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ORIGINAL PAPER

Morphotectonic analysis of alluvial fan dynamics: comparative study in spatio-temporal scale of Himalayan foothill, India

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Abstract

Alluvial fan is a depositional fluvial landform that is characterised by sediment flow and hydrological processes and is also controlled by tectonic activity. These extraordinary features have always attracted researchers since the past as they preserve the past records, but now, this study is focused on the formation meso-level fans with its spatio-temporal dynamic nature. These tributaries have formed secondary alluvial fans at their debouching points. The dynamics of the fans are controlled by the hydrological responses and tectonic base and also by the sedimentation processes. The origin of these tributaries and their respective fans are related to the last stage of Himalayan uplift. This is the region of Himalayan foreland basin which contains the main frontal thrust and makes the region tectonically very active. The region is drained by many large rivers and their numerous tributaries. The active tectonism, the configuration of the basin and also the deposition of the sediments carried by these rivers have formed alluvial fans where the channel debouches into the widened valley. In the present study, the meso-level alluvial fans formed by River Gish and the Rivers Neora and Murti have been studied. Both these fans are present in the piedmont region of the Himalayas, but they deliver different characteristics, and the nature of their deposition is also different. This is mainly because of the influence of the minor faults in the region which control the channel pattern and also have a great influence in the sediment delivery to the downstream section of the channels. Thus, in order to understand the influence of tectonics in the dynamics of these fans, some morphotectonic parameters have been taken into consideration. These include mountain front sinuosity index, valley floor width-to-depth ratio, and tectonic tilt. The calculated hypsometric integral also depicts that the two fans are at different stages of development.

Keywords Tectonic control · Morphology · Alluvial fan

Introduction

Alluvial fans are the resultant landform of fluvial aggradation process (Gohain and Prakash, 1990; Fraser and DeCelles 1992; Nemec and Postma 1993; Kumar 1993; Miall 1996; Gupta 1997; Singh et al 2001; Weissmann et al. 2005; Gibling et al. 2005; Fontana et al. 2008; Singh and Tandon 2010) and hydrological variation and also are controlled by tectonic interferences (Hodges 2000; Horton and DeCelles 2001a; Horton and DeCelles 2001b; Viseras et al. 2003; Harvey et al. 2005; Leier et al. 2005; Harvey 2005; Suresh et al. 2007; Kar and Chakraborty 2014; Jones et al. 2014). These are the accumulated masses of loose rock materials (largely sand and gravel) that are shaped like an open fan deposited following the gentle gradient. They form at the base of mountains where fast-flowing streams meet the relatively flat surfaces of basin floors or broad valleys. A series of alluvial fans are much larger features that are persistent in the landscape over millennia, characteristically dating from Late Quaternary**.** Studies of these extraordinary features, present at the mountain front, are important as they depict the history of the changes that have taken place in the region. They give evidences of the past climate and the tectonic activities (Pratt et al. 2002) that had governed the morphology and sediment shape and size of these features. The

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Himalayas is one of the most active orogenic belt, and the effects of the tectonic forces are reflected in the morphology of the present-day landscape. The alluvial fans of the western and central Himalayan range have received much attention in the recent past (Kumar et al. 2007; Tandon et al. 2008); however, the study of these extraordinary features in the eastern Himalayan range is confined only to the Matiali fan, Tista fan and the Chel fan (Guha et al.2007; Meetai et al. 2007; Chakraborty and Ghosh 2010; Goswami et al. 2013; Kar et al. 2014; Mandal and Sarkar 2016). Thus, the present study is on the alluvial fan formed by River Gish and its tributaries which is situated in the forelend basin of the North Bengal Himalayan foothills. A comparative study has also been done between the Gish alluvial fan and the Matiali fan (Fig. 1) where the former is newly developed while the latter is moving towards maturity. The foreland basin of the Himalayas was formed in the late Pliestocene due to the flexural subsidence of the lithosphere as a response to the ongoing collision between the Indian and Eurasian plates and the formation of the mighty Himalayan orogeny. The Himalayan range in this foreland basin is neotectonically active after Pleistocene glacier age marked the persistence of several fault lines which are the outcome of the two major faults of the region, i.e. the Himalayan frontal thrust (HFT) which is parallel to the Himalayas and the Gish transverse fault (GTF) which lies transverse to the Himalayan range. This region of the Himalayan foreland basin contains the main frontal thrust (MFT) (Gansser 1964). This MFT was called the Himalayan frontal fault by Nakata (1989). This foreland basin of the Himalayas is traversed by many large rivers and their numerous tributaries and has remained tectonically active since the time of its formation, and the Gish transverse fault which lies in the upstream section of the Gish along the Lethi channel is the most active fault of this region. Rivers respond very rapidly to tectonically imposed changes (Burbank and Anderson 2001), and these changes are clearly reflected in the planform, morphology and morphometry of the rivers that are traversing the southern end of the Himalayan thrust belt which is considered to be the most active zone (Nakata 1989, Nakata et al. 2003; Kumar et al. 2010; Singh and Jain 2007).

Concerning the previous works done by geologists and geomorphologists, emphasis has been given on the fan morphology in a broad scale, but it has been visualised that neotectonic activities often have an impact on meso- to micro-scale fan depositions and their dynamic nature in spatio-temporal scale. The minor faults and fractures are predominantly controlling the change of shape and size of individual fans as well as the nature of lobe expansions towards gentle gradient concerning the hydrological components and climatic consequences. This study has tried to examine the neotectonic imprints which are discernible in morphology of the fans formed by River Gish and Rivers Neora and Murti. The attributes like valley floor width-to-height ratio, mountain front sinuosity index, tectonic tilt, stream length gradient index, overall stream gradient, hypsometric integral and drainage pattern help to understand the active tectonic activity that has governed the morphology of the two fans These aspects have helped to understand the role of tectonism in the formation of the two fans and the modifications of the deformed morphology

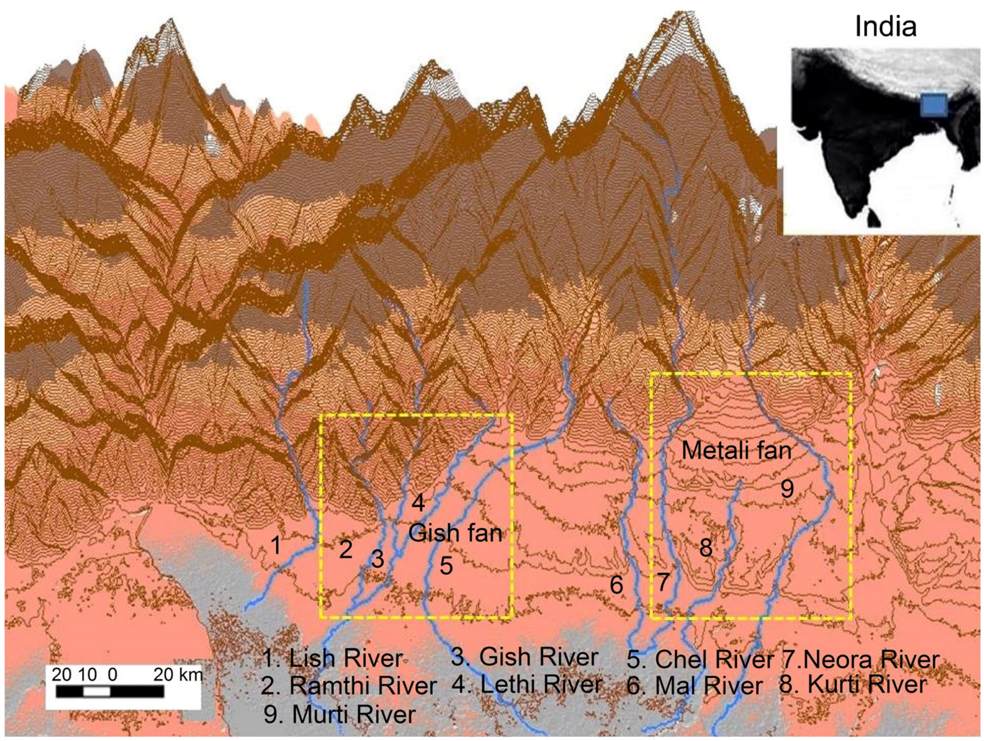


Fig. 1 Digital elevation model (DEM) of the study which is clearly depicting the alluvial fans formed by Rivers Lish, Gish, Chel, Mal, Neora and Murti at their debouching points. The convex shape of the contours is a clear indicator of the chain of alluvial fan formed by these small tributary channels, and these fans have coalesced to form a fan in fan topography. The two main fans concerned in this study are shown in the dashed box

of these two fans. This work has also analysed the dynamic nature of the alluvial fan formed by Gish River, a left bank tributary of the River Tista. The changing course of River Gish and its tributaries, the shifting of the lobes and the eastward expansion of the fan have been analysed. The lobes of the fan have been identified, and a statistical technique has been employed to understand the dominant factor for the active nature of the lobe and the sediment deposition. The changing course of the river has been observed for the last seven decades, and the increase in the rate of deposition has resulted in the expansion of the fan lobes eastward. Thus, regarding all above discussions, the present study is formed under two distinct objectives: The first objective is to study the morphotectonic control over the meso-level alluvial fan mechanism and, secondly, to do a comparative analysis of two idealised fans with respect to morphological attributes. These two kinds of analyses will ensure the impact of meso- to micro-level neotectonic imprints on small-scale alluvial fan process which had not been discussed before in a comparative mode.

