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Reconstructing the channel shifting pattern of the Torsa River on the Himalayan Foreland Basin over the last 250 years

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Abstract. The varied physiography, incidences of high seasonal discharge, influences of neo-tectonic activity and the young geological foundation with less consolidated cohesive and non-cohesive sediment have left the Himalayan foreland basin a formidable ground, where silt-laden rivers tend to migrate frequently. A set of maps prepared after 1764, space photographs captured in 1970 and current satellite images from 2015 and 2017 were studied to reconstruct the fluvial dynamics of the Torsa River on the foreland basin of Sikkim-Bhutan Himalaya considering a time span of nearly 250 years. Evidence collected from colonial literature, the above-mentioned satellite images and a field survey, were combined to verify results taken from the old maps used as the base of the study. The application of satellite remote sensing and analysis of the topographic signatures of the palaeo-courses in the form of the palaeo-levee, abandoned courses and ox-bow lakes were the major operational attributes in this study. As a consequence of the channel migration of Torsa River since 1764, the historical floodplain of Torsa has been topographically marked by beheaded old distributaries, a misfit channel system and the presence of abandoned segments. Morphometric changes in the old courses, major flood events and neo-tectonic activity guided an overall trend of channel migration eastwards and has led to a couple of channel oscillation events in the Torsa River over the last 250 years. The mechanism of the avulsion events was thoroughly driven by sedimentation-induced channel morphometric changes and occasional high discharge.

Key words:
Channel oscillation,
colonial literature,
Himalayan foreland,
remote sensing

Introduction

The fluvial environment of any particular river on the Himalayan foredeep basin is continuously adjusting its character as the river encounters a certain change in the morphodynamic domain of the controlling variables. This is caused by the gradient dropping considerably between the mountainous stretch and the foreland plain. This has substantially contributed to the rivers being both highly dynamic and hyper-avulsive. The rate of migration is so rapid that the rivers can be transitive at a temporal scale of a few decades to a century (Chakraborty and Ghosh 2010; Jain and Sinha 2004; Sinha and Ghosh 2011; Roy and Sinha 2005; Jana 2006; Chakraborty and Dutta 2012; Mukhopadhyay 2014). At such rates of change, combining old maps with recent satellite datasets can provide valuable discernments of the channel dynamicity at a moderate temporal scale for a couple of centuries (Passmore et al. 1993;

Mitra et al. 2005; Chakraborty et al. 2010; Scorpio et al. 2018).

Rivers on the Himalayan foredeep part portray a suffering due to increasing bed elevation as a result of sedimentation. Often, this results in the active channel becoming blocked, and in frequent changes in cross valley slope (Mukhopadhyay 2014; Sinha 1996; Jain and Sinha 2004; Sinha 2009; Chakraborty and Ghosh 2010). Previous works by Leopold et al. (1965), Aslan et al. (2005), Slingerland and Bridge (1998), Mukhopadhyay (2014), Perez-Arlucea and Smith (1999) and Sinha et al. (2014) have linked avulsion or a certain change in river course with the super elevation of the existing channel and an inevitable change after a flood for rivers flowing through areas with topographic transition. A high rate of channel sedimentation and significant flood events often result in channel avulsion on the Himalayan foredeep plain.

In this study, an inventory of old data since 1764 in the form of maps, colonial literature and recent satellite images was used to reconstruct the drainage of the Torsa River, one of the major rivers in the eastern part of the Himalayan foredeep plain, incorporating past and present fluvial corridors for a time span of roughly 250 years. An effort was made to bring out the complex and diverse nature of the lateral migration of the Torsa River, which is well known for its hyper-avulsive nature, advocated both in the past and present-day context. GIS-based integration of old maps prepared post-1764 with satellite images from 2015 and 2017 was performed to compare the migratory characteristics of the Torsa River at an interval of decades.

Physiography and geological setup

A drop in gradient of 75 m/km from the mountainous catchment to 4.53 m/km immediately on the foredeep plain (Mukhopadhyay and Dasgupta 2010) provides a favourable ground for the Torsa River to develop an elongated fan deposit perched between its course and that of the Kaljani river in the east. Broadly, on the eastern part of the Teesta river, three different physiographic zones associated consecutively from north to south are Bhabar, the Terai region and the low-lying northern plains (Das 2012). All these regions differ from one another in sediment sorting and decreasing diameter of the mean sediment compositions. On these three physiographic regions, respectively, the bed material of the Torsa varies from north to south from gravel bed with occasional boulders to mixed sediment of gravel and sand and, finally, a mixture of sand and silt (Saha and Bhattacharya 2016). The overall channel gradient changes from 2.70 m/km on the piedmont region to 0.30 m/ km on the northern plain (Fig. 1). The active mountain front and south-eastward-dipping foredeep basin of the Himalaya has given rise to a structure-controlled drainage system in the studied part of North Bengal (Gansser 1983; Goswami et al. 2013; Soja and Sarkar 2008). The Quaternary surface with a marginal basement of Siwalik molasses is well associated with several NNW–SSW bound and traversing lineaments (Fig 2). An uplifted alluvial surface on the north-western part has restricted the growth of the braidplain of the Torsa River and presently it is confined between that uplifted block and Quaternary fan deposits on the east. On the eastern side, an elongated narrow alluvial fan has also been observed guiding the eastern boundary of the Torsa River (Soja and Sarkar 2008).

Methodology

Georeferencing of the old maps

Co-registration or image-to-image registration of the old maps was done using a three-step georeferencing process following the work of Walz and Berger (2003) and Hackeloeer et al. (2014). Firstly, georeferencing of the old maps was done based on 41 place marks collected from Google Earth using the affine transformation model. Valid place marks on the old maps were only considered after a cross check performed based on relative locations, i.e. distance and direction between two places, as well as the relative locations of those points from famous locations such as Coochbehar and Jalpaiguri town. A considerable area of the studied spatial extent was labelled as Royal Estate during colonial rule in India. The presence of popular archaeological sites

