.1. Semi-logarithmic profile of the rivers and average SL index

The semi-logarithmic profiles or the Hack Profiles (Hack, 1973) of the rivers are an important indicator of the deformation in the region. If there is some lineament or fault lying in the region then the rivers will make adjustments in its profile. Thus there will be deviation in the ideal profile of the river which is a straight line in a semi-logarithmic scale. Rivers in many tectonically active regions have been studied which show changes in their anomalies. Brookfield (1998) showed convex Hack Profiles of major rivers of South and south-east Asia caused by the tectonic processes during the Cenozoic because of the collision of Indian and Eurasian plates. Convex-upward long profiles of the rivers are observed in areas of
general uplift as seen in South Carolina Coastal plain. Concave profiles for the rivers in the Kaveri river basin have been observed, which is an indicator of some form of disturbance in the region (Kale, 2009). Hack profiles are convex in high uplifted areas, and almost straight or slightly concave in low uplifted areas. In Taiwan in the Central foothill region, Hack’s profile of the rivers are convex indicating early stage of the rivers adjusting to fault movements while in the south-western foothills the profiles are convex–concave indicating later stage of adjustments to fault movements (Chen, Sung, Chen, & Jean, 2006). The segments of the rivers above the equilibrium have high grade energy promoting erosion and down cutting while those below equilibrium have low grade energy and are promoting deposition (Kale, 2009). In the present study, it has been observed that almost all the rivers have convex profiles indicating early stage of adjustment to fault movements, while some rivers show convex–concave profiles indicating later stage of adjustments to fault movements (Figure 2). This is an implication of disturbance in the areas and completely convex profiles of Rivers like Lish, Pabriong, Mal, Murti, and Kurti are indicators of adjustments made by the rivers due to recent tectonic movements.

4.2 Modelling long profiles

In order to understand the forms of long profiles, it is better to fit simple, logarithmic, linear, exponential, and power regression models to the elevation-distance data. Thus a best fit model is used to understand the form-process relationship. The long profile show low degree of concavity and trends towards a straight line and better fit the linear function, when the grain size of the river is greater than its transportation capacity (Lee & Tsai, 2009). The long profile fits the exponential function when the deposition and transportation rate of the channel attains dynamic equilibrium. When the channel becomes graded, i.e., the sediment grain size decreases downstream, then long profile fits more suitably for logarithmic function. When the discharge and load suspension are large then the long profile fits the power function. Thus the evolution sequence for the long profiles of the channels should be linear–exponential-logarithmic-power (Lee & Tsai, 2009). Thus the profiles which exhibit linear to exponential model implies less concavity in their profiles thus are evidences of disturbances in the course of the rivers and implications of recent tectonic movements. The task of fitting the best fit model has been undertaken for the left bank tributaries and sub-tributaries of Teesta River. All the channels like Lish, Gish, Pabriong, Ramthi, Neora, Mal, Murti, and Kurti exhibit exponential model except Lethi. Though Lethi River, being a zone of active fault exhibit logarithmic best fit curve mainly because of small length of its course (Figure 3; Table 1). However there is complete absence of power regression models which is a clear indicator of recent disturbances in the region.

Figure 2. Semi-logarithmic or the Hack’s Profile of the different tributary rivers (after Ayaz et al., 2018). The rivers which have convex profiles indicate early stage of adjustment to fault movements and convex-concave profiles indicating later stage of adjustments to fault movements.
4.3. Segment-wise stream gradient index (SGL index)

Stream length gradient index is a clear indicator of the control of lithology and tectonics in the long profile of the river. This index was proposed by Hack (1957). Many studies have been conducted recently to understand the impact of lithology and tectonics in the profiles of major rivers (Bishop, Hoey, Jansen, & Artza, 2005; Goldrick & Bishop, 1995; Lee & Tsai, 2009; Seeber & Gornitz, 1983). Normally, for homogeneous terrain, the SL Index of a river reduces downstream. This is mainly the result of decrease in channel slope as one move downstream away from the source. But most of the rivers in the study area are showing a rise in the values of SL at the downstream section and thus are indicators of areas undergoing uplift (Kale, 2009). Rivers Lish, Pabriong Khola, Mal, Ramthi Khola, Lethi, and Chel are showing positive values of SL downstream (Figure 4). Neora and Murti Rivers are showing very irregular plots of SL values. Thus in order to understand the rate of change in the SL values, a simple trend line was fitted to the scatter plot between rate of change of SL index and relief ratio (Figure 5). The statistical mechanics of the figure is indicative of the fact that the river basin have high rate of changes in Stream Gradient Indices. Thus the result clearly depicts that all the rivers are flowing in the zone of active tectonics and their profiles are controlled by the underlying faults.