Geotectonic set-up

The Himalayan orogeny is delineated by the Indus-Tsangpo suture zone in the north and the MFT in the south. This mountain belt could be divided into five distinct orographic domains: (i) the Tibetan Himalayas, (ii) the Greater Himalayas, (iii) the Lesser Himalayas, (iv) the sub-Himalayas or Siwaliks and (v) the piedmont zone containing the Quaternary sediments (Nakata 1989). However the southern end of the Himalayan thrust belts is considered to be the most active zone. (Nakata 1989; DeCelles 1998; Malik and Nakata 2003; Kumar et al. 2010; Singh et al. 2010). The beginning of Pleistocene is marked by a great havoc as a result of reactivation of the main boundary thrust (MBT) which heaved up the Lesser Himalayas. Till the Quaternary period, the Himalayas rose to great heights. The later part of the Pleistocene marks the formation of the foreland basin due to the flexural subsidence of the lithosphere as a response to the ongoing collision between the Indian and Eurasian plates and the formation of the mighty Himalayan orogeny. This region is the Himalayan foreland basin which contains the MFT (Gansser 1964). The MFT (Mukhopadhyay and Mishra 2004) was called the Himalayan frontal fault by Nakata (1989). The thrust front migrated towards the frontal basin which resulted in the erosion and deformation of the Siwaliks (older foreland sediments) and in the shift of the basin further south (Burbank et al. 1996). The southern part of the Himalayan fold-and-thrust belt (FTB) is considered to be tectonically active and marks the presence of numerous active faults (Nakata 1989; Malik and Nakata 2003; Kumar et al. 2006; Guha et al. 2007; Kumar et al. 2010). This foreland basin of the Himalayas extends for about 2000 km long and is traversed by many large rivers and their numerous tributaries. Since the Early Cenozoic times, the deposition pattern and the sedimentation pattern of the foreland basin were influenced by the tectonism, the climate and the configuration of the basin at that time (Burbank et al. 1996; Yin 2006; Najman 2006). The Himalayan foreland basin derives its sediments from the sediment-rich rivers that flow over this region (Sinha 2009). The deposition from the rivers of the foreland basin dominates the dynamics of the basin since the Pliestocene (Sinha 2009). The presence of numerous fluvial megafans (Burbank et al. 1996; Einsele et al. 1996; Chakraborty and Ghosh 2010) and many small mountain-attached micro fans is the main characteristics of the eastern Himalayan mountain front. Two groups of faults are noticed here, viz. the east-west trending faults along the mountain fronts and the NNE-SSW to NNW-SSE trending faults along the river courses like Gish, Lish, Chel and Lethi Nadi. However, the evidence of these faults is obscured by the unconsolidated alluvial fan deposits (Bisaria 1980).

The GTF, situated between the Pathorjhora and Maynabari blocks, is the most active fault in the region (Mullick et al. 2009; Mukul et al. 2014). The east-west extension of the fault at a rate of 10.9 ± 1.6 mm per year has been measured through a network of GPS stations (Mullick et al. 2009). This fault had once guided the Chel Nadi and the Lethi nadi into the Gish Nadi (Bisaria 1980). The 10- to 15-m-high scarp along the eastern margin of Bagrakota is also an indicator of this fault. The Matiali and Chalsa scarps extend across the major channels, i.e. River Neora and River Murti. The Matiali fault represents the MBT, and the Chalsa fault represents the HFT (Nakata 1989; Goswami et al. 2012). Apart from these lineaments, there are also Neora and Murti lineaments along which the two rivers are flowing. The different tectonic units of the Sikkim-Darjeeling Himalayas are formed by the metamorphic rocks of Darjeeling gneiss, the Daling group of rocks (schist and quartzite), the Buxa series and also the sedimentary rocks of Gondwanas and Siwaliks (Banerjee 1955; Acharya 1971).

Data and methods

Several literatures were reviewed regarding the study which helped in finding a research gap. Then, a research design was prepared from the previous literatures and we formulated our research objectives. A data sheet was prepared which helped in easy collection of data from the field. Secondary data was also collected like the topographical map of the study area (78B/9, 78 B/13) and the satellite images. The satellite images of the study area and the Shuttle Radar Topography Mission (SRTM) 30-m digital elevation model (DEM) were downloaded. Softwares like ArcGIS 10.2.2., Arc Scene 10.2.2 and IBM SPSS 22 were used. The study involved morphotectonic analysis for which various morphometric parameters were required. The identification of tectonic features in the field is obscured by thick forest cover and also the unconsolidated deposition of alluvial fans by the rivers. Thus, to analyse the morphotectonic aspects, the satellite imageries and DEM (SRTM 30 m) have been employed. Georeferencing and enhancement of the satellite imagery were accomplished with ArcGIS (10.2.2). The drainage pattern was examined using this satellite imagery. The various morphologic and morphometric characteristics, like the width and depth of the channel, the slope of the fan, the longitudinal and transverse profiles and the shape of the fan, were examined using the DEM. The tectonic tilt of the fan was calculated following the method of Pinter and Keller (1995). The measurements of all mathematical calculations were performed in ArcGIS 10.2.2. Some important mathematical formulas are briefly explained in the "Result analysis" section for suitable understanding. These data from the total station survey that was done in the field was used to make the DEM in the same software. The dynamics of the Gish fan, the shifting nature of its lobe, the avulsion of the channel and the expansion of the fan were analysed using the topographical map and the Landsat imageries. The Survey of India topographical maps (78 B/9) for 1941 and 1971 were used to study the fan development at those times. Landsat 5 was used to map the Gish fan in 1991, and Landsat 7 was used to study the morphological changes of the fan in 2011. All the maps were prepared in ArcGis 10.2.2. The area of the fans was also calculated in this software using the calculate geometry command.

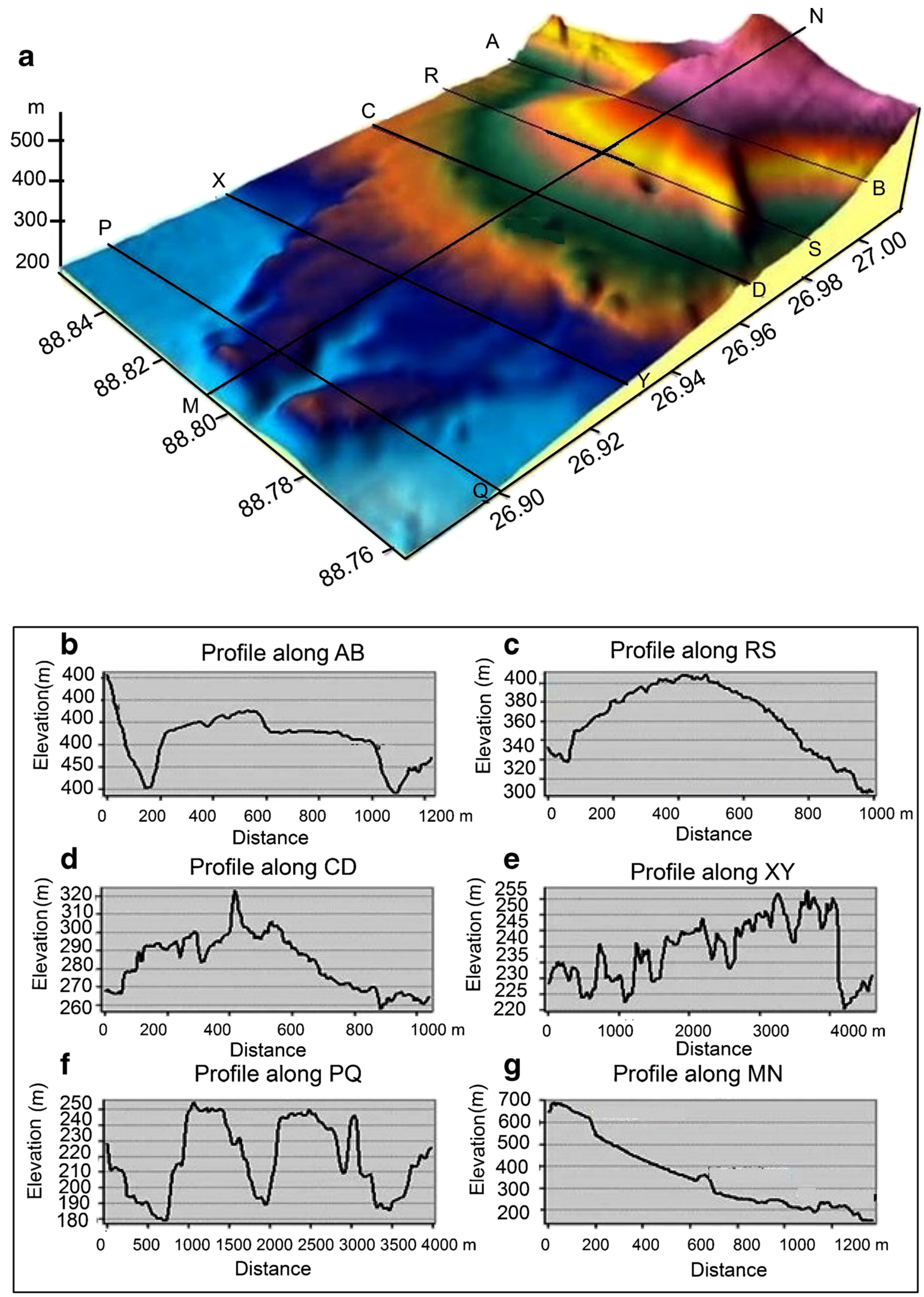


Fig. 2 **a** Digital elevation model of the Matiali fan with minor variation in elevations is represented. **b**–**f** Different line segments of the Matiali fan are indicating the uneven topography of the fan surface with incised valleys of major and minor streams