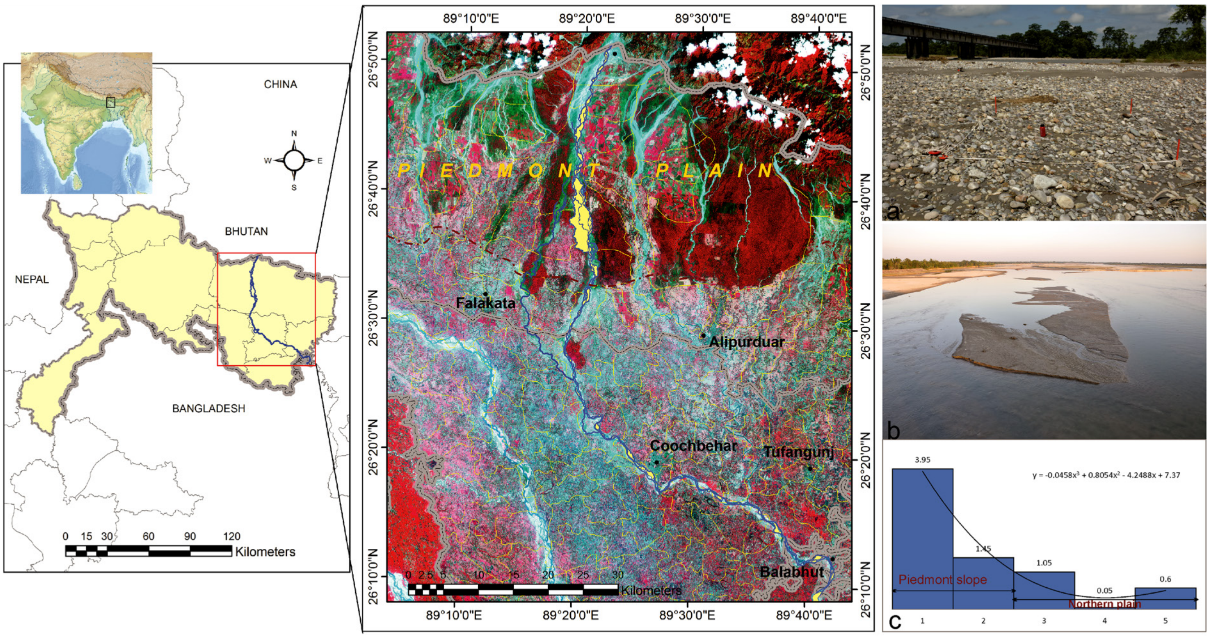


Fig. 1. Location of the selected stretch of the Torsa River. a. gravel bed Torsa River on the piedmont slope, b. deposition of mid-channel sand bars in the Torsa River on the northern plains, c. channel gradient calculated from DTM, GEOTOPO 30; (https://earthexplorer.usgs.gov) where each stretch represents a channel length of 20 km

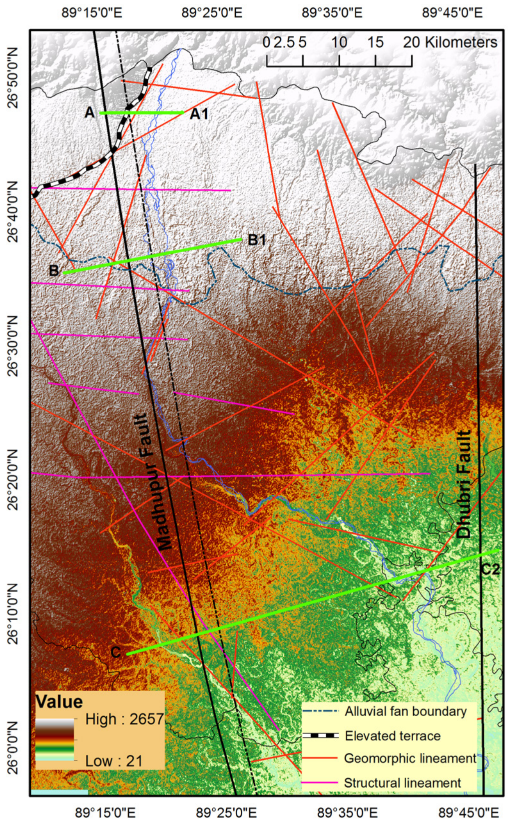


Fig. 2. Tectonomorphic map of the study area with elevation character in the backdrop. Source: Modified by authors after Chattopadhyay and Das, 1979; Rashid and Islam, 2016. Elevation map was prepared from DTM, GEOTOPO 30

and urban centres made the selection a lot more profound and easier.

Secondly, the georeferenced maps were further resampled using the georeference model of the satellite image. This was done in order to reduce distortion of the map and to bring both the images into the same referencing datum and model platform. Finally, the resampled map was again co-registered using the same place marks as those used in the first step.

Accuracy assessment

Root Mean Square Error (RMSE) was calculated in order to judge the deviation of the rectified map by referencing it with the present-day satellite image (Table 1). Errors occur while georeferencing because of inherited errors in reading co-ordinate systems in old maps and the topographical map, as well as shrinkage of scanned copies. The root mean of the residual value x and y coordinates has been considered an ideal measurement of georeferencing or image transformation processes (Thapa 1992; Klang 1996). It was calculated from the Georeference panel of Edras Imagine software applying the formula as follows:

$$\mathrm{RMSE} = \surd_{i} \text{- real}_{i})/n$$

Table 1. Interpretation of satellite images, old maps and literature are useful while identifying an old channel system (Bandyopadhyay 1996; Connor et al. 2002; Chakraborty et al. 2010; Rudra 2010, 2014; Ghosh and Jana 2019) and field verification of the obtained results has been a part of likewise systematic study

Old Maps and Toposheet

Material	Time period	Scale	RMSE (in metre)	Source
Map of Bengal and Bihar	1964-77	60 geog. miles to 1 inch	18	Bengal Atlas, 1777 by Major J. Rennell
Map of Rajshahi and Koch-Behar Division	1867-1871	1 inch to 16 miles	16	Statistical Account of Bengal, 1875, vol 10 by Sir W. W. Hunter
Map of Rinzin Nimgyl's exploration	1886-87	1 inch to 15.78 miles	11	Great Trigonometrical Survey of India, 1871
Toposheets 78F/5/6/7/8/11/12	1917-18	1:63360 (contour interval 50 feet)	6	Survey of India, 1931

Satellite Images

Satellite	Sensor	P/R	Resolution	Date of Acquisition
Landsat 8	OLI	139/42	30 m	15.03.2015
Sentinel 2	MSI	Coordinates: 26.6037653 , 89.5593356	10 m	16.03.2017

Space photograph

Programme	Organised by	Date of Acquisition	Resolution
CORONA	Central Intelligence Agency Directorate of Science & Technology	16th March 1970	20-30 feet

