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RESEARCH ARTICLE - HYDROLOGY

Channel evolution of the Himalayan tributaries in northern Brahmaputra plain in recent centuries

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Abstract

Himalayan tributaries of the northern Brahmaputra plain are vulnerable to rapid channel shift and planform adjustment. Yet, the information and knowledge of their morphological changes are sparse. This paper uses multiple geo-informational data such as archival maps, aerial and satellite imaginaries, field mapping and interviews with the locals, and previous literature to document the channel evolution of the tributaries in recent centuries, which can be an essential input to understand the contemporary adjustments of the Himalayan rivers. We infer that several tributaries along the northern plain of Brahmaputra have gone through major avulsions. Fingerprints of those avulsions, identified from archival maps and satellite imageries, suggest that the tributaries had a hop of an average distance of ~ 5.5 km. However, those migrations did not follow any geometric scale and select their path randomly. Paleochannel fingerprints indicate that the rivers once meandering have transformed into straight, braided and anastomosing channels. Intriguingly, the majority of the tributaries have widened by ~ 2.5–5 times compared to their parent courses. Evidence suggests that several river migrations are driven by surface warps, most likely, induced by seismic activities. Large rupture in the hilly catchments of Jiadhal (and its eastern tributaries) and associated sedimentation due to 1950 Assam earthquake have affected their channel morphologies. It suggests the potential role of the high sedimentation in the channel evolution of the tributaries. Consistency in the planform changes of the tributaries affirms that the northern plain of Brahmaputra is going through a spell of intensified sedimentation in recent times. The Brahmaputra is a young basin where ample surface signatures are available to link up the process–response mechanism of its tributaries. An extensive study should be a future priority to examine the nature of the tributaries more closely.

Keywords Himalayan tributaries · Northern Brahmaputra plain · River avulsion · River planform changes · Co-seismic surface warp · Intensified sedimentation

Introduction

Historical channel migrations and river planform changes are two critical indicators of channel evolution in a floodplain. Numerous paleochannels along the Himalayan foothills of the Brahmaputra floodplain provide geomorphic footprints of such channel migrations and planform changes. Based on these fingerprints and other historical information, researchers have reported several Himalayan tributary migrations in the Brahmaputra plain (Lahiri 1996; Goswami et al. 1999; Lahiri and Sinha 2012; Borgohain et al. 2017). However, these studies are mostly limited to the particular rivers or stretches of interest. Compared to river migrational studies, works on planform changes of the tributaries in the region are even sparse (Goswami et al. 1999; Sarma 2005; Borgohain et al. 2019). These works mainly focused on planform changes of specific rivers. Moreover, these works are often limited to qualitative descriptions of the planform changes of the tributaries. The existing results fail to provide an integrated representation of the tributary migrations and their planform changes in the Himalayan tributaries of the Brahmaputra plain. With this comprehension, this work will

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study the tributary migrations and their planform changes at a regional scale. This study seeks to contribute to the regional understanding of the channel evolution of the tributaries along the northern Brahmaputra plain in recent centuries.

For the last three decades, researchers have tried to link between the environmental and human factors influencing the river channels, and the morphological responses of the tributaries along the northern Brahmaputra plain (Lahiri 1996; Rajendran et al. 2004; Lahiri and Sinha 2012, 2014; Borgohain et al. 2017; Nongkynrih 2011). They suggested that neo-tectonics, basement topography, and co-seismic surface warps are the significant drivers of the morphological adjustments of the tributaries. Although these works are limited to local surveys, they provide essential process mechanism links between the drivers and the channel morphological changes. Considering the susceptibility of the region to seismic activities, it can be inferred that earthquakes are cardinal to the morphological adjustments of the tributaries of the area. The impetus has been put forward in this work, where we tried to explore the role of regional and local surface warps and rapid sedimentation in tributary migrations and their planform changes.

Considering the two key factors, tributary migrations and their planform changes, this work assesses the channel evolution in the Himalayan tributaries of the northern Brahmaputra plain in recent centuries. The purpose of this paper is twofold. The first one is to investigate the major channel migrations and planform changes in the northern tributaries of Brahmaputra. It includes: (a) identification of sequences and directions of tributaries' migrations, (b) measurement of the hop and length of the channel fragments that were subject to avulsion, (c) evaluation of river pattern changes, and (d) quantification of river width changes. The second purpose is to identify the link between the drivers and the morphological responses. It includes: (a) exploration of surface warps (horizontal terrain relief) at regional and local scales and evaluation of their role in river migrations and (b) observation based on depositional characteristics, field surveys, and previous literature to examine the role of seismic activities in sedimentation and related planform changes in the study plain.

River characteristics

The study includes Himalayan tributaries flowing along the northern Brahmaputra plain. It extends from Simen river in the east to the Sankosh river in the west (Fig. 1). The Himalayan tributaries along the study stretch vary in size and originate in the part of Himalayas of diverse topography. The larger tributaries originate in southern Tibet from Himalayan glaciers; the intermediate ones originate in the lower Himalayas and the smaller ones in the alluvial plain of Brahmaputra. The main tributaries of the north bank are Subansiri, Jiabhareli, Dhansiri, Puthimari, Manas and Sankosh. The channel patterns of the rivers vary broadly along the study plain. The larger tributaries have mostly braided or anastomosing-braided channel patterns. The rivers of intermediate size mostly form straight and aggraded channels upstream, followed by meandering stretches downstream. However, the smaller rivers are mostly meandering. The topographic distinctions are pronounced in the rivers of Himalayan origin. The rivers flow through the high gradient terrain of Himalaya, and, after descending into the plains, are characterized by a sudden change in the flow energy.

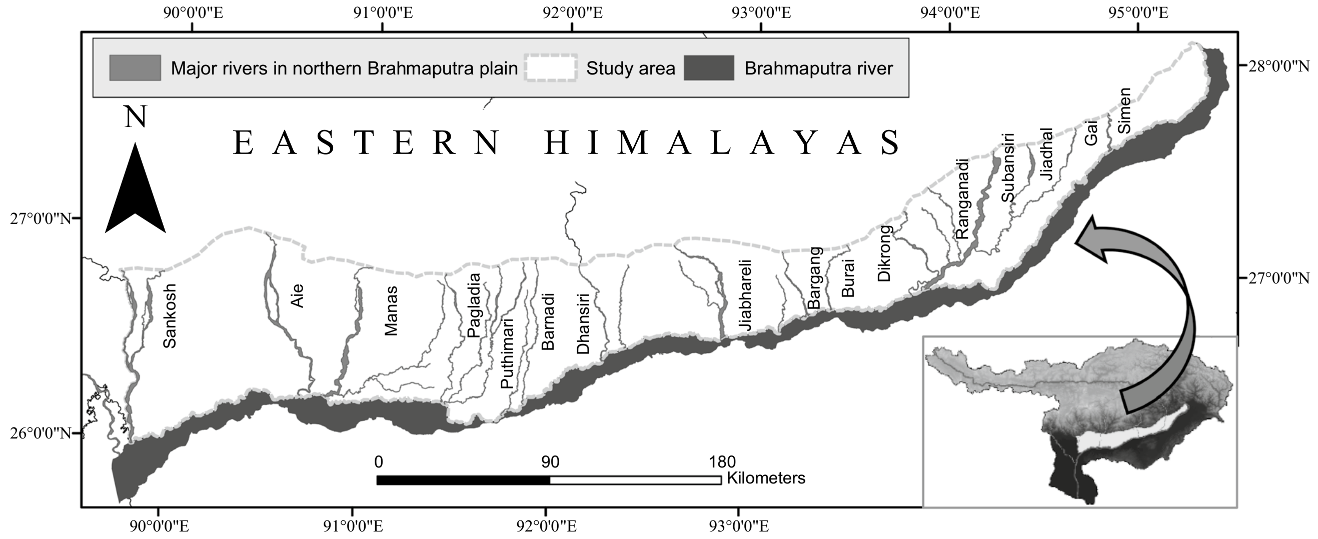

Fig. 1 Study area map: showing major tributaries of northern Brahmaputra plain

Multi-thread river patterns can be noticed in the Himalayan foreland of eastern Bhutan. Such distributaries often form separate tributaries to the Brahmaputra. Some rivers exhibit a distinct morphological transition along their longitudinal span, i.e., distributary formation is common closest to the foothills and then an aggraded alluvial river bed is formed, followed by a relatively tortuous channel till the confluence with the Brahmaputra (Fig. 2).