The data collected for the active lobe of the Gish fan like river velocity, stream power, width of channels, gradient and hydraulic radius were used to understand the dominant factor responsible for the active nature of this lobe and the sedimentation process.

Result analysis

Hydromorphological attributes

This study focuses on the alluvial fan formation on the piedmont zone of the east Himalayan foothills in West Bengal. This piedmont plain originally had a coalescing alluvial fan morphology which was later modified due to the dissection by the younger streams (Bisara 1980). The area is drained by rivers like Gish, Lish, Chel, Mal, Neora and Murti in a parallel manner from the west to the east. These rivers have formed the morphology of alluvial fans which are the primary landforms and river terraces as the deformed landforms (Sinha and Friend 1994). The development of the deformed landform is furnished by neotectonic activities in recent times, and as a result, in the Matiali area near Kurti River, fans are situated in higher elevation followed by terraces in lower elevation near the channel. The present study has been done on the two alluvial fans formed by the River Gish and Rivers Neora and Murti.

Matiali fan

The Matiali fan is bounded by Neora River towards the west and Murti River towards the east. Matiali is an abandoned fan, and the modern drainages have incised the fan body. The width of the fan is approximately 10 km, and the length is around 15 km. The small streams like Kurti and Juranti also incise the fan surface and are deformed by tectonic activities. As a result, this fan surface is restructured and represented by three scarps, i.e. Samsing, Matiali and Chalsa scarps, which are very clearly distinct in Fig. 2a and the longitudinal profile of the fan (Fig. 2g). These scarps have made remarkable changes in the elevation of the fan surface. The slope of these scarps is between 9° and 17° towards the south and south-east. Five cross-profiles have been plotted from the different segments of the fan. (Fig. 2b–f). The profile along AB is showing a convex profile in the centre with steep breaks at the two ends marking the upstream segment of the Neora and Murti streams

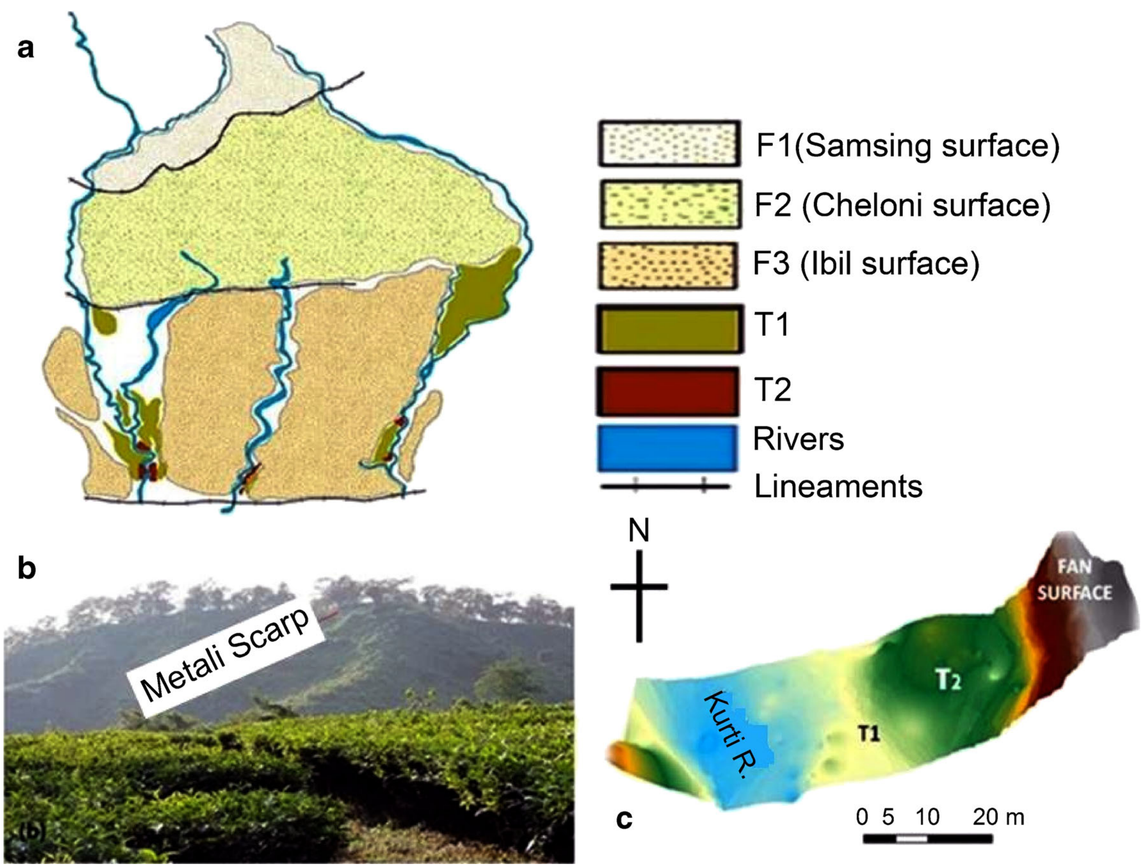


Fig. 3 **a** Topography of the Matiali fan with lineaments marked in black lines and the major and minor streams marked in blue lines. **b** The photograph of the Matiali scarp near the Nagaisuri tea garden which shows the clear imprint of neotectonism. **c** The digital elevation model prepared from the field survey by total station and is clearly demarcating the two terraces (T1 and T2) and the fan surface along River Kurti near Matiali School. The terraces are the result of sediment aggradation, and their unpaired nature is a clear indicator of neotectonics

(Fig. 2b). The profile RS is completely convex which is the fan surface south of the Samsing scarp (Fig. 2c). The profile CD is marked by several undulations, but the overall shape is convex. It shows the deformation in the fan surface adjacent to the Matiali scarp (Fig. 2d). The profiles XY and PQ show the micro features developed on the Matiali fan surface south of the Matiali scarp. The profiles are undulating in nature which mark the presence of numerous incised channels on the fan surface. The profile PQ is plotted north of the Chalsa scarp. The incised valley cut by the Neora, Murti and Kurti Rivers is clearly visible in this profile (Fig. 2f).The neotectonic imprints on this deformed surface are well-evidenced by the existence of unpaired terraces which are the most important micro landform structure present along the banks of the incised rivers Neora, Murti and Kurti. These terraces (Fig. 3a) are also the result of sediment aggradation within the incised valleys. Most of the segments of the channels have formed a single terrace (T2), and in some areas, a second level of terraces below the T2 has been observed. This is the T1 which has been aggraded due to the incision of T2. The presence of these terraces is attributed to the impact of tectonism that has caused the deformation of the fan surface and incision of the channels as a result of this. The DEM imagery prepared from the data collected by the total station survey shows the T1 and T2 terraces along the Kurti River (Fig. 2c).