Image processing

Delimitation of the fluvial landforms in satellite images is often regarded as a useful method to identify palaeo courses (Sinha 2008; Bandopadhyay 1996). Palaeo-levee, scroll marks, palaeo bank lines, cutoffs and oxbows were used as identification tools for tracing the abandoned channels. A Landsat 8 satellite image acquired during the pre-monsoon period of 2015 was used to trace the old courses of the Torsa River. An image fusion technique was applied for the Landsat images using the Brovey method (Brovey 1990) where Band 3, Band 4, Band 5, Band 6 and Band 8 (PAN) were fused to obtain comparatively higher resolution data (15-metre). Geo-rectified Sentinel data of March 2017 ware also used as an additional reference while tracing the courses of abandoned channels and for the rectification of vector layers. Minor corrections were made by taking spatial references from Google Earth. A freely available global digital terrain model data set, GEOTOPO 30, was used to calculate channel gradient and to construct the topographic profiles (Fig. 3).

Assessing geomorphological signatures and cultural attributes

The scale and resolution of the old maps were not as precise as the satellite images or topographical maps. Although the accuracy of the georeferenced old maps was doubtful, it can still provide a portrayal of the scenario that existed in the past. Channels generated from the old maps were considered as the base location and were validated using high-resolution satellite images by tracing the abandoned courses around those locations. Topographic studies were conducted to verify the abandoned courses as evidenced from the old maps (Fig. 4). This involved field verification of the abandoned channels sketched from satellite images and finding palaeo fluvial evidences of the old courses (Fig. 7). Co-ordinates of 21 relevant points were collected using a Garmin eTrex 30, and field photographs of abandoned channels, cut-offs, and palaeo-bank lines were taken in 2016 and 2017 (Table 2). For further investigations, experienced local inhabitants of different areas were interviewed to gather valuable knowledge regarding past fluvial activities around certain areas. As per Hindu mythology, burning ghats are located near an active water source to devote ashes after cremation. To incorporate this cultural domain as evidence, locations of burning ghats near the abandoned courses were traced down and GPS points taken at those sites were included in this study.

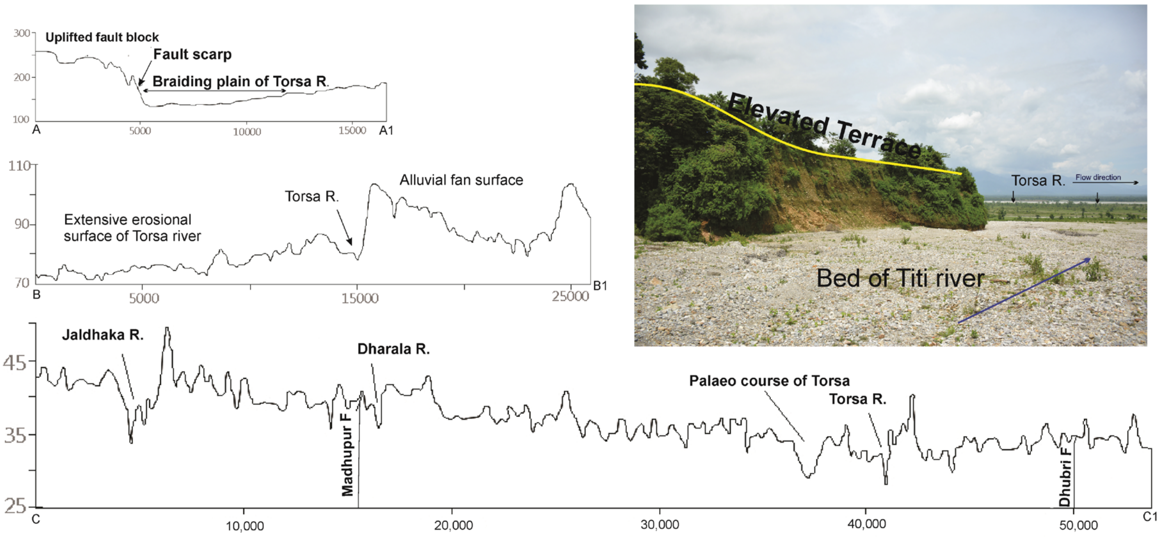
Results

Changing courses of the Torsa River

Historical accounts of the Coch Dynasty, colonial survey records of O'Donnell (1893), Choudhury (1903), Hunter (1867–71), Gunning (1911), Gazetteers of Coochbehar (1951) and maps prepared by Major James Rennell in 1776, surveyor J.B. Tassin during 1841, W. Hunter in 1867–71, maps prepared after great trigonometric survey during Rinzin Nimgyl's exploration in 1886–87, Survey of India maps prepared in the early 20th century and satellite data inventory were scrutinised intensively to generate results regarding the pattern of channel migration of the Torsa River over the last 250 years.

Shifting between 1764 and 1871

During 1764–77, the Torsa and the Mujnai or Mansai River had a combined flow as the Torsa joined the Mujnai near Moamari, 16 km southwest of Coochbehar town. The Torsa had crossed Coochbehar through its western flank and further downstream the united course of the Torsa and the Mujnai River, locally known as the Mansai or Nil-



Distance and heights are in metre

Fig. 3. Topographic profiles constructed from DTM. The reference locations of the profiles were shown in Fig. 2. the profile along A-A1 reflects a scarp face on the west due to the upliftment of the terraces along the neo-tectonic fault line. The profile B-B2 showed the development of the alluvial fan on the eastern side of the Torsa and the profile C-C1 showcased the association of several palaeo courses on the nearly flat plain surface