Data and methods

Necessitated by the nature of the work, multiple geo-informational data are utilized for this study. It includes historical and topographical maps, Landsat and Sentinel imageries, Corona photographs, and SRTM DEM. The historical maps and accounts included the works of Rennell (1776); (scale 1:750,000), Wade (1800), Hunter (1879), and Allen (1905a, b). Survey of India topographical maps of 1:50,000 along with the earliest available Landsat Multispectral Scanner (MSS) imageries (1972–1973) and Sentinel-2 imageries of the year 2019–2020 were utilized to identify the parent channels (paleochannels) and their present courses. For the region, cloud-free satellite imageries are mostly available for lean phase periods. Therefore, the satellite imageries (georeferenced) were downloaded for the months of November, December, and January. Based on 16 GCPs distributed across the study rivers (taken on road intersections and river bridges), the accuracies of satellite imageries were assessed. The accuracy of the georeferencing was found to be mostly ~ 30–60 m, which is smaller than or equal to a pixel size of the Landsat imageries. Corona photographs of 1962 were utilized to determine the recent major migration of the Dhansiri tributary. SRTM DEM data (surveyed in 2000) of 30 m spatial resolution were downloaded from the USGS website and used to draw elevation profiles along the northern Brahmaputra plain. Along with these data, Google Earth Pro is also used for paleochannel verifications.

False color composites (FCC) were prepared for both Landsat and Sentinel imageries in the GIS environment using NIR, red, and green spectral channels. The topographical maps were georeferenced using the geographical coordinate system with WGS 84 datum. Four GCPs on each georeferenced toposheets (spreading across) were used to assess

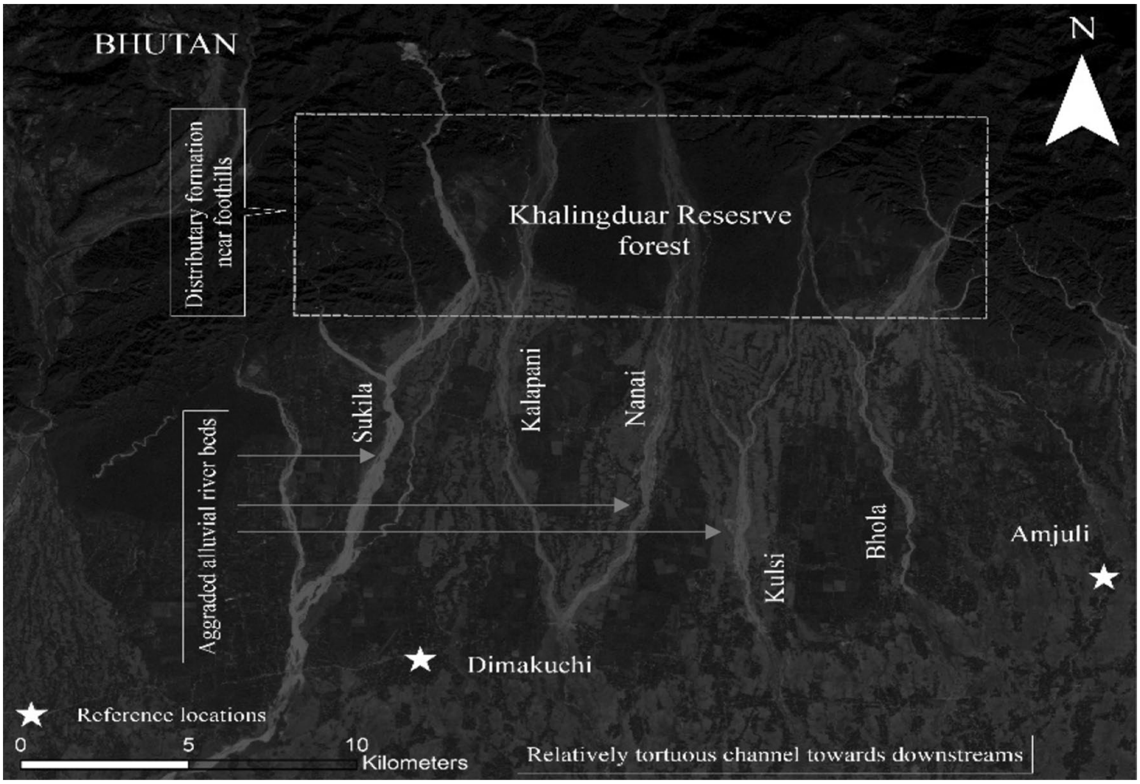

Fig. 2 Distinct morphological transition can be seen in the rivers—Kulsi, Nanai, and Sukla—along the Himalayan forelands region in eastern Bhutan. These rivers form distributaries near the foothills and then an aggraded river followed by relatively tortious channel toward downstream. For this demonstration, 2019 greyscale image of Sentinel-2 (red channel) is used in the background. Tributaries, in the Himalayan forelands region of eastern Bhutan, exhibit a typical morphological pattern-distributary formations closest to the foothills, then aggraded alluvial river bed followed by relatively tortuous channel in the downstream

their georeferencing accuracy. The accuracies were found to be mostly ~ 20–60 m. Subsequently, Landsat and Sentinel's FCC imageries and the georeferenced topographical maps were utilized to identify the parent channels and their present courses. Names of the paleochannels, channel geometry resemblances, and historical accounts and maps were used for paleochannel identification. Interviews with the locals were also carried out to collect information about the paleochannels and avulsion activities. Names of the paleochannels provide essential information in the identification of their current courses. For example, all along the plains of Brahmaputra, we can find rivers with prefixes 'Mora' and 'Jia' refer to 'Dead' and 'Alive,' respectively. This hydronym information is utilized to trace the parent channels of the study rivers. For the paleochannels with no such information, channel geometry resemblance is used as the tool for identification of the parent channels. Historical accounts and maps are essential sources of paleochannels information. They were also explored to identify the paleochannels and their present courses. Some of the river migrations are verified by the narratives of the locals. The long association of the authors to the region has also supplemented the interpretations.