4.4. Valley-floor width to height ratio (Vf)

From selective eight sites and their output results clearly indicated active tectonic evidence of this region. Rivers Lethi, Gish, Ramthi Khola, Chel,
and Neora are showing low values of valley-floor width to height ratio (VF), Mal and Murti are provided almost moderate value of valley-floor width to height ratio and exceptionally river Lish indicated high value of valley-floor width to height (Figure 6, Table 2). Rivers Lethi, Gish, Ramthi Khola, Chel, Neora, Mal, and Murti are very active according to VF values because low valley-floor width to height ratio indicated active tectonic evidence (Bull, 1977; Sarkar, 1999, 1999; Mandal and Sarkar, 2016; Ayaz et al., 2018).

4.5. Hypsometric curve and hypsometric integral (HI)

The different stages of the evolution of the erosional landform are understood by the hypsometric analysis (Strahler, 1952). The degree of different part of basin or basin and relative landform age can be analysed through the hypsometric value. The value of hypsometric integral close to 1 is quietly eroded and near to 0 are highly eroded regions (Schumm, 1956; Strahler, 1952). Hypsometric curve is very useful tool to explain the age of a landscape. The hypsometric
integral value which is obtained from the calculation of hypsometric curve with the help of elevation and area data indicates whether the region is in youth, mature or old stage. Alluvial fans formed by the rivers are signs of tectonic disturbances in the region. Thus in this study the hypsometry values of the alluvial fans formed by the concerned rivers have been calculated instead of the whole basin. Major four alluvial fans like Lish alluvial fan, Gish alluvial fan, Chel-Mal alluvial fan and Mattiali alluvial fan are showing their maturity by this technique. Lish alluvial fan, Gish alluvial fan, Chel-Mal alluvial fan are indicated 0.60, 0.64, and 0.69 hypsometric integral values (Figure 7) which is youth to mature stage of their evolution.

This region is characterised by chain of alluvial fans formed by the rivers when they debouches from the mountains to the plains and thus line of rivers have formed fan-in-fan topography in the Himalayan mountain front of eastern India. Braided channels, mid-channel bars, straight channels are other results by influence of the recent tectonics in this region (Figures 8 and 9). Morphotectonic events over the fluvial from, process and landform deformation are very alive; there closed integration makes an outstanding geomorphic footprint and speciality (Figure 10).

5. Conclusion
The drainage system, pattern, and the fluvial associate morphology of the piedmont zone of the Eastern Himalayas are affected by the active tectonics. Rivers Lish, Pavriong, Mal, Murti, and Kurti show recent tectonic movements because of convex semi-logarithmic profile. It is clearly indicating early stage of adjustment to fault movements. Long profiles which display linear to exponential model imply less concavity in their profiles thus are evidences of
Figure 7. Hypsometric curve and integral of different alluvial fans of Eastern Himalayan foothill region (after Ayaz et al., 2018) namely Lish alluvial fan, Gish alluvial fan, Chel-Mal alluvial fan, Metiali fan.

Figure 8. Heterogeneous fluvial forms of Eastern Himalayan piedmont zone, India. The fluvial landforms observed like Channel bars, straight channel form, channel avulsion, alluvial fans braided channels are evidences of recent tectonics.
Figure 9. Photographs showing field evidences of Fluvial form, process and landform deformation of Eastern Himalayan Rivers which is strongly related with recent tectonics: 1. vertical incision of river valley, 2. synformal axis near Neora River and straight channel, 3. vertical drop of Lish River which results in the development of alluvial fan composed of new alluvium, 4. mid-channel bars in lower part of Chel River are common features of North Bengal Rivers.

Figure 10. Tree diagram summarising the mechanism that has resulted in the present morphology and morphometry of the region tectonics evidences and their response over the fluvial system and subsystems such as river incision, alluvial fan, straight channel, mid-channel bars, uneven deformation of sediment aggradation and degradation were integrated part of fluvial form, process and landforms in this regions
disturbances in the course of the rivers and implications of recent tectonic movements. Rivers Lish, Gish, Pabriong, Ramthi, Neora, Mal, Murti, and Kurti exhibit exponential model. Similarly, Lish, Pabriong Khola, Mal, Ramthi Khola, Lethi Nadi, and Chel are showing positive SL values of downstream. Neora and Murti Rivers have very irregular plots of SL values. Rivers Lethi, Gish, Ramthi Khola, Chel, and Neora are showing low values, Mal and Murti provides almost moderate value and exceptionally river Lish showing high value of valley-floor width to height. Rivers Lethi, Gish, Ramthi Khola, Chel, Neora, Mal, and Murti are very active. Lish alluvial fan, Gish alluvial fan, Chel-Mal alluvial fan are indicating youth to mature stage of their evolution. Thus the result clearly depicts that all the rivers are flowing in the zone of active tectonics and their form, process and landform deformation are affected by result of recent tectonic activities.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

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