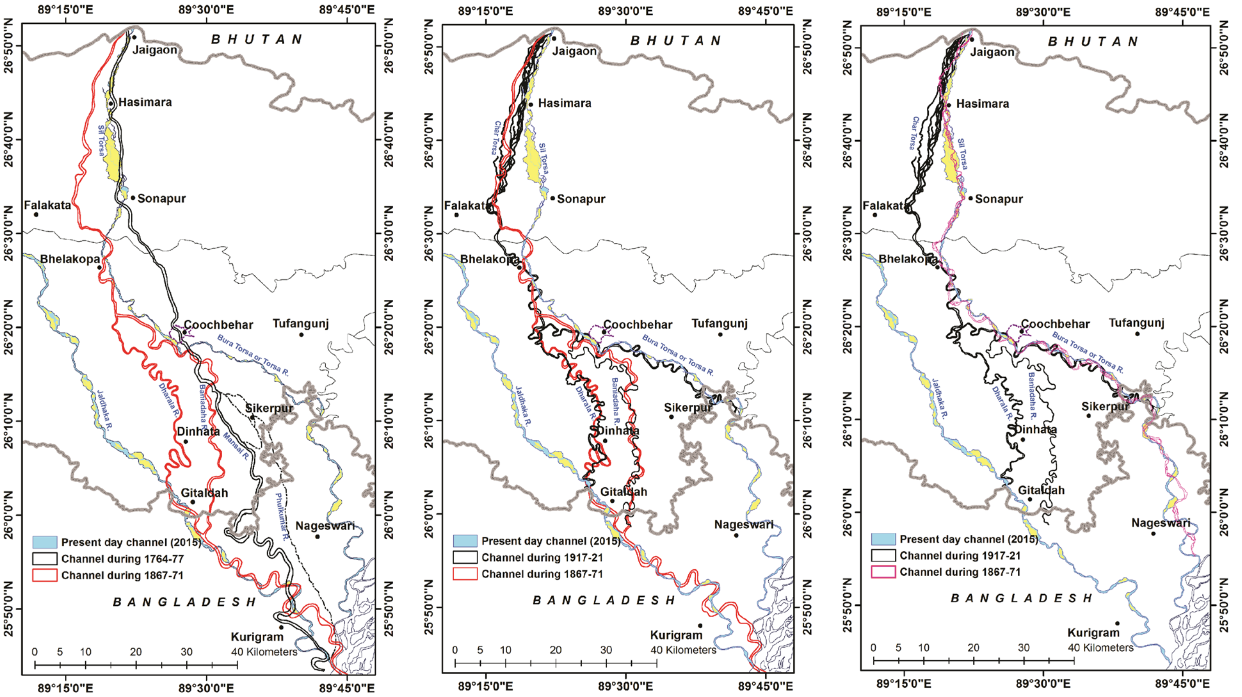


Fig. 4. Shifting of the main course of the Torsa River between 1764 and 2015

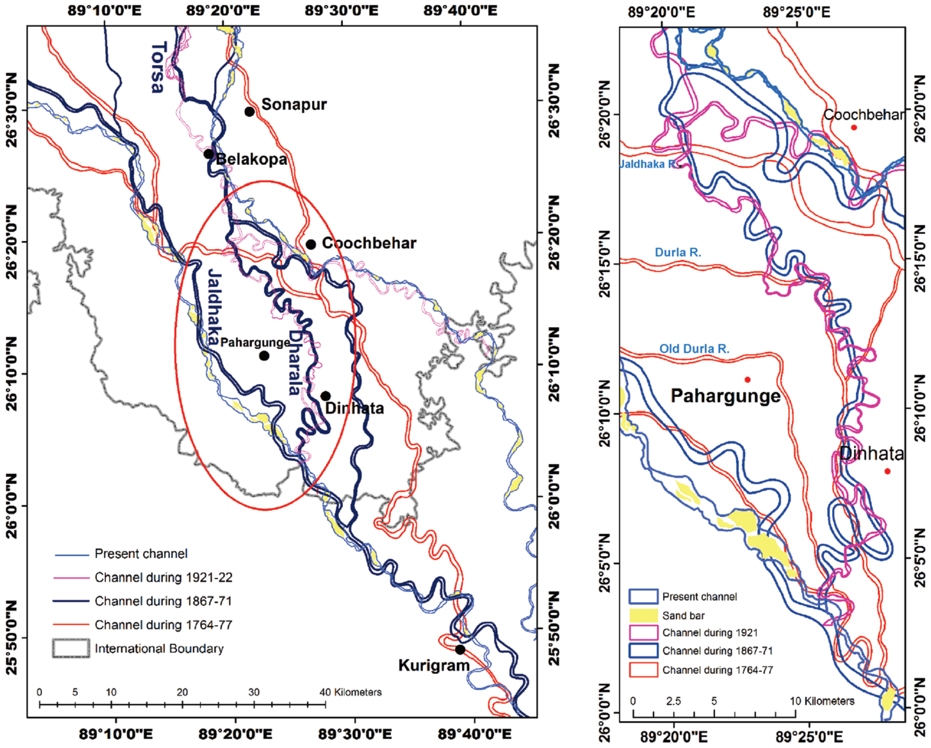


Fig. 5. a. The existence of the Dharala and Baniadaha Rivers during 1867–71 and development of the easterly course between 1877 and 1921. b. Development of the Dharala River by capturing the abandoned courses of the Durla River