We also measure two avulsion variables on 14 avulsion cases (measured along 7 rivers): (1) the hop length, which is defined as the average distance between the present channel-belt centerline and the corresponding paleochannel channel-belt centerline, and (2) the avulsion length, which is measured on the paleochannel from the point of avulsion to where present channel rejoins the parent channel-belt centerline (Edmonds et al. 2016). These measurement methods fit well in a local avulsion where the avulsion channel rejoins the parent channel downstream. However, regional avulsions are common in the studied rivers where the avulsion channel joins the contiguous river and does not return to the parent channel. In those cases, the length of the avulsion channel (or its channel-belt length) is considered based on the dominant flow. For example, if an avulsion channel joins an inferior (in terms of flow magnitude) river, then the captured river is the part of avulsion channel. On the contrary, if an avulsion channel joins a river of higher flow magnitude, then the length of the avulsion channel is considered till their point of confluence (see Fig. 3 for more details). The distinction in flow magnitudes of rivers can be made based on their channel width. River channel width is a valuable measure of flow magnitude, especially with remote sensing data (Sah and Das 2017; Valenza et al. 2020). Some of our considered avulsion cases have passed through intermediate avulsions. Consideration of such intermediate avulsions is sometimes hampered by: (1) insufficient paleochannel fingerprints and (2) the chronology of the shift of a channel. Therefore, only distinct avulsion footprints are considered for the hop lengths and avulsion lengths (Supplementary material 1). Channel adjustments associated with bank erosion and accretion are common in the northern tributaries of Brahmaputra. It can be seen in the case of Manas tributary. The lower reach of Manas has shifted westerly from its avulsion channel in recent decades. To minimize the effect

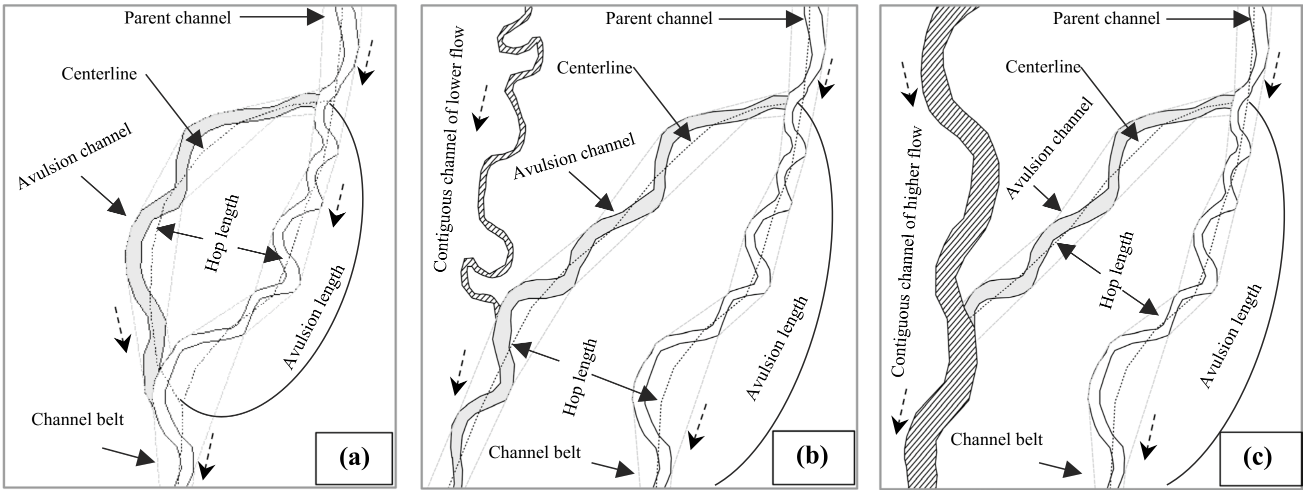

Fig. 3 **a** The hop length and avulsion length for a local avulsion (following the methodology of Edmonds et al. (2016)). In case of regional avulsions, the length of avulsion channel can be considered based on the relative flow magnitudes (river channel width) of avulsion and contiguous channels. In the demonstrated example of (**b**), the avulsion channel has higher flow magnitude, and therefore, its length continues after the confluence with the contiguous channel; however, in case of (**c**) the avulsion channel joins a contiguous channel of higher flow magnitude, and therefore, the length of the avulsion channel is considered till the confluence. Dashed arrow lines show the flow direction of the rivers. In case of regionalavulsions, the length of avulsion channel can be considered based on the relative flowmagnitudes of avulsion and contiguous channels. If an avulsion channel joins a contiguousriver of lower flow magnitude, then the length of avulsion channel will continue after theconfluence (b), however, if the avulsion channel joins a river of higher magnitude, then thelength of the avulsion channel should be considered till the confluence (c)

of such after-avulsion shifts in hop length and avulsion length measurements, avulsion channels were considered based on the earliest available Landsat imageries (1972–1973). The paleochannel fingerprints were also used to measure parent channel-belt width. Scaling relationships between the avulsion parameters and parent channel-belt width were drawn in MS excel using power function trendlines.

The rivers' sinuosity is measured using the sinuosity parameter $(P) = L_{\mathrm{cmax}}/L_{\mathrm{R}},$ where L_{cmax} is the mid-channel length of the widest channel and L_{R} is the overall length of the channel belt (Friend and Sinha 1993). The changes in sinuosity of the tributaries were measured from the paleochannels and the corresponding length of their present courses. The present courses of the tributaries were delineated from Sentinel imageries of the year 2019–2020. Changes in the width of the rivers in recent centuries are quantified using distinct fingerprints of the former channels on the satellite imageries. Former river channels include both paleochannels and meander scars (Supplementary material 2). The basic planform characteristics—channel patterns and alluvial fans of the paleochannels and their present courses—are interpreted visually from satellite imageries.

Regional and local slopes are evaluated along the northern Brahmaputra plain to explore their role in river migrations. Variation in regional slope is identified using SRTM DEM (30 m resolution). A cross-section line roughly passing laterally through the middle of the plain is drawn (Fig. 4a), which is used to generate the regional elevation profile in ArcGIS (Fig. 4b). Local slope variations along the foothill region are explored by developing elevation profiles using horizontal lines across the stretches of interest (Figs. 8, 10).

Results

River avulsions in the north plain of Brahmaputra

This section discusses the major avulsions of the Himalayan tributaries across the northern plain of Brahmaputra. The tributaries include: Simen, Gai, Jiadhal, Subansiri, Ranganadi, Dikrong, Burai, Bargang, Jiabhareli, Dhansiri(N), Barnadi, Puthimari, Pagladia, Manas, Aie, Champamati, Gaurang, Tipkai, Sankosh, and Raidak.

Simen to Dikrong

Among the Himalayan tributaries of Brahmaputra, Simen, Gai, and Jiadhal are known for their frequent avulsive activities (Sah and Das 2018). The paleochannels scars across the rivers are the evidence of their former avulsions. Presently, these tributaries have a general orientation toward the southwest direction.

Subansiri has shifted progressively and formed several paleochannels along its left bank (Fig. 5a). At present, it has a southwest orientation similar to that of Gai and Jiadhal. Based on the historical maps (1828 and 1916), Gogoi and