Gish fan

The Gish fan is a fan formed by River Gish at its debouching point. The tributaries of Gish, i.e. Lethi (left bank) and Ramthi Khola (right bank), have also greatly contributed in the formation of this fan (Fig. 4a). The width of the fan is approximately 5 km, and the length is 7 km. The Gish fan has numerous incised channels which are the extension of the feeder channel downslope. These channels are very dynamic in nature and carry a good amount of fluid and sediments which are deposited by them at the middle and distal zones of the fan. These incised channels extend for tens or thousands of meters

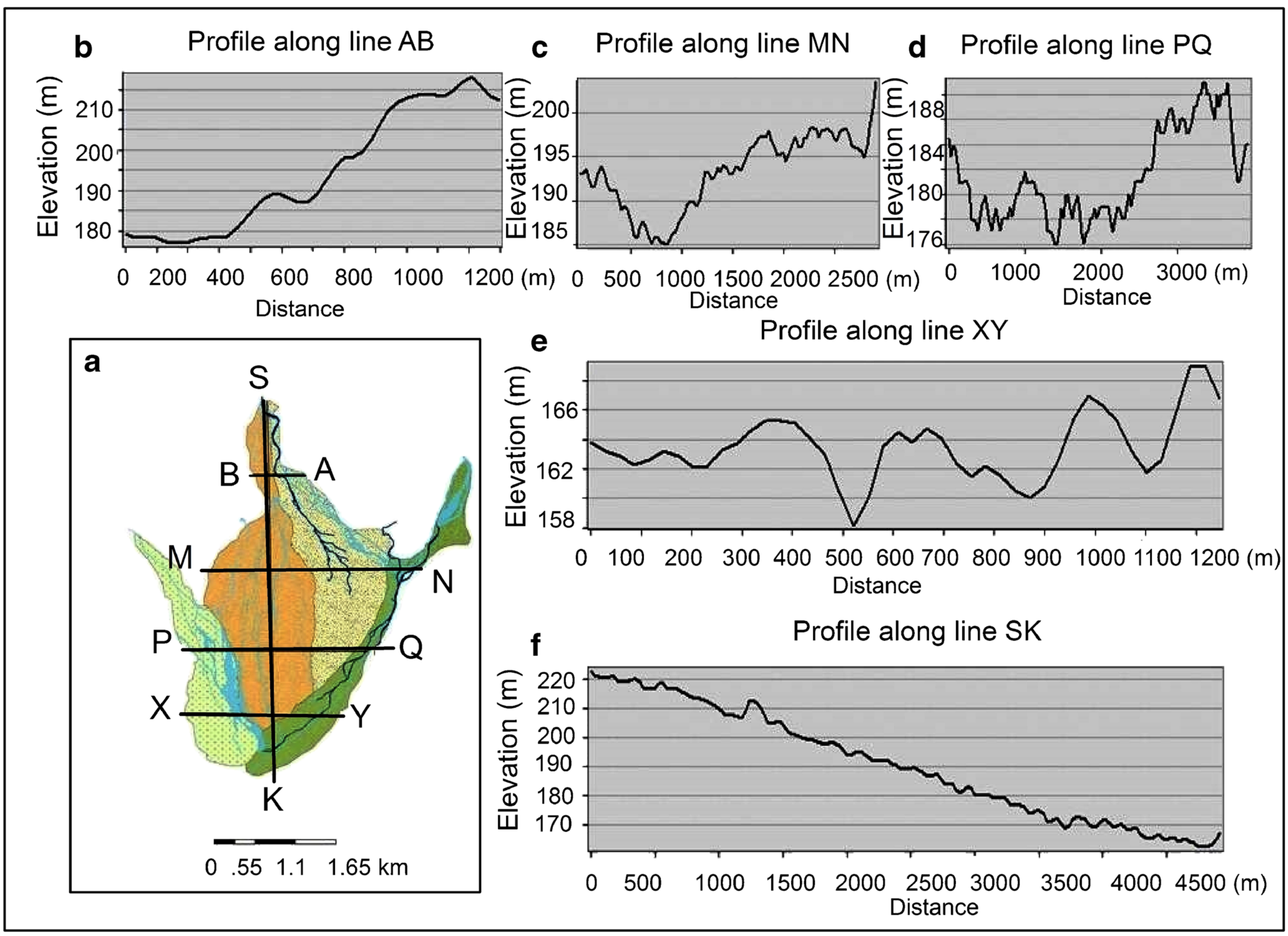


Fig. 4 **a** The topography of the Gish Fan with its lobes where lobes 3a and 3b are the most active and lobe 1 is inactive in nature. The right side of all the profiles shows higher relief which is the part occupied by the active lobes (lobes 3a and 3b) where continuous deposition is taking place by the active channels, mainly the Lethi Nadi, which is responsible for maximum depositional because of the presence of the active Gish transverse fault in the upstream section of this channel. **f** The smooth long profile of the fan where a significant drop in elevation is observed from the apex to the toe of the fan with minor irregularities in its surficial relief

Fig. 5 The photograph representing the topographical characteristics of the active lobe of the Gish fan with active channels during the period of post-monsoon in the month of October

and have vertical walls. There are numerous boulder and gravel bars in the Gish fan. These bars extend for long distances down the fan and are marked by the presence of active and abandoned channels between them. These are the depositional features in an alluvial fan. The formation of these micro features is attributed to the materials carried down by the channels in an alluvial fan and their deposition in the areas where the stream power decreases.

Lobes are one of the most important characteristic features of the Gish fan. The Gish fan has a multi-lobate character comprising four lobes. These four lobes are identified using satellite imagery. Each lobe has a radial drainage pattern and is identified by the disordinance of the drainage pattern in the adjacent lobe. The multi-lobate character of the fan is discernible from the cross-profiles in the form of laterally stacked multiple convex up-segments. The cross-profile and long profile of an alluvial fan reflect its depositional history which is controlled by the erosional and tectonic changes in the drainage basin situated upstream of the fan. These profiles also depict the different morphological characteristics at different segments of the fan. Four cross profiles (segments BA, MN, PQ and XY) are plotted (Fig. 4b–d) using the DEM imagery of the area. The radial profile of the Gish fan is concave to convex. The shape of the profile is convex at the proximal part of the fan, but at the distal end, it becomes slightly concave (Fig. 2f). There is a sharp drop in the slope at the middle part of the fan (Fig. 5).

Table 1 The calculation of the mountain front sinuosity index where the value of Smf for the Gish fan is lower than that for the Matiali fan

Fan	L_{mf}(m)	L_s(m)	L_{mf}/L_s	$S_{mf}=L_{mf}/L_s$
Gish fan	9.58	7.98	1.2	1.2
Matiali fan	21.78	16.08	1.29	1.29

Morphometric and morphotectonic study

Mountain front sinuosity index

The mountain front sinuosity index was defined by Bull (1977) and Keller and Pinter (1996) as

$$S_{mf} = L_{mf}/L_s \tag{1}$$

where L_{mf} is the length of mountain front along the mountain piedmont and L_s is the straight-line length of the front. S_{mf} is a measure of the degree of irregularity at the mountain front. The S_{mf} value in the study area calculated for different segments of the mountain fronts ranges between 1.0 and 1.48. The mountain front sinuosity index for the Gish fan is 1.2, and that for the Matiali Fan is 1.29 (Table 1).The value should range between 0 and 6. The lesser the values, the more active the mountain front.

Valley floor width-to-height ratio

The valley floor width-to-height ratio was put forward by Bull (1977). It is expressed as

$$\mathrm{Vf} = 2Vfw/[(\mathrm{Eld}-\mathrm{Esc}) + (\mathrm{Erd}-\mathrm{Esc})] \tag{2}$$

where Vfw is the valley width, Eld is the altitude of the left bank, Erd is the altitude of the right bank and Esc is the altitude of the channel. The Vf values for the Rivers Gish, Lethi Nadi, Ramthi Khola, Neora and Murti have been calculated at a distance of 300 m from their source. The value for the Gish River valley is 0.228, that for the Lethi River valley is 0.071 and that for the Ramthi River valley is 0.3076. The value for the Neora River valley is 0.26, and that for the Murti River valley is 0.43 (Fig. 6, Table 2).

Stream length gradient index

In order to understand the tectonic and structural influences in the region and their influence in the channel dynamics, it is important to study the major and abrupt changes in the longitudinal profiles of the river. This could be done by calculating the segment-wise stream gradient index as proposed by Hack (1957). Many researchers have used the segment-wise stream gradient index to understand the influence of tectonics and lithology in the longitudinal profiles of the river (Bishop et al. 1985; Lee and Tsai 2009) The stream gradient (SL) index of a segment of the river between two points is calculated by the formula postulated by Hack (1957) which is stated below:

$$\mathrm{SL} = (\mathrm{h1}-\mathrm{h2})/[\ln(d2)-\ln(d1)] \tag{3}$$

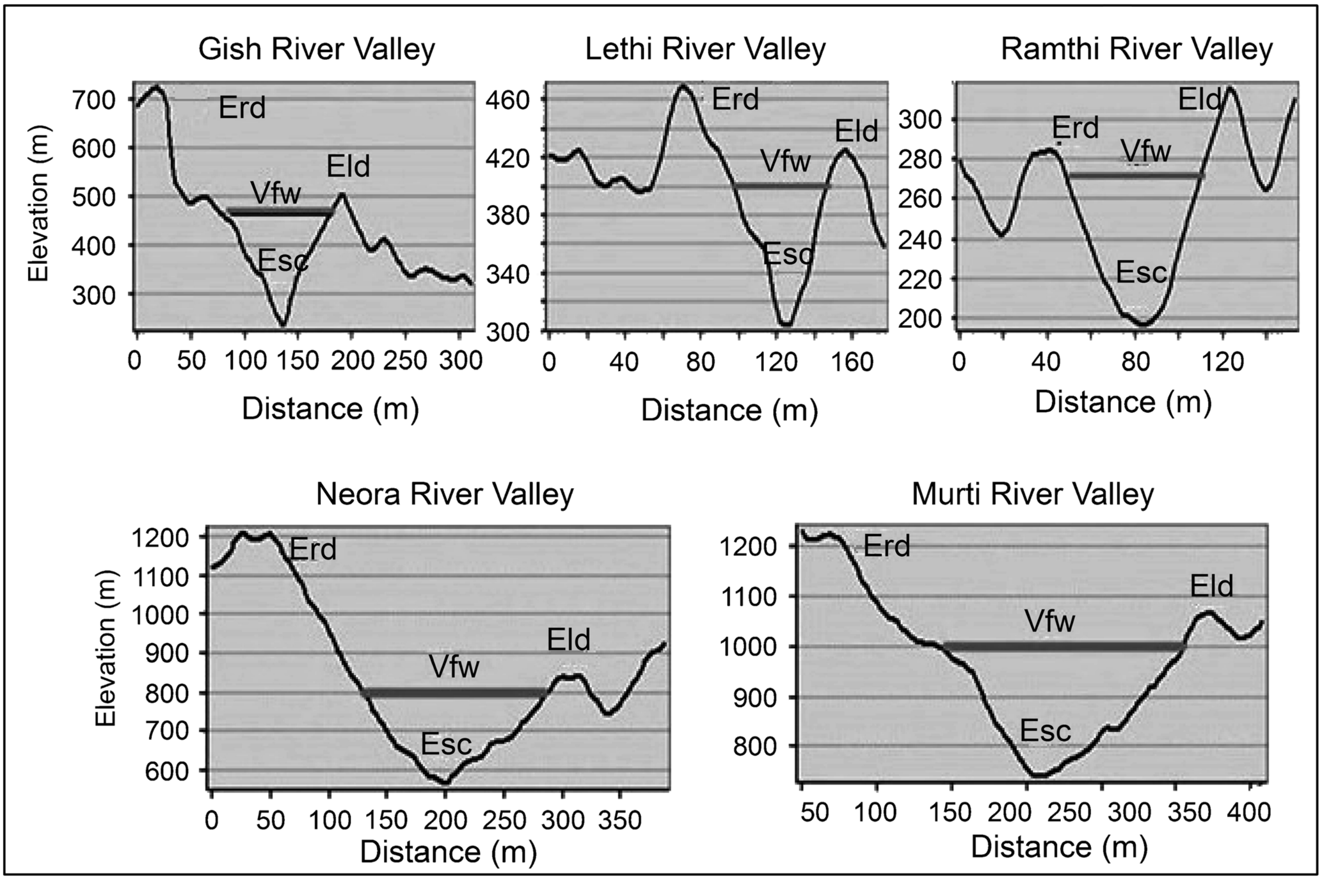


Fig. 6 Graphs showing calculations of valley floor width-to-depth ratio for the different valley sections. The valleys of Gish River and Lethi River are narrow and V-shaped which are indicators of the tectonic disturbance. The Neora and Murti have broader valleys; thus, the region is not tectonically active at present

where SL is the stream gradient index, h1is the height of the first point from the source, h2 is the height of the second point from the source, d1is the distance of the first point from the source, d2 is the distance of the second point from the source and ln is the natural log. The SL value for the Gish River is 318.7, that for the Lethi Nadi is 210.9 and that for the the Ramthi Khola is 148.2. The Gish River is 29.36 km long while Lethi is just 14.71 km in length. Thus, the value of SL for Lethi is quite high if the length is taken into consideration. This is a clear indicator of some sort of disturbance in the course of the river which is responsible for the high rate of deposition of the Gish fan. The SL value for Neora River is 549, and that for the Murti River is 201.3. The length of the Neora River is 34 km, and that for the Murti River is 39 km. Shorter length and higher SL values are clear indicators of disturbance along the course of the river (Fig. 7).

Normalised stream length gradient index

The normalised SL index is used in order to identify the points or the reaches with abnormally very steep SL index than the rest of the section. The SL index of each reach or segment of the river was divided by the idealised gradient index (k), which is the slope of the graded river profile, to obtain the normalised

Table 2 The calculation of the valley floor width-to-depth ratio for major feeder channels of the Matiali and Gish fans

Streams	Vfw (m)	ELd (m)	Esc (m)	Ed − Esc) (m)	ERd (m)	Erd − Esc (m)	2Vfw/[(Eld − Esc) + (Erd − Esc)]
Gish River	80	500	200	300	700	500	0.2
Lethi River	10	420	300	120	460	160	0.071
Ramthi River	40	400	200	200	260	60	0.31
Murti River	150	900	700	200	1200	500	0.43
Neora River	450	900	450	450	650	200	0.266

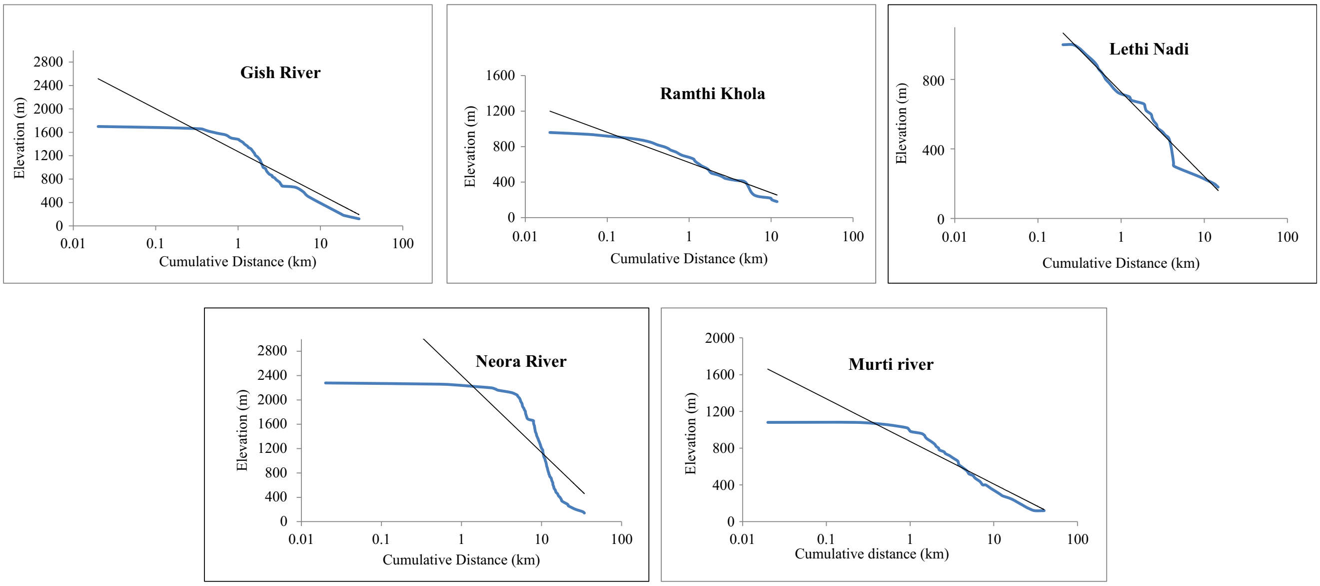


Fig. 7 Semi-logarithmic or Hack profile of the rivers with their SL index

SL index for each reach of the river (Seeber and Gornitz 1983). Mathematically, the statement can be represented as

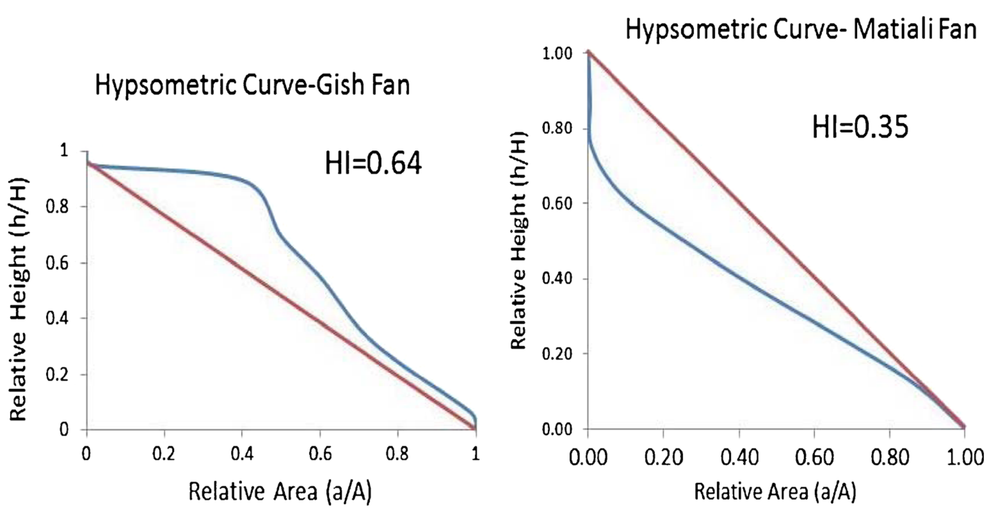
$$\mathrm{NSL} = \mathrm{SL}/k \quad (4)$$

where NSL is the normalised gradient index for a given stretch, SL is the stream gradient index for a given stretch and k is the slope of the idealised Hack's graded profile. Segments having NSL ≥ 2 are regarded as significantly steeper while the reaches of the rivers with NSL ≥ 10 are classified as extremely steep reaches. The values of NSL < 2 imply gentle gradient. The NSL value for the feeder channels of the Gish alluvial fan, namely, Gish River, was 2.09, that for the Lethi Nadi was 2.1 and that for Ramthi Khola was 1.3. NSL values for the feeder channels of Matiali fan are 2.1 for Neora and 1.5 for Murti.