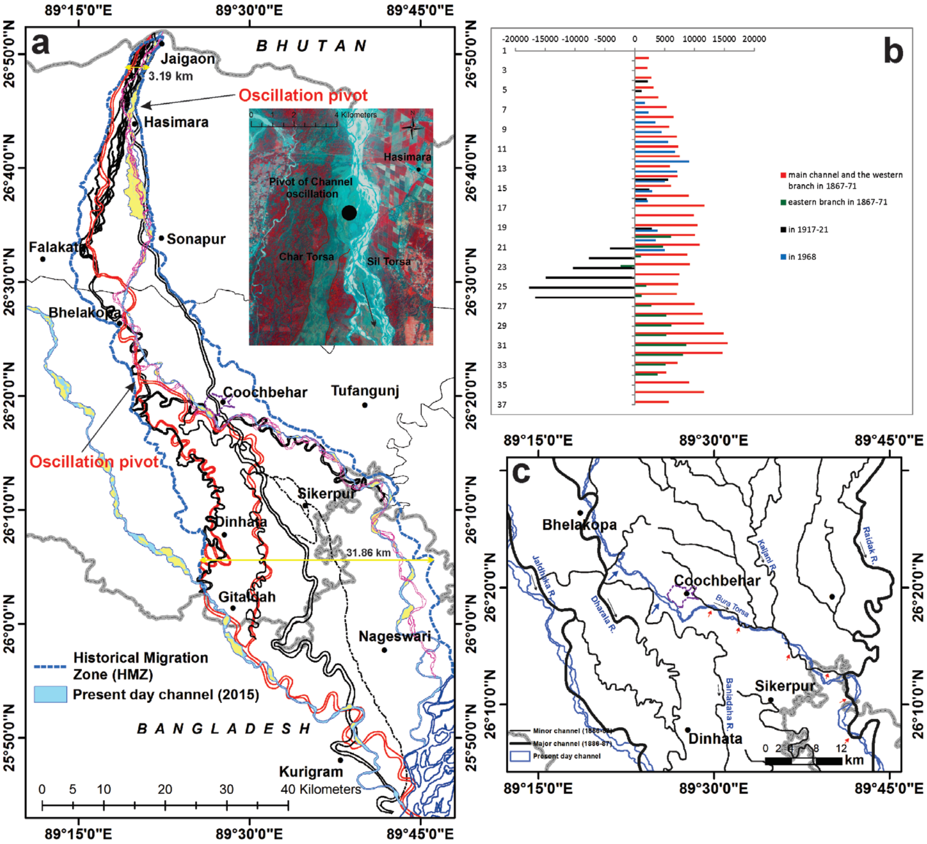


Fig. 6. a. Demarcation of HMZ of the Torsa River considering the locations of the palaeo courses with oscillation pivot near Hasimara shown in the inset. b. the relative length (in metres) of shifting of the main course. c. the location of the palaeo course of the Bura Torsa as shown in the map prepared during 1886–87 and the oscillation pivot that acted as the bifurcation point of the Dharala and Baniadaha Rivers to the north of Coochbehar town

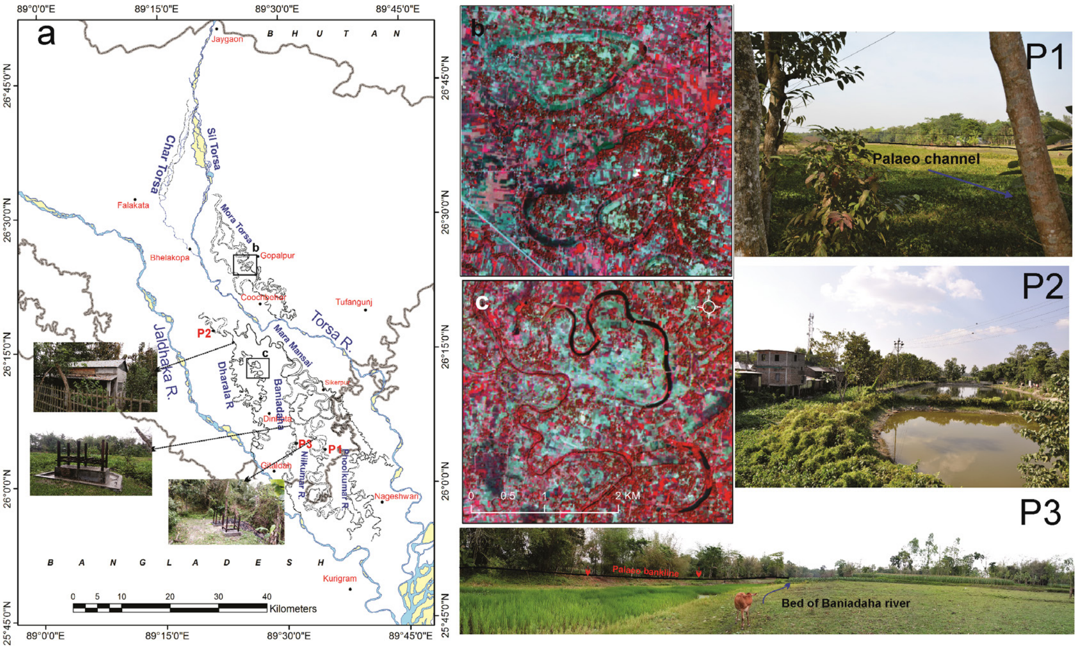


Fig. 7. Locations of the demarcated palaeo courses of the Torsa River. a. burning ghat found along the palaeo courses. b and c. geomorphic signatures used for identifying the palaeo courses. P1, P2 and P3 are the present conditions of the palaeo courses. All the respective locations are shown on the map

Table 2. Geomorphic significance of the locations surveyed along the palaeo courses

ID	Coordinates	Accuracy (m)	Name of the palaeo channel	Geomorphic signatures
1	26° 9.071'N; 89° 30.569'E	3	Baniadaha	Narrow channel with a broad floodplain, palaeo-levee
2	26° 6.935'N; 89° 32.900'E	3	Spill channel of Baniadaha	Palaeo bank lines, cutoffs
3	26° 7.918'N; 89° 26.028'E	3	Dharala	Misfit channel system
4	26° 3.645'N; 89° 30.081'E	3	Baniadaha	Misfit channel system, micro-terraces
5	26° 18.672'N; 89° 19.637'E	3	Dharala	Incised channel with misfit characteristics
6	26° 17.115'N; 89° 21.445'E	3	Dharala	Linear orientation of ponds, palaeo bank lines
7	26° 18.178'N; 89° 24.289'E	3	One of the off take points of Dharala	Scroll marks, linear orientation of ponds
8	26° 1.061'N; 89° 32.445'E	3	Nilkumar	Palaeo bank line, decayed channel segment with runoff water, cut-off
9	26° 7.096'N; 89° 31.108'E	3	Baniadaha	Decayed channel , palaeo-levee
10	26° 6.973'N; 89° 33.278'E	3	Nilkumar	Scroll marks
11	26° 18.042'N; 89° 24.289'E	3	Off take of Mansai-Baniadaha	Scroll marks, palaeo levee, linear orientation of ponds
12	26° 14.075'N; 89° 30.399'E	2	Bifurcation of Baniadaha and Nilkumar	Scroll marks, decayed channel and palaeo levee
13	26° 13.692'N; 89° 31.044'E	2	Baniadaha	Palaeo bank lines, micro terraces
14	26° 16.212'N; 89° 26.551'E	2	Mansai-Baniadaha	Decayed channel
15	26° 17.825'N; 89° 25.895'E	3	Mansai-Baniadaha	Decayed channel, Scroll marks
16	26° 13.822'N; 89° 23.917'E	3	Dharala	Incised meandering channel with misfit character, micro terraces
17	26° 12.551'N; 89° 23.566'E	3	Dharala	Incised meandering channel with misfit character, micro terraces
18	26° 24.412'N; 89° 26.186'E	3	Spill channel of Mara Torsa	Cut-off, decayed channel segment
19	26° 20.632'N; 89° 28.125'E	3	Mara Torsa	decayed channel segment