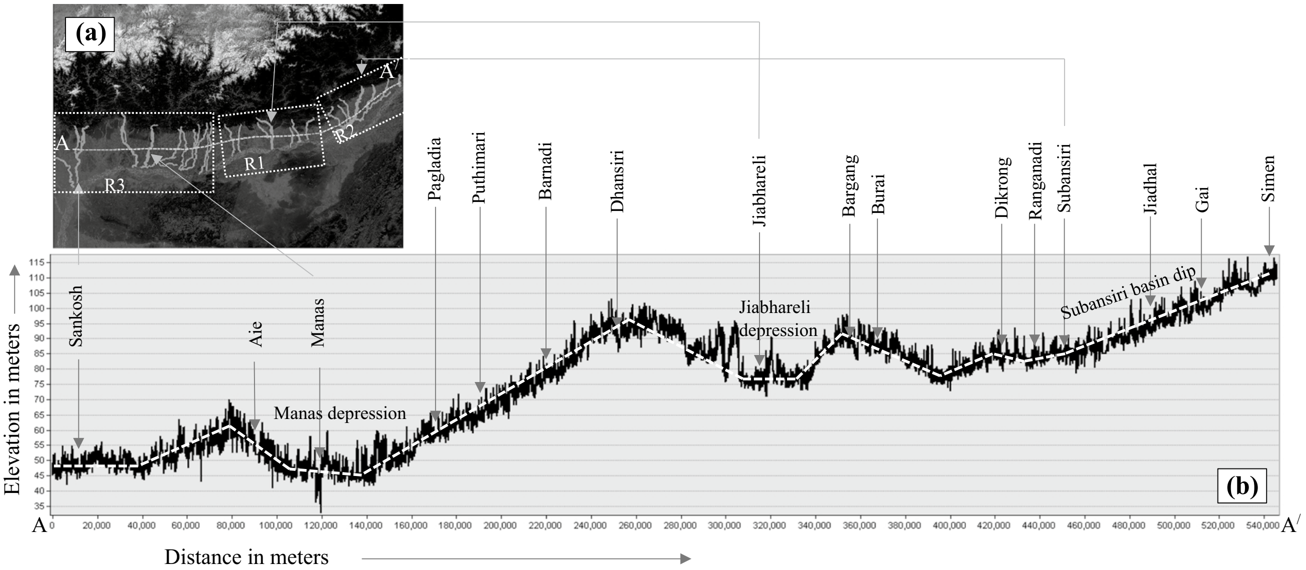

Fig. 4 Cross-section profile line (AA$^{/}$) which roughly passes, laterally, across the middle of the northern Brahmaputra plain (**a**) and the regional elevation profile developed using the cross-section line on SRTM DEM in ArcGIS software (**b**). White dashed line shows the generalized profile of slope across the northern Brahmaputra plains. The white dotted boxes (R1, R2, and R3 in Fig. 4a) represent the sections of northern Brahmaputra plain that are shown in Fig. 5. Illustrates the drawn cross-section line (AA$^{/}$) which roughly passes, laterally, across the middle of the northern Brahmaputra plain (**a**) and the regional elevation profile developed using the cross-section line on SRTM DEM in ArcGIS software (**b**)

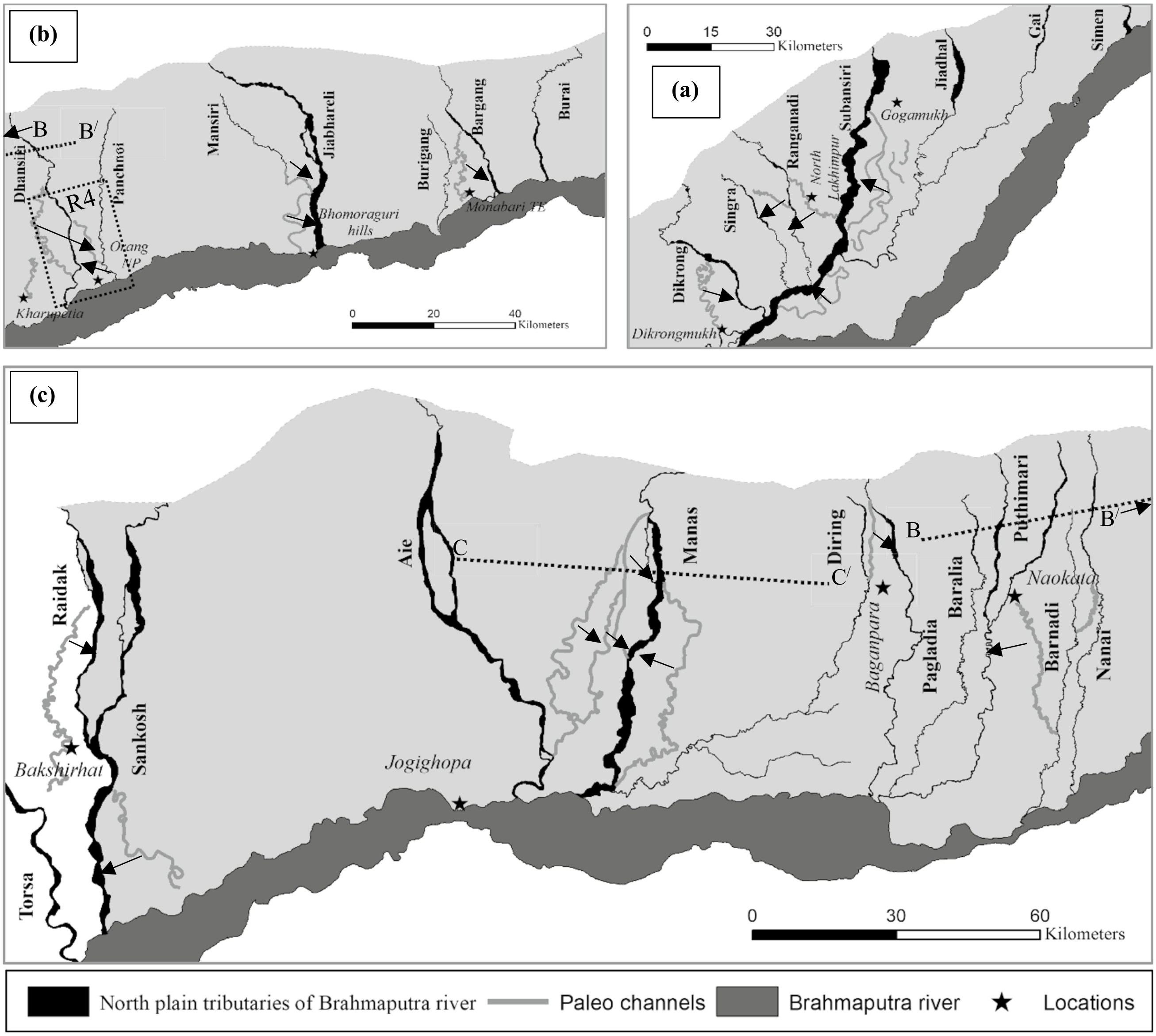

Fig. 5 Major avulsions in the Himalayan tributaries of northern Brahmaputra plain in upper (**a**), middle (**b**), and lower sections (**c**). The black dotted box (R4 in Fig. 5b) represents the section that is illustrated in Fig. 6. The black dotted lines (BB/ and CC/ in Fig. 5b, c) represent the cross-sections used in Fig. 8

Goswami (2014) inferred that the upper stretch of Subansiri was flowing along the east of its present course. The old scars near foothills indicate a southeasterly flow of Subansiri in the past, and the river was flowing along the eastern corner of Gogamukh village. The progressive migrations indicate that Subansiri has a persistent tendency to move toward its right. Two major tributaries of Subansiri, viz. Ranganadi and Dikrong, have also shown channel migrations. The paleochannel along the left bank of Ranganadi indicates that the river (or its major distributary) was flowing through the Sumdiri river near North Lakhimpur (Fig. 5a). The misfit river Sumdiri suggests its larger flow in the past. Another paleochannel on the west of Ranganadi is the old course of the Singra river. Singra was a tributary of Ranganadi (Fig. 5a). The westerly migration has shifted its course from the previous channel, and now it empties to Subansiri. All three rivers (Subansiri, Ranganadi, and Singra) have migrated to the west showing agreement with the southwesterly inclined regional slope of the Subansiri basin (Fig. 4b). Dikrong, however, has migrated toward the east. The river had a confluence with Brahmaputra/Luit near Dikrongmukh, shifted to about 10 km upstream (Fig. 5a).

Burai–Bargang–Jiabhareli

Meander scars can be noticed along the left bank of Burai, but they are primarily confined in and around its river belt and do not suggest any significant migration. On the other hand, the paleochannels of Bargang are evidence of its previous link with the tributary Burigang. As the names suggest (the prefixes 'Bar' and 'Buri' refer to 'Bigger' and 'Old', respectively), Burigang might be the older route of Bargang. Bargang was conceivably flowing through Kalapani to join Burigang (Fig. 5b). Another paleochannel of Bargang passes through the western part of the Monabari tea estate. Wade's account (1800) mentioned that Bargang had a confluence with the Brahmaputra nearly 2 miles below Behali tributary confluence to Brahmaputra. It resembles the present confluence of Bargang. His account also mentioned Burigang as a separate tributary. These indicate that the avulsions in Bargang must be before the eighteenth century.