Hypsometric analysis

The hypsometric analysis of the study area is the study of the distribution of the horizontal cross-sectional area of the landmass with respect to the elevation (Strahler 1952). The hypsometric analysis is used to differentiate between erosional landforms at their different stages of evolution (Strahler 1952; Schumm 1956). The hypsometric curve and integral can be interpreted in terms of the degree of basin dissection and the relative landform age. The hypsometric integral relates the percentage of total relief to the cumulative percentage of the area. The value of the hypsometric integral (Pike and Wilson 1971) ranges between 0 and 1. A value close to 1 is slightly eroded regions, and values close to 0 are highly eroded regions. The value of the hypsometric integral for the Gish alluvial fan is 0.64, and that for the Matiali fan is 0.35 (Fig. 8).

Fig. 8 The hypsometric curve of the Gish alluvial fan and the Matiali alluvial fan, respectively, where the HI of Gish is 0.64 which indicates a youthful stage of development while Matiali has a lower HI value of 0.35 and shows a mature stage of development



Tectonic tilt

The tilting of the fans takes place in response to the tectonic activities and upliftment of a section of the fan. In the fans where tilting has not taken place, the contours of the fan are in the shape of concentric semicircles while the fans that have tilted have ellipse-shaped contours on the fan surface (West 1991). This could be tested by using the morphometric technique put forward by Keller and Pinter (1996). The equation of the tectonic tilt is expressed as

$$\beta = arcos\left[\sqrt{\left\{(b/a)^2 sin^2 a + cos^2 a\right\}}\right] \qquad (5)$$

where α is the original depositional slope, which is derived by measuring the slope along the minor axis of the ellipse, and b is the half of the length of the minor axis of the ellipse and is the half of the length of the major axis of the ellipse. The analysis of the tilt was applied to both the Matiali fan and the Gish Fan. The angle of tilt was less in terms of the Matiali fan (0.8° towards the south-east direction) and more in the case of the Gish fan (0.93° towards the south-east direction) (Fig. 9).

Discussion

The region is a tectonically active mountain front marked by the presence of the active HFT and several small minor faults like the Gorubathan thrust fault (HTF), the GTF, the MTF and the Chalsa fault (CLF). Thus, the neotectonic study was conducted to understand the difference in the characteristics of the two fans formed in the same region. The mountain front sinuosity index values (S_{mf}) of the two fans are very low. However, the value of S_{mf} for the Gish fan is between 1.0 and 1.2 while the Matiali Fan has a slightly higher range of S_{mf} value (1.24–1.4). Thus, the Gish fan is tectonically more active than the Matiali fan. The valley floor width-to-depth ratio also shows very low values between 0.07 and 0.43. The Vf value for the Lethi River is 0.07 which is the least and a clear indicator of the active tectonic activity. The Gish River valley and the Ramthi Khola valley also show low values of 0.228 and 0.307. The higher value of Vf is observed for the Murti river (0.43). The hypsometric integral values are very clear indicators of the present stage of the landform. In this study, the hypsometric integral values are calculated for the fan surfaces. The hypsometric integral value for the Gish fan is 0.64, and that for the Matiali fan is 0.35. Thus, it is evident from the hyposometric integral (HI) values that the Gish fan is at its younger stage of development and aggradation is taking place while the lower value of HI for the Matiali fan indicates that the fan has reached maturity and is moving towards the old stage of development. Thus, it is a stable fan where no more deposition is taking place; rather, the active downcutting by the rivers has deformed the landscape completely. The segment-wise stream gradient or the SL index also shows very high values for the Gish and Lethi Rivers

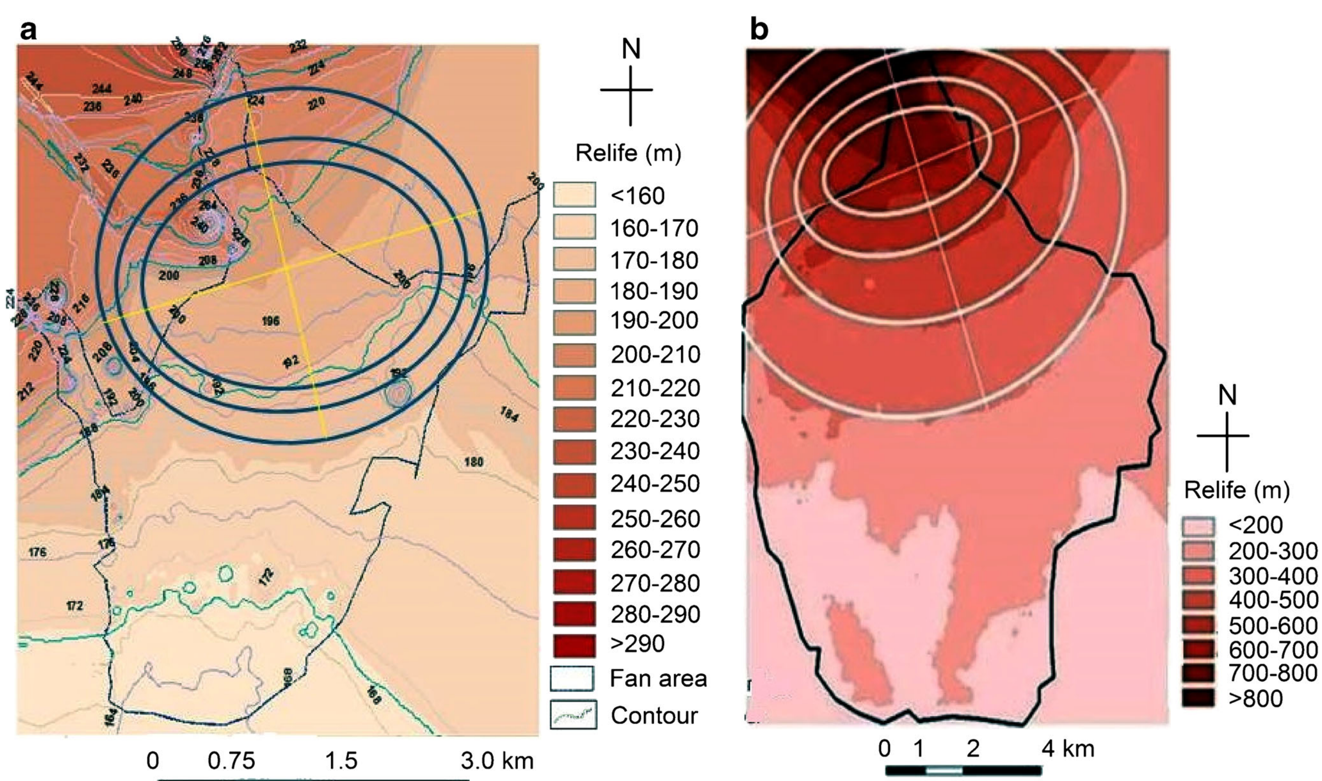


Fig. 9 **a** The calculation of tectonic tilt of the Gish River fan by fitting the ellipses. **b** Fitting of the ellipses for calculating the tilt of the Matiali fan