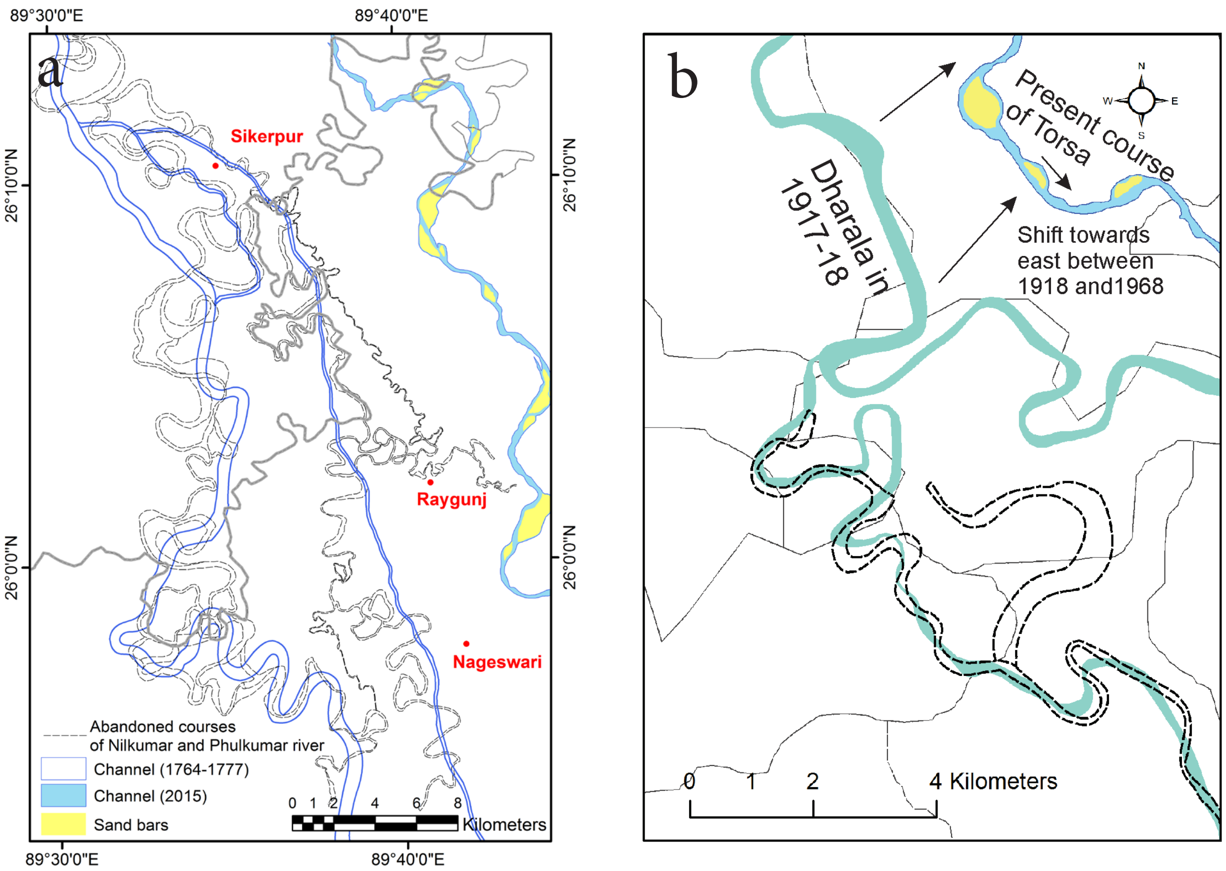


Fig. 8. a. validation of the demarcated palaeo course of the Nilkumar River at the place of active course observed in the map prepared in 1764–77. b. shifting of Torsa River around the bifurcation of the Torsa and Dharala with fluvial remnants of the active courses

kumar river, used to flow from the east of Dinhata (Fig. 4). On the piedmont surface the flow was concentrated into the eastern branch, namely Sil Torsa, and developed a course flowing from the west of Sonapur. The united course had two spill channels – one used to flow through the east of Nazirgunj while the other channel used to run along the eastern flank of the present boundary of Coochbehar district in India and joined the main course around 12 km downstream from Kurigram in Bangladesh (then India). Torsa was quite erratic in nature and had several bends in its downstream after it passed Coochbehar town (Choudhury 1903) and it was well reflected in the decayed course of the Nilkumar containing several bends with high flow turn angles (Fig. 7). Hunter (1877) in his writing quoted Buchannan in 1809 having described the Nilkumar River as having a much wider channel than the Dharala but with hardly any flow. That statement provided a vital clue regarding a time of the flow reversal towards the west that had probably occurred between 1777 and 1809. Certain changes that occurred during this time span resulted in the formation of a new course to the west of the previously active course and started flowing through two branches, namely the Dharala and the Baniadaha (Fig. 4). The western branch, or the Dharala River, flowed to the west of Dinhata while the eastern branch, or the Baniadaha River, developed to the west of the Nilkumar River. These two outlets joined the Singimari or Jaldhaka River near Gitaldah. Over the piedmont surface, during 1871 the channel was flowing from the east of Falakata and Bhelakopa and that was probably due to an avulsion that occurred at the pivot of channel oscillation near Hasimara. The resultant flow reversal from the eastern channel, or Sil Torsa, to the western channel, or Char Torsa, led to the opening of the Dharala River and the section of the previously active course of Torsa between Sonapur and Coochbehar became completely abandoned (Chattopadhyay and Das 1986; Mukhopadhyay 2014) (Fig. 5). The shift westwards not only abdicated a section in the north of Coochbehar town but also led to a significant change in the downstream. The main flow that branched out into two channels had renounced the Nilkumar or the united flow of the Torsa and the Jaldhaka. The bed of the Phulkoomar, or Old Nilkumar – the eastern-most spill channel of the Torsa present in 1764 – is considered to be the oldest bed of the Torsa to have been occupied by the main flow before 1764–77 (Choudhury 1903). Gradual siltation over the years made the course of the Nilkumar lose its flow.

Shifting between 1871 and 1917–21

By the early 20th century the course of the Torsa had begun flowing through a new course, by the north of Balarampur, which was actually developed by the Raidak and the Kaljani and later captured by the Torsa (Fig. 6). The eastern branch of the Torsa, the Baniadaha river, had by the early 20th century been completely beheaded and left as a fluvial remnant with a feeble flow that showed signs of irregularity at certain places in the topographical map of Survey of India in 1917–21. The Baniadaha was regarded as an important waterway for business and recreation (Hunter 1871; Bandopadhyay 1884) but an avulsion occurred during the late 19th century that started diverting the major share of flow into the Bura Torsa that ended up in the Brahmaputra near Nageshwari in Bangladesh (Bandopadhyay 1884). Later, changes in channel morphometry and siltation gradually caused the Baniadaha to become abandoned. Importantly, the formation of a structure-controlled meander bend (probably due to neo-tectonic deformation after 1897 – "the great Assam earthquake" [Hough and Bilham 2008]) predates an eastward shift in the course of the Torsa that reoccupied the course of the Bura Torsa, leaving Baniadaha completely abandoned (Fig. 5). On the piedmont slope, there was no such change, as the flow was still concentrated into the course of the Char Torsa and the eastern branch, Sil Torsa, seemed to be a shallow spill channel. The Torsa was still flowing through two branches where the western branch, the Dharala, had experienced no such changes and the Bura Torsa came into existence as the eastern feeder.

Shifting between 1917–21 and 1968

In 1954, an avulsion occurred around 3 km downstream from Hasimara Railway Bridge at the avulsion pivot of the Torsa (Fig. 6). It then reoccupied the eastern channel known as Sil Torsa, and left Char Torsa (the western course) abandoned (Mukhopadhyay and Dasgupta 2010). In 1968, in the downstream segment, the main flow was concentrated only into the course of the Bura Torsa as the Dharala River, the western feeder on the northern plain, had been completely beheaded by that time. Several literature sources and reports prepared during the 1800s mentioned the Dharala as one of the major rivers of North Bengal used for inland navigation (Hunter 1871; Gunning 1911; Bandopadhyay 1884; Choudhury 1903). During 1917–18, Dharala was as wide as the eastern feeder that became the main course of the Torsa later on. An eastward shift in the Torsa between 1918 and 1968 near Atharokotha left the Dharala beheaded (Fig. 8). The course during 1968 got its name of Dudhkumar River due to its highly silt-laden white water. There were no such changes in the course of the Torsa except for a few cut-offs that occurred downstream of Coochbehar town. The braidplain of the Torsa over the piedmont surface significantly widened during this time.

Spatial pattern of channel shifting

The Torsa River is known as the most notorious river in the Sub-Himalayan region of West Bengal, as it changes its course intermittently. However, the lateral shifting was not unidirectional, but oscillatory for the Torsa River. Two evident oscillation pivots were recognised through the analysis of old maps of the last 250 years. The oscillation pivots near Hasimara registered oscillation events sometimes in between 1764–77 and 1871, and in 1954 (Fig. 4). Another pivot located 11 km upstream of Coochbehar town acted more as a bifurcation point than as an oscillation (Fig. 6). An eastwards channel shift sometimes between 1764–71 and 1917 around this location led to the formation of the present course of the Torsa, leaving the Baniadaha abandoned. Further eastwards shifting of the Torsa River, around the bifurcation point of Dharala and Torsa, between 1917–21 and 1968 left the Dharala abandoned. On the piedmont slope the average length of shifting of the courses over the last 250 years was 4.16 km between 1764–77 and 1867–71, 0.29 km between 1867–71 and 1917–21, and 2.82 km between 1921 and 1968. On the other hand, in the downstream section of the Torsa, on the northern plain, the average length was quite high. The average length of channel shifting from the active course during 1764–77 to the course of the Torsa River through its western branch called the Dharala was 9.40 km, and 3.80 km for the eastern branch called the Baniadaha during 1867–71. It was 1.41 km westwards on average and 11.87 km eastwards between 1867–71 and 1917–21 on the northern plains. Here, the western course was not considered, as it did not change between 1871 and 1921. The average length of shifting on the northern plain in 1921–1968 was 3.83 km, where the major shifting was only observed up to Coochbehar town and the rest remained the same while the western branch, the Dharala River, became abandoned by that time and hence was not considered a shifting event.

Palaeo-fluvial corridor and palaeo courses of the Torsa river

Delineation of the palaeo courses

The characteristic scenario for geomorphic signatures consists of the linear orientation of ponds, the location of cut-offs, traces of a palaeo-levee in the form of linear vegetation patches, and palaeo bank lines as traceable scars around the places of the channel found in the old maps (Table 2). Palaeo courses named Mara Torsa and Nilkumar were demarcated, with numerous cut-offs and a couple of narrow channels ranging from 8 to 10 metres average width found around the places where active channels were present during 1764–77. The Mara Torsa is accompanied by a couple of other abandoned courses, which is evidence of channel shifting or spilling of flood water into those during the 18th century (Fig. 8). One of the two parallel flowing abandoned courses of the Mora Torsa was traced up to Jhinaidanga, and the southern branch could only be traced up to Coochbehar Sadar. Several ponds located in a linear fashion within the boundary of Coochbehar municipality have confirmed the extension of the southern branch up to the present channel with a possibility of its path through the west of Coochbehar town (Fig. 7). During the 1800s the capital of the Koch dynasty was formed at Coochbehar town, for security from invasion of the Bhutias (natives of Bhutan) as it was surrounded by rivers on all sides (Bandopadhyay 1884; Choudhury 1903), which was only possible if the channel in the north of Coochbehar was active. The courses of the Baniadaha and the Dharala were actually similar to the presently identified abandoned courses of those rivers. The palaeo-levee, cut-offs, shallow channels and ponds oriented in a linear fashion were utilised as an indicator while demarcating the palaeo channels (Table 2).

The mythological particulars of the palaeo courses

The mythological name of the Torsa River was "Punnotoya", which means that touching its water can erase one's sins (Choudhury 1903). According to Hindu mythology the remnant of a dead body after cremation should be emancipated into the holy rivers as it is believed to bring peace to the soul. There has been a tradition of building temples near water bodies in India. Each of the palaeo courses of the Torsa was found along crematories or temples (Fig. 7). This only proves the presence of active discharge in each of the palaeo courses at some time in the past and, more importantly, that all the decayed courses had served as passage ways of flow in the Torsa River.