Along its lower reach, Jiabhareli has migrated toward the east, and the abandoned channel is known as Mora Bhareli (Fig. 5b). Allen (1905a) reported that Jiabhareli had changed the course sometime before the British occupation of the province (the British annexed Assam in 1826). Jiabhareli has also changed its course near its confluence with Mansiri. The misfit river Mansiri along its lower course is the abandoned course of Jiabhareli (Fig. 5b).

Dhansiri(N)–Barnadi–Puthimari

Previously Dhansiri had a confluence with the Brahmaputra near Kharupetia village (Sarma 1993). Another abandoned channel can be noticed on the right bank of Dhansiri, which is known as Mora Dhansiri (Fig. 5b). Later, an eastward shift of Dhansiri captured Panchnoi (a tributary of Brahmaputra) near the Orang national park. Dhansiri did not settle to the course and eventually shifted toward the west in 1962 near Dhansirighat (Fig. 6).

The name of the river Barnadi ('Barnadi' means 'Big river') suggests its considerable size in the past. However, its abandoned course only carries a lean flow now. The lobe of alluvial fans on its left suggests the river was flowing easterly than its present route. The westerly migration has separated Barnadi from its previous course and now it flows through Puthimari (Fig. 5c) which joins the Brahmaputra near Barsulia village.

Manas to Raidak

In the past, Manas was joining the Brahmaputra above Jogighopa town. A series of easterly migrations of the tributary is noticed in the last century (Fig. 5c). However, the oldest traceable paleochannel (known as the Palla river) lies east of the Manas. Rennell's (1776) map suggests that Manas had confluence with the Brahmaputra near Jogighopa. The oldest traceable paleochannel of Manas is a previous course to it. It indicates that Manas was flowing along an eastern route (oldest traceable paleochannel) before preparing Rennell's map. Along the eastern section, the Manas basin was extended to Baralia (Hunter 1879; Allen 1905b). Later, the rivers—Baralia and Pagladia—were separated and become a direct tributary of Brahmaputra.

The tributaries Champamati, Gaurang, and Tipkai—are found to be relatively stable in the past. West to Tipkai is Sankosh, whose lower reach flowed easterly and joined the

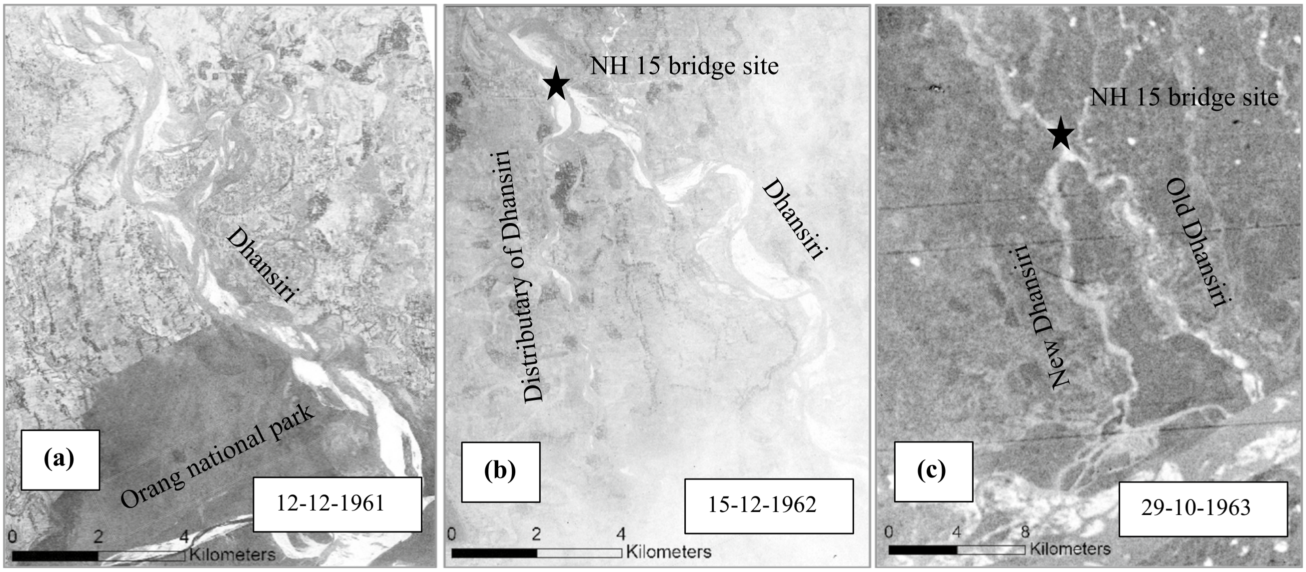

Fig. 6 Corona photographs of Dhansiri river for the periods 1961, 1962, and 1963. In 1961, Dhansiri was flowing along the eastern corner of Orang national park (**a**). During 1962, the river formed a major breach downstream to NH 15 bridge which led to the migration of Dhansiri river (**b**, **c**)

Brahmaputra near Dhubri (Rennell 1776). The abandoned course of Sankosh is known as Gadadhar. Raidak has also changed its course near its foothills. Earlier it was a tributary of Torsa. Now, the river has shifted southeasterly and joins Sankosh near Bakshirhat (Fig. 5c).

Hop length and avulsion length

Observation on a set of fingerprints suggests that the avulsions shown by the tributaries had an average hop length of ~ 5.5 km (Table 1). Migration of Sankosh had hop a distance of ~ 9.4 km, which is the highest among the considered fingerprints (Table 1; Supplementary material 1). Considering the high density of rivers in the northern plain of Brahmaputra, such migration often led to the capture

Table 1 The hop length, avulsion length, and channel-belt (paleochannels) width of Himalayan tributaries in northern Brahmaputra plain

Rivers[a]	Avulsion activities[b]	Hop length (in meters)	Avulsion length (in meters)	Channel-belt width (in meters)
Sankosh	1st avulsion (S1)	9322.58	29,337.49	1935.28
Manas	1st avulsion (M1)	5894.82	43,207.18	2241.78
	2nd avulsion (M2)	6353.00	57,925.18	2124.57
	3rd avulsion (M3)	2983.53	15,533.43	3551.56
	4th avulsion (M4)	5976.84	34,069.19	2370.85
Dhansiri	1st avulsion (D1)	7405.15	30,442.96	1007.32
	2nd avulsion (D2)	5667.26	20,606.38	1375.68
Jiabhareli	1st avulsion (J1)	6294.85	19,119.09	3417.07
	2nd avulsion (J2)	4254.91	15,990.50	2641.91
Dikrong	1st avulsion (DI1)	1729.17	7560.18	1542.18
	2nd avulsion (DI1)	7427.58	19,995.11	1435.36
Singra	1st avulsion (SI1)	4902.41	12,332.75	510.73
Subansiri	1st avulsion (SU1)	5548.16	24,924.10	2087.65
	2nd avulsion (SU2)	4070.39	34,130.61	4308.81
Average		5559.33	26,083.87	

[a] The avulsions of the rivers are shown in supplementary material 1

[b] The avulsion activities are listed in a chronological order. It follows from the earliest one to the latest in the table