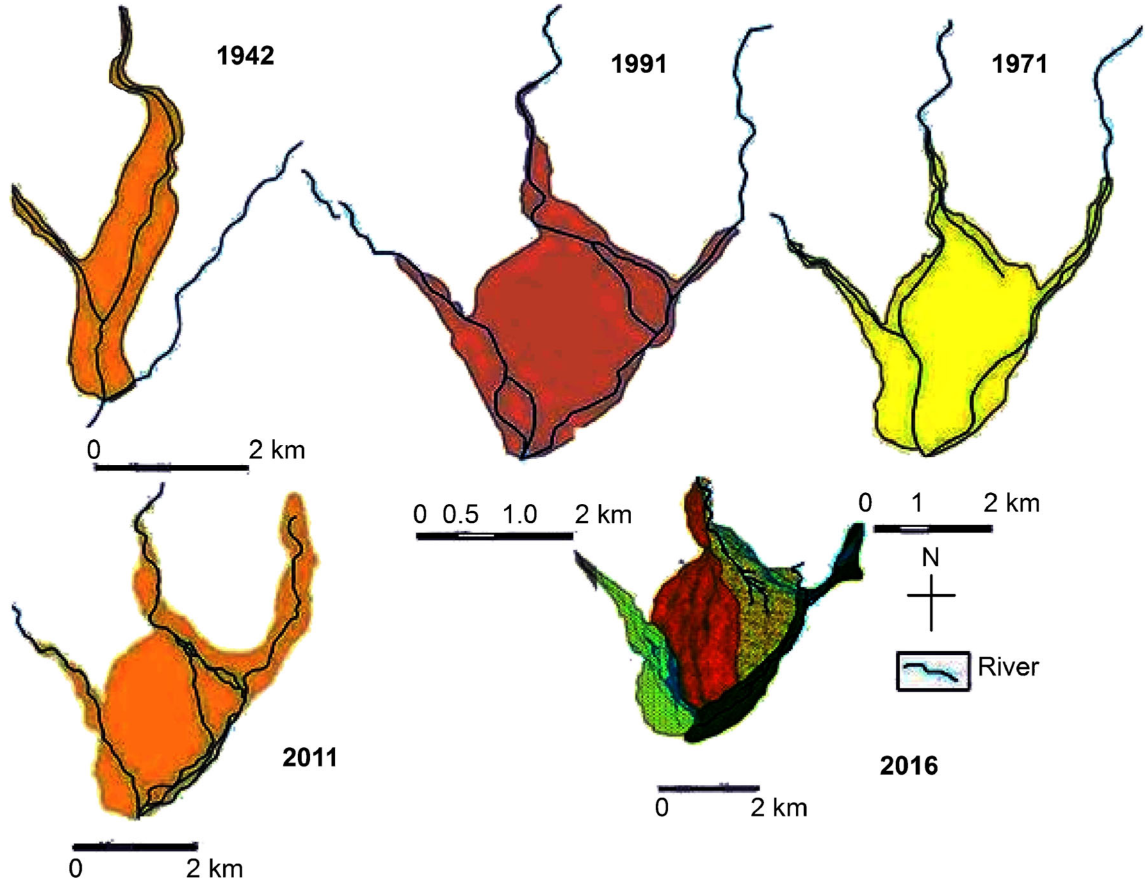


Fig. 10 The dynamic nature of the Gish River since 1942 and the changing topography of the Gish fan surface. The fan in 1942 was on the verge of development, but the fan shows development on the eastern side after 1942 which is clear in the image of 1971. The eastern part of the fan shows maximum aggradation (1991, 2011, and 2016), and the major contributing factor for this is the Lethi River which is the most active channel and a tributary of the Gish River. It contributes maximum sediment to the fan as the Gish transverse fault on the upstream section of the Lethi is the most active fault of the region

(318.7 and 210.9, respectively) which are indicators of disturbance in the course of the river due to the presence of faults. The Neora River also shows a higher value of 549.

The normalised stream gradient index also shows higher values for Gish and Lethi Rivers (2.09 and 2.1, respectively) which are indicators of steeper segments. Ramthi Khola has the lowest value of 1.3. The Murti River also has a lower value of 1.5. The value of NSL is slightly higher for Neora River, i.e. 2.1. Thus, these also clearly show that the Gish River and the Lethi Nadi are the most active and are tectonically controlled. Thus, they are responsible for the dynamic nature of the Gish fan and its expansion eastward. The presence of the GTF along the course of the Lethi River is the most important factor behind this. The GTF is extending at a rate of 10.9 ± 1.6 mm per year (Mullick et al. 2009). The disturbance in the upstream section of the Gish and the Lethi Rivers is responsible for the sediment supply which is being carried and deposited by these channels. This is the major factor for the eastward extension of the fan.

Since the Matiali fan has almost reached its maturity and no further deposition is taking place, the tectonic tilt for the Matiali fan was calculated. The fan is tilted at an angle of 0.8° towards the south-east direction. There is no evidence of very recent deposition and tectonic movement on this fan surface. The morphotectonic values also indicate that the fan

Table 3 Calculation of the geomorphological attributes of the active lobe of the fan

Fan area	Mean width (m)	Mean depth (m)	Cross-sectional area (m^2)	Mean velocity (m s^{-1})	Cross sectional area (m^3 s^{-1})	Slope (m m^{-1})	Stream power (kW m^{-1})
NW upper lobe	11.6	1.12	12.992	1.881	15.43579	0.455726255	68.93764679
NE upper lobe	13.2	1.58	20.856	1.71	35.66376	0.354118572	123.7661577
Middle lower lobe	17.2	1.76	30.272	1.605	48.58656	0.258617584	123.1403199

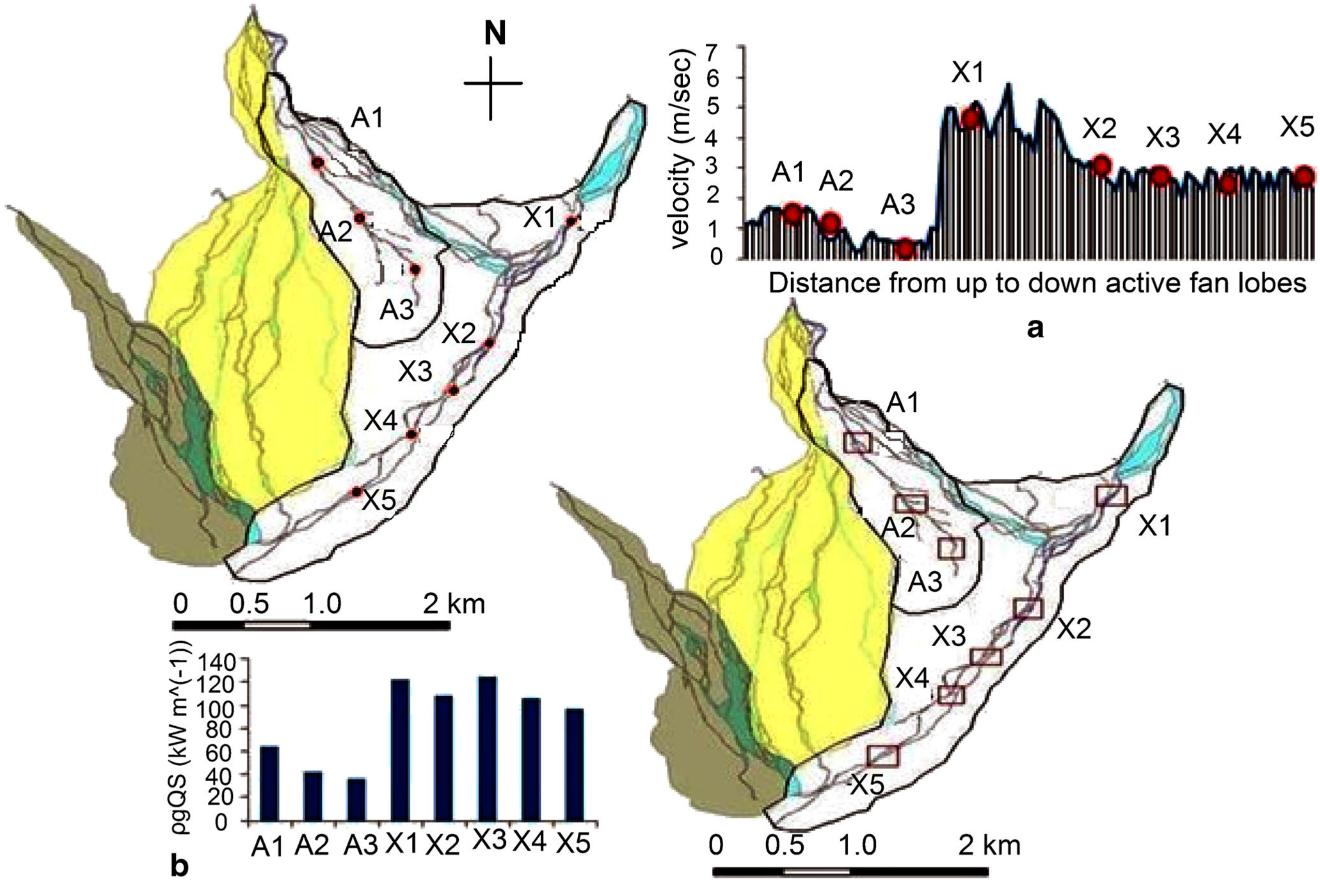


Fig. 11 The stream power and velocity of the channels in the active lobe of the fan show a decrease from the upper segment of the lobe to the lower segment. **a** The map of the Gish fan portraying the two active lobes and the points from where the velocity data was collected. The graph symbolises the decrease in velocity from the upstream to the downstream, i.e. from A1 to A3 and from X1 to X5. **b** The stream power of the different segments on the channel of the active lobe was collected which also shows a decreasing trend from the upper segment of the lobe to the lower segment