Historical Migration Zone (HMZ)

The spatial extension within which a river restricts its migration passages is known as the Historical Migration Zone (Piegay et al. 2005; Thatcher et al. 2009). A vast corridor of migration during the last 250 years has been formed by the lateral passage of the Torsa River. The width of the migration zone increases in the south due to the decreasing gradient and the fact that rivers experience comparatively flatter alluvial plains that are less restrictive to migration (Fig. 3). Quaternary fan deposits along the left bank and elevated terraces along the right bank were able to restrict Torsa into a narrow corridor on the piedmont surface than on the northern plains

(Fig. 3). The confined piedmont surface, aided by its high surface gradient (Figs 1 and 3), was responsible for the narrow top of the HMZ. With decreasing gradient and the valley confinement scenario, the Torsa River got favourable ground to oscillate within a larger extent. The average width of the HMZ is 8.41 km, but the differential nature of channel oscillation of this hyper-avulsive system, restricted by morphotectonic factors, results in the Torsa's HMZ being funnel shaped, with width ranging from 3.19 km to 31.86 km from north to south (Fig. 6).

Discussion

Pattern of channel oscillation

Most of the tributaries of the Torsa River are left-bank tributaries, while the abandoned courses are present on the west or right-hand side of the present course. Overall, this particular orientation of tributaries and abandoned channels and the spatial pattern of shifting bear significant evidence that the Torsa River shifted westwards from the present course (Bura Torsa) which was regarded as the oldest channel and again oscillated towards the east. Since the early 20th century, the Torsa River has again started flowing through that oldest course from which the shifting initiated. The role of flood in the case of avulsion in the course of rivers on the Himalayan foredeep plain has been well mentioned in several studies (Mukhopadhyay 2014; Sinha 1996; Jain and Sinha 2004). Rivers in the northern part of West Bengal carry a great bulk of sediments mainly drawn from the sub-Himalaya, and this is greater than the world average rate of transported load by rivers (Gupta 2008). Thus, in-channel sedimentation leads to clogging of the course and avulsion becomes evident after a high flood situation. In the writings of Hunter (1871), Gunning (1911) and Bandopadhyay (1884), several flood events were portrayed with incidences of damage in both the social and the riverine environment in the study area. Floods of 1801, 1809, 1820, 1878, 1916, 1953 and 1954 caused a significant history of damage in the riverine environment. The correspondence between these major flood years and events of channel changes were quite high. The old data inventory indicated a flow diversion into Dharala during the early 19th century, when the floods of 1801 and 1809 probably played a significant role in carving out the course of the Dharala. The flood that occurred in 1878, regarded as one of the most devastating floods in this area, has been described as a predated event of flow diversion from the Baniadaha River (Choudhury 1903). The floods of 1953 and 1954 were responsible for the last event of oscillation at the oscillation pivot near Hasimara when the flow was diverted into the Sil Torsa (Chattopadhyay and Das 1986; Mukhopadhyay and Dasgupta 2010). Beside those controls, the mechanism of the channel avulsion led the Torsa River to capture the courses of other rivers over time. River capture was evident while the flow got diverted from the active channel. The present channel of the Torsa engulfed the course of the Kaljani River (Fig. 6) as the flow diverted further east around the 1900s. Even the course of the Dharala River actually developed through capturing palaeo channels of the Mansai and Durla rivers during the early 19th century. Rivers on regions with topographic transition have been well attested to have such similar nature of diversion into the courses of other rivers in the works of Sinha (1994), Smith et al. (1998), Slingerland and Smith (2004) and Jain and Sinha (2005).

Controls of the Quaternary environment

The Quaternary tectonics in the Himalayan foredeep region and along the Himalayan thrust has produced a tilt towards the east due to the Quaternary upheaval of the Himalaya. This late Quaternary change has been proposed in earlier works by Chattopadhyay and Das (1986), Guha et al. (2006), Das (2012) and Rashid and Islam (2016) as the major influence behind the overall trend of migration of rivers towards the east in the north-eastern part of India. However, in the case of the Torsa River, the migratory pattern has been of oscillatory nature on the HFB where tectonic control has been widely accompanied by physiographic controls on channel shifting. The sedimentary structure of the HFB has become progressively younger and finer towards the south, where recent deposits have built up a significant floodplain that is favourable to channel migration (Chattopadhyay and Das 1986; Goswami et al. 2013). For the Torsa River, the low-lying alluvial plain has been a ground conducive to channel migration, and hosts the majority of the palaeo courses. This has been also reflected in the spatial extension of the HMZ (Fig. 6).

The overall flow direction of the Torsa is strictly towards the south-east, following the surface slope. Quaternary sedimentation and structural deformation have restricted the growth of the passageway of the Torsa River on the piedmont slope. The fault scarp developed on the north-western part of the upper segment of the Torsa (Fig. 3) has probably tilted the downthrown surface towards the east, which has compelled the Torsa to move accordingly, and the alluvial fans developed between the Torsa and the Gabur Basra River have restricted the braidplain development into a narrow strip (Fig. 3). In the downstream portion the low-lying plains with dead flat topography allowed the river to behave differently than it did on the piedmont slope. Therefore, the upstream segment of the Torsa River on the piedmont slope has been experiencing acute valley confinement, which led the Torsa River not to generate a wide HMZ on the piedmont slope. A NNE–SSW and one N–S bounding fault line – the Madhupur fault to the west and the Dhubri-Jamuna fault to the east, respectively – have also been restricting the Torsa River to oscillate within it (Fig. 2). Apart from that, the present course has encountered several lineaments and the river is flowing parallel to it in certain segments (Fig. 2). All these structural confinements, the physiographic character and the Quaternary depositional pattern have been responsible for giving the HMZ of the Torsa a funnel shape with a narrow head and a wide base (Fig. 6).

Conclusions

Combining topographic surveys and analysis of satellite datasets with old data inventory was quite beneficial for extracting the pattern of channel migration of the Torsa River over the last 250 years. The methodology used for a scientific fusion of old and new has generated a methodological framework that can be utilised in analysing the migratory behaviour of any river on a terrain that possesses a topographic transition. The major findings from this study have been deduced to seek answers from investigations based on the spatio-temporal migration characteristics of the Torsa and its major controls.

1. The Torsa River has continuously been experiencing channel migration with a varying nature during different time spans. The pattern of migration indicates that any of the palaeo courses can be reoccupied after the clogging of the active course. The temporal nature of channel migration has not been unidirectional but, rather, oscillatory.
2. Besides channel migration being temporally variable, it also differed spatially, reflecting the controls implied by the structural confinements and physiographic elements at certain sections.
3. The chronology of