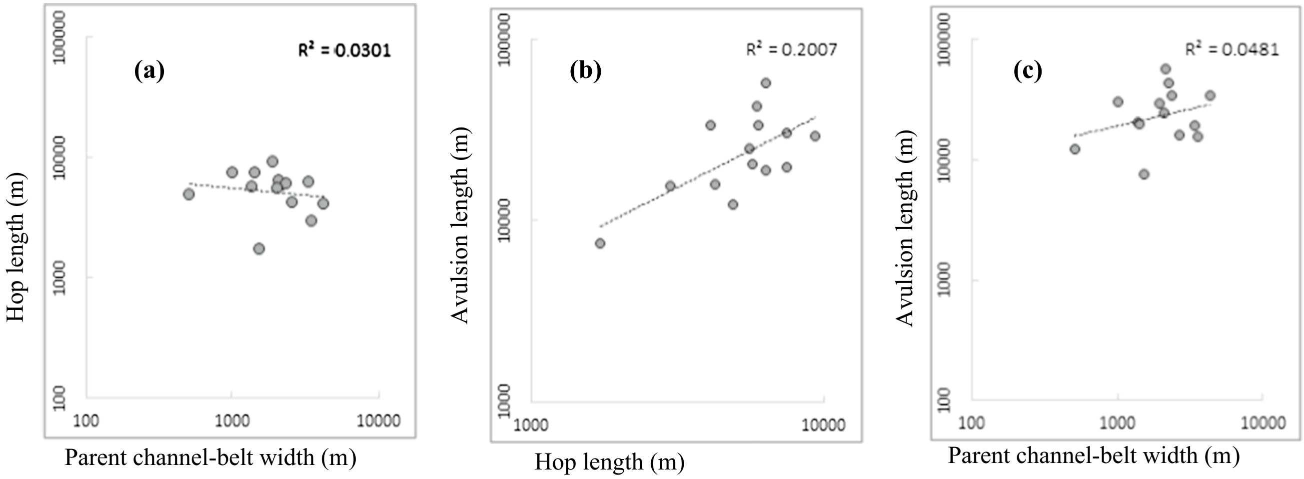

Fig. 7 Scaling relationship between the avulsion parameters (hop length and avulsion length) with parent channel-belt width (**a**, **c**) for the Himalayan tributaries of northern Brahmaputra plain. It also demonstrates the relationship between hop length and avulsion length (**b**) of the tributaries. Scaling relationship between the hop length and parent channel-belt width (paleo channels) (**a**), avulsion length and hop length (**b**), and avulsion length and parent channel-belt width (**c**) for the Himalayan tributaries of northern Brahmaputra plain

of contiguous tributaries. Moreover, we noticed that the hop lengths measured on avulsion fingerprints do not correlate with the parent channel-belt (paleochannels) widths (Fig. 7a). We also tried to draw the relationship between the measured hop lengths and avulsion lengths (Fig. 7b). But the observation suggests that the measured hop lengths are not associated with avulsion length (with R^2 value being insignificant). Avulsion length of the tributaries also varies largely across the floodplain, with an average of ~ 26 km. Similar to hop length, avulsion lengths are also inconsistent with the parent-channel widths (Fig. 7c). With the help of local avulsions in rivers of foreland basins, Edmonds et al. (2016) found that avulsion length is 13.4 parent channel-belt widths where they measured parent channel-belt width (average) upstream of the avulsion site. They inferred that both hop length and avulsion scale with parent channel-belt width. On the contrary, our result suggests that avulsion length did not follow any geometric scale and select their path randomly. In the Brahmaputra plains, however, such avulsion path selections of the tributaries are controlled mainly by annexation. It is because of the presence of a large number of paleo- and active channels in the plains. They provide readymade conduits for avulsion channels.

Change in river patterns

The paleochannels of the north bank tributaries of Brahmaputra represent different planforms compared to those of the present day. The rivers have transformed from meandering to straight, braided, and anastomosing courses. Subansiri, which was a tortuous river, has changed to a braided one. Dikrong has straightened significantly compared to its earlier course. The sinuosity of the old course was about 2.2 compared to 1.2 at present (Table 2). Short-term assessment also showed a decrease in sinuosity of the Dikrong river (Borgohain et al. 2019). Likewise, Burai and Bargang were also meandering rivers. Jiabhareli, however, was a winding braided river. Mid-channel bars can be noticed in its lower abandoned channel. Dhansiri was also tortuous with a sinuosity ratio of about 2.5, which has reduced to 1.2 (Table 2). Compared to its earlier course, Manas has widened manifold. Aie, a former tributary of Manas, has also transformed itself into one of the widest tributaries of Brahmaputra. In contrast to its width, Aie originates in the lower Himalayas, and its basin area is not larger among the tributaries of Brahmaputra. Sankosh has also transformed from meander to braided river. However, the migration of Raidak to Sankosh has also contributed to the associated planform changes.

Table 2 Changes in sinuosity of the Himalayan tributaries in northern Brahmaputra plain

Rivers[c]	Sinuosity parameters		Decrease in sinuosity (in percentage)
	Paleochannels	Current channels	
Sankosh	2.05	1.11	46.14
Manas	1.95	1.34	31.32
Dhansiri	2.46	1.21	50.87
Jiabhareli	2.01	1.19	40.94
Dikrong	2.15	1.24	42.34
Singra	1.61	1.11	31.19
Ranganadi	1.76	1.25	29.00

[c] Only the tributaries having distinct paleochannels for a considerable length are taken for sinuosity parameter measurements

River width

Paleochannel fingerprints indicate that the tributaries were flowing through narrow channel reaches compared to their present courses (supplementary material 2). Paleochannels suggest that the width of two major tributaries, i.e., Manas and Jiabhareli, was ~ 0.5 km, which has increased by ≥ 3 times in recent centuries (Table 3). Smaller tributaries (e.g., Singra) have also shown significant widening in their channel reaches. We measured a widening of ~ 2.5–5 times parent channel width in several tributaries (Table 3). An exception is the Sankosh river which has widened more than eight times. Table 3 suggests a consistency in the channel widening of the Himalayan rivers along the northern plain.

Table 3 River width modifications shown by the Himalayan tributaries of northern Brahmaputra plain

Rivers[d,e]	Channel width (in meters)		Changes in width (in multiples)
	Paleochannels	Current channels	
Sankosh	190.38	1578.09	8.29
Manas	499.57	1765.63	3.53
Dhansiri	85.45	327.70	3.83
Jiabhareli	573.30	1689.47	2.95
Bargang	96.25	476.79	4.95
Burai	192.40	510.21	2.65
Dikrong	102.88	469.37	4.56
Singra	90.54	263.56	2.91
Ranganadi	83.36	187.12	2.24

[d] The paleochannels and the present courses of the tributaries considered for width measurements are shown in supplementary material 2

[e] Only tributaries having distinct avulsion footprints (both paleochannels and meander scars) are considered for width measurements

Major causes

Surface warping and river migrations

Rivers' hop directions showed a general compatibility with the local and regional slope. Some rivers have sharp channel turns, while few show a similar orientation of their channel direction, where the role of surface warps seems to be crucial. In this section, we tried to find out such surface warps by drawing (using SRTM DEM in GIS) the regional and local slopes in the region (Figs. 4, 8, 10).

The regional slope profile along the cross-section of the northern Brahmaputra plain identifies few basin depressions (trough) and elevated plains (crest). Subansiri, in the plains, looks like a southwesterly inclined basin without a dominant central dip (Fig. 4b). This tilt in the surface has promoted the rivers' unidirectional (southwest) flow (Subansiri, Jiadhal and Gai). The southwesterly orientation of the Subansiri basin dip has also encouraged westerly shifts of the trunk channel.

The rivers Burai and Bargang flow through the alluvial crest (relatively elevated plain) (Fig. 4b), having less lateral inclination. It contributes to the stability of the rivers, which has shown no significant dynamics in recent times. Alike Subansiri, Jiabhareli also forms its basin dip (Fig. 4b). The elevation profile suggests that the present course of Jiabhareli is flowing through it. Researchers suggested that the current course of Jiabhareli flows through a graben (Viswanathan and Chakrabarti 1977; Debnath 2007). Opposite to its past migrations, Jiabhareli, in its lower reach, is gradually migrating to the west in recent decades. This lateral incision of Jiabhareli near its confluence to the Brahmaputra suggests that Jiabhareli is still seeking an adequate pathway.