has reached its maturity, but the values of various morphometric and morphotectonic parameters show evidence of active tectonic activity on the Gish fan mountain front. By observing the topographical maps and satellite imageries of the Gish fan, it is noticed that the fan is rapidly expanding since 1942 and the fan is showing eastward expansion. The Rivers Gish and Lethi are also shifting continuously since the past few decades. The Gish fan is showing a multi-lobate character. Lobes are mesoscale depositional forms of an alluvial fan. At the intersection points on an alluvial channel, the main channel becomes shallow which causes sheet floods to occur and thus forms lobes comprising coarse boulders, cobbles and sand. The materials near the front of the lobes are coarser and become finer away from the lobes. Lobes are one of the most important characteristic features of the Gish fan. The Gish fan has a multi-lobate character comprising four lobes. These four lobes are identified using satellite imagery. Each lobe has a radial drainage pattern and is identified by the disordinance of drainage pattern in the adjacent lobe. The multi-lobate character of the fan is discernible from the cross-profiles in the form of laterally stacked multiple convex up-segments. Lobe 2 is present in the westernmost side of the fan. Lobes 3a and 3b lie in the eastern and northern margins of the fan. Lobe 1 is between lobe 2 and lobe 3. The trunk channel of the fans and the respective lobes are associated with the number of crevasse channels. The cross-profile of the fan at different sections indicates that lobe 3 is the youngest as it overlies all other lobes. The drainage of lobe 3a cuts across the drainage of lobe 3b; thus, lobe 3a is considered to be the youngest. However, lobe 3b is also one of the active lobes but the rate of deposition of lobe 3a is higher compared to that of lobe 3b. This is evident from the maps of 1941, 1971 and 1991, 2011 and 2016 (Fig. 10). From 1942 to the present, the lobe has developed at a very fast rate thus indicating the active rate of deposition that is taking place. The drainage of lobe 2 overlies that of lobe 1; thus, lobe 1 is the oldest of all the lobes. Lobe 3 of the Gish fan is the most active as already mentioned. Velocity, stream power, width of channels, gradient and hydraulic radius were included in the study for the active deposition of lobe 3 (Table 3). The rate of velocity is the controlling factor for grain size distribution in a single lobe. The stream power and the velocity are decreasing from the apex of the lobes to the

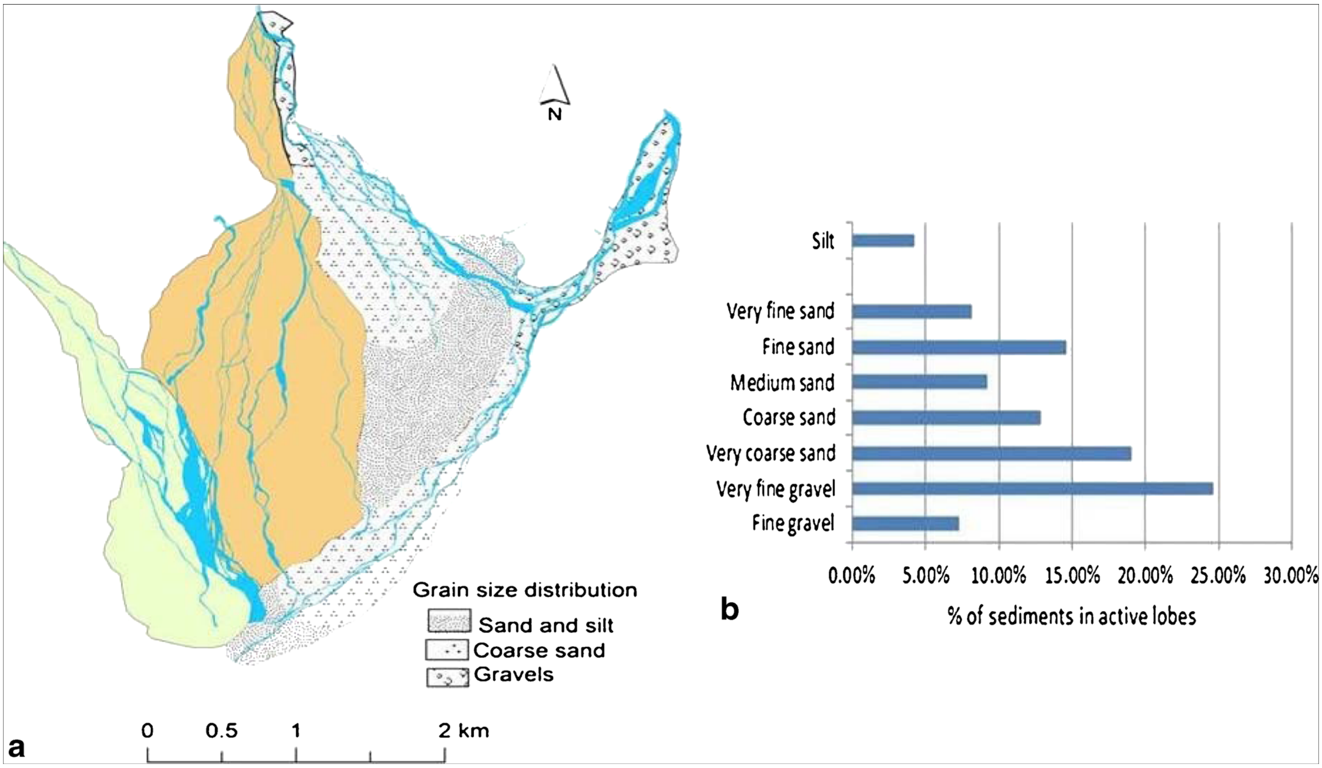


Fig. 12 **a** The map of the sediment character in the active lobe has been prepared which represents a decrease in grain size from the upper segment to the lower segment. **b** Grain size distribution was done on the basis of Wentworth (1942), and the percentage of individual sediments was calculated and represented in the form of a graph. Very fine gravel and coarse sand dominate the lobe sediments

Table 4 The calculation of fan tilt, where the Gish fan shows a higher value of tilt as compared to Matiali

Fan	arc cos	a (m)	b (m)	$(-)_a^b 2$	$\sin^2 a$	$\cos^2 a$	$\arccos\sqrt{\left(\frac{b}{a}\right)^2 \sin^2 a + \cos^2 a}\ \sqrt{}\cos^2 a$
Gish	4.1	2.27	4.43	0.0250	0.001217	0.99878	0.927121
Matiali	17.89	8.95	14.18	0.3983	1.22E − 05	0.999988	0.887638

Table 5 The grain size distribution according to Wentworth with their respective phi values for the active lobe of the Gish fan indicating the percentage of individual grain present in the lobe

φ scale	Size range (metric)	Size range (in)		Grain size out of the total fan area (%)
− 2 to − 3	4–6 mm	0.157–0.31	Fine gravel	7.26
− 1 to − 2	2–4 mm	0.079–0.157	Very fine gravel	24.64
0 to − 1	1–2 mm	0.039–0.079	Very coarse sand	19.10
1 to 0	0.5–1 mm	0.020–0.039	Coarse sand	12.84
2 to 1	0.25–0.50 mm	0.010–0.020	Medium sand	9.24
3 to 2	125–250 μm	0.0049–0.010	Fine sand	14.58
4 to 3	62.5–125 μm	0.0025–0.0049	Very fine sand	8.14
8 to 4	3.9–62.5 μm	0.00015–0.0025	Silt	4.20

toe (Fig. 11) and so is the grain size (Fig. 12, Table 4). In the upstream section, the gravels dominate, but as the stream power and velocity start to decrease, the grain size becomes smaller from coarse sand to fine sand and silt. To calculate the grain size distribution of the active lobe, the method put forward by Wentworth (1942) was followed (Table 5). The dominant grain size of the lobes was very fine gravel and coarse sand. Thus, a small fan like Gish can show such heterogeneous character in its morphometry and grain size mainly influenced by the hydraulics and tectonics of the region.

Conclusion

The study of the two fans conducted in the piedmont zone of the eastern Himalayas gives evidences of the neotectonic activities prevalent in the formation of the fans. The differences in the morphology and morphometry of the two fans reveal different characteristics. The two fans show evidences of neotectonism, but the Gish fan is unstable because of the presence of a very active fault (GTF) in the catchment of the Lethi River as evidenced from the pattern of the lobe development in the eastern segment of the fan which shows maximum deposition recently. On the other hand, the Matiali fan is moving towards stability as revealed from the calculated values of the morphotectonic indices. The Matiali fan is tilted at an angle of 0.8° towards the south-east direction as there is no evidence of fan deposition recently. Lobe 3 is the newly formed and the most active of all the lobes in the Gish fan. Lobe 3 overlies all the other lobes as revealed from the profiles drawn on the fan surface. The active rate of deposition of the lobes is noticed from the satellite images since 1942 till the present which show the expansion of the lobes. The impact of tectonics is stronger in the development of alluvial fans in this region which is visible in the hydrologic characteristics and dynamic nature of the fans especially those of the Gish Fan. As the lobes are extending eastward and south-eastward due to the high rate of deposition, they coalesce with the Chel-Mal fan in the east. In time, a huge fan comprising the fans of Gish-Chel-Mal would emerge which would characterise the most important nature of the fans of North Bengal commonly described as fan-in-fan.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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