Dhansiri displays a sharp southeasterly turn near the foothills. Several other rivers lying on the west of the Dhansiri also show similar characteristics. It prompted us to explore the presence of any dominant surface high in the foothill region. Consequently, the drawn elevation profile along the foothills shows a dominant surface high near the Khalingduar reserve forest (marked as Khalingduar high in Fig. 8a, b). The rivers' flow orientation and progressive shift along the stretch indicate a possible upliftment in Khalingduar high. The Khalingduar high (which is evident in Fig. 8b) is a dominant factor in the migration of the Dhansiri river. The immediate downstream reach of the river followed the regional and local slopes and accordingly carved its course. The Khalingduar high has also influenced the migration of Puthimari toward the west near the foothills. This westward migration led to the separation of Puthimari from Barnadi river.

Pagladia migrated easterly near the foothills. We drew an elevation profile along the foothills but did not observe any distinct surface warp. Instead, the interfluve ridge between Pagladia and Diring seems to be formed by foreland deposits. Migration of Pagladia near foothills is the morphological adjustment induced by the foreland deposits. Downstream to the foothills, Pagladia lies in the southwesterly slope (Fig. 4b). The river tried to capture its previous course through a major breach in 2004. The breach led to a southwesterly flow migration of Pagladia where the role of the regional slope seemed to be decisive. However, later the diverted flow was blocked by dike.

Like other larger tributaries of Brahmaputra, in the plains, Manas also forms its basin dip. The Kukulong surface uplift and fluvio-tectonic aspects are described as the factors responsible for Manas river migration (Nongkynrih 2011). The elevation profile near the foothill region of the Manas river shows a persistent down-tilt to the east of the Kukulong high (Fig. 8a, c). The unidirectional shift of Manas is complimentary with this down-tilt. A massive breach near the Bahbari tea garden that captured Palla

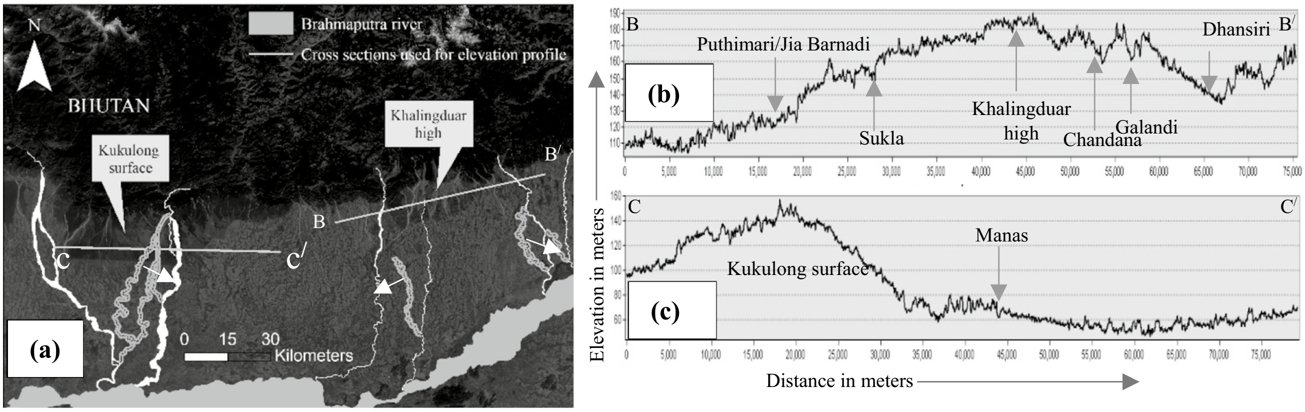

Fig. 8 The drawn cross-sections: across Khalingduar high ($BB^{/}$) and Kukulong surface high ($CC^{/}$) (**a**). The local elevation profiles are drawn using the cross-sections ($BB^{/}$ and $CC^{/}$) on SRTM DEM in GIS environment (**b**, **c**). The white arrow lines show the avulsions of the rivers referred to Khalingduar high and Kukulong surface

river (the historical channel of Manas) in 2004 reveals the river's pressure along its left bank.

Earthquake and sedimentation

Leaving aside the climate factor, earthquake seems to be an essential contributor in the changes of the fluvial environment of the northern Brahmaputra plain. Figure 9 shows the susceptibility of the region to earthquakes. The 1950 Assam earthquake, one of the recent seismic activities, is explored to evaluate the significance of such activities in the current channel evolution of the tributaries.

Researchers mention the role of the 1950 Assam earthquake, especially on the proximal tributaries of Brahmaputra (Goswami 1985; Devi and Bora 2016). Interviews with the locals suggest that the rivers have been subjected to large sediment waves after the earthquake. The isoseismal of 1950 earthquake (Poddar 1950) suggest large rupture in the hilly catchments of Jiadhal and its eastern tributaries (Fig. 9). Jiadhal, a proximal river to the 1950 earthquake, was mapped as a meandering river in old topographical maps surveyed between 1916 and 1924 (Borgohain et al. 2016). Comparison to the satellite imageries after 1950 and the terrain mapping of the landforms, we can assert that the recent morphological change is due to the high sedimentation caused by the Assam earthquake. Distinct depositional features can be noticed along the upper reaches of Jiadhal and Gai. We also drew an elevation profile to explore the surface morphology along the stretch. It identifies well-shaped alluvial fans of Jiadhal and Gai (Fig. 10). Within the last

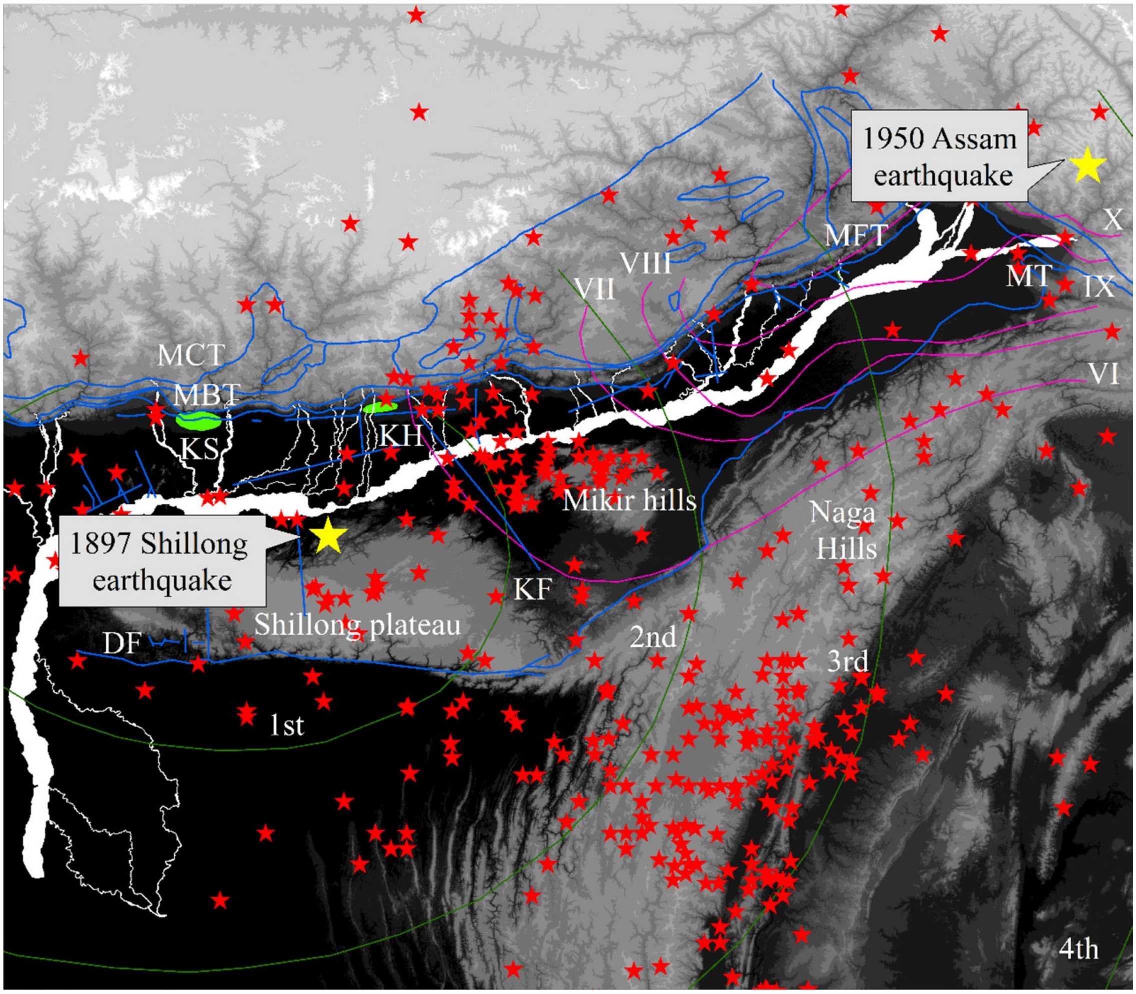

Fig. 9 The tectonic features of the study area and its surrounding region are from Dasgupta et al. (2000). Major tectonic features of the region are indicated as: MCT—Main Central Thrusts; MBT—Main Boundary Thrust; MFT—Main Frontal Thrust; DF—Dawki Fault; MT—Mishmi Thrust; KF—Kapili Fault. The green circles represent the Kukulong surface and Khalingduar high (marked as KS and KH, respectively). The red stars indicate the recent earthquake events of ≥ 3 magnitudes in the region which is downloaded from Open Government Data (OGD) platform India. Pink color isoseismal lines of the 1950 Assam earthquake are from Poddar (1950). Green color isoseist lines of the 1897 Shillong earthquake are from Oldham (1899). The study rivers and Brahmaputra are shown in white color. The grayscale background is SRTM DEM

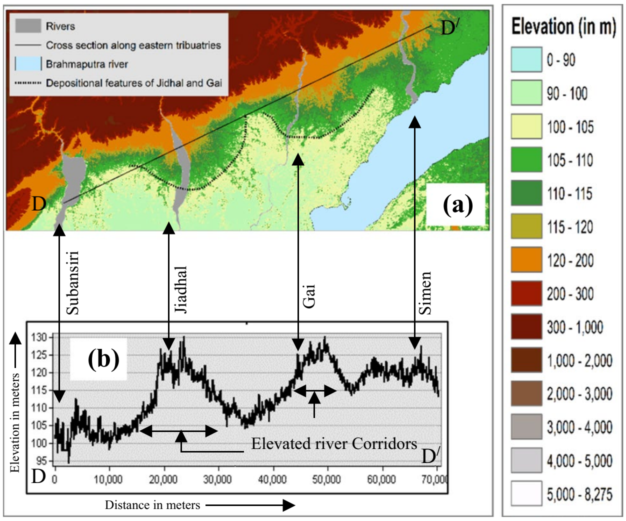

Fig. 10 The cross-section line (DD/) across Subansiri to Simen tributaries (**a**). SRTM DEM highlights two distinct depositional features near the foothills of Gai and Jiadhal river (**b**). The elevation profile drawn using the cross-section (DD/) identifies prominent elevated river corridors along the two rivers (**c**). The toes of the depositional features are marked with the dotted black lines

century, the 1950 earthquake is undoubtedly the dominant activity that can bring such intensified morphological adjustments. The imbalance created by the earthquake-induced sand splay deposits along the fan of Gai and Jiadhal triggered them to migrate frequently.

The 1950 earthquake has affected the recent channel evolution of the Jiadhal and Gai rivers. The quake has released nearly 45×10^9 m^3 sediment to the Brahmaputra and its tributaries (Sarker and Thorne 2006, and reference therein). Notably, apart from this well-known earthquake, the researchers recognized several major earthquakes in the seventeenth and eighteenth centuries (Oldham 1883; NEIST 2013, and references therein). The rapid change in planforms of the tributaries explains their transition in hydro-geomorphic conditions where the seismic activities conceivably have played a crucial role. However, a future work examining the impact of land cover changes, river flow changes and anthropogenic pressure is imperative for comprehensive understanding of the recent river geomorphic triggers in the region.

Discussions

We observed several major migrations in the tributaries of the northern Brahmaputra plain in recent centuries. The fingerprints taken from those avulsions suggest that such migrations had a hop of an average distance of ~ 5.5 km in their floodplain with an average avulsion length of ~ 26 km. Exploration of terrain reliefs at regional and local scales and referring it to the avulsion direction point out its possible role in tributaries' avulsions. Both progressive and unidirectional river migrations were found in study area The evidence from this study suggests that basin tilt and general slope directions are playing crucial roles in those migrations. Prior studies have noted the role of the down-tilted side in such unidirectional movement of a river (Holbrook and Schumm 1999; Lahiri and Sinha 2012). Lateral tilt in basin locus naturally gravitates a river toward the down-tilted zone. The rapid aggradation process has also triggered tributary migrations in the northern Brahmaputra plain. The migration of Pagladia is a result of such rapid aggradation near the foreland region. The northern tributaries of northern Brahmaputra plain, which have shown several major avulsions, are dictated by high sediment flux. It is generally accepted that aggraded beds reduce channel water and sediment transportation capacity, resulting in frequent and forced course adjustment (e.g., Jones and Schumm 1999).

The Himalayan tributaries in Brahmaputra northern plain have undergone intense channel transformation in recent centuries. The majority of the tributaries have transformed their planforms from meandering to braided. Our observation suggests that several tributaries have widened by ~ 2.5–5 times parent channel width. Researchers related the sediment transport, and the proportions of bed load and suspended load with river channel patterns (Schumm 1963; Church 2006, and references therein). The river's width can increase with the increase in bedload (Smith and Smith 1984). The effect of the rapid influx of sediment in the recent evolution of the Brahmaputra river is suggested by several researchers (Goswami 1985; Sarma 2005; Sarma and Acharjee 2018). The Assam earthquake of 1950 released approximately 45×10^9 m^3 of sediment to the Brahmaputra and its tributaries and affected the morphology of the entire Brahmaputra river (Goswami 1985; Sarker and Thorne 2006, and reference therein; Sarker et al. 2014). It is apparent that, leaving aside the climate factor, seismic activities are the dominant contributors to the sediment flux in the region. The rapid influx of sediment has transformed the channel pattern of the tributaries in the northern Brahmaputra plain. The sedimentation in the proximal rivers of Brahmaputra after the 1950 earthquake and its effect on the river morphologies substantiates the fact.

Conclusions

The purpose of this study was to investigate the channel evolution of the Himalayan tributaries of Brahmaputra in recent centuries. The study has identified that the rivers have gone through major avulsive activities. One of the significant findings from the study is that all the rivers have transformed their planform characteristics. The rivers once with meandering courses have changed to a braided or anastomosing channel. The rivers have also widened several times compared to their parent courses. Our observation and previous studies indicate that induced surface warps and rapid sedimentation in northern Brahmaputra plain have played a significant role in the tributaries' avulsive activities and their planform changes. The consistency in planform (channel width and pattern) changes in the tributaries indicates that the entire plain has come across an intensified sedimentation in recent times. These observations are essential for the understanding of the channel evolution processes in Himalayan rivers.

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Data availability The information related to this paper is provided as supplementary materials.

Code availability Not applicable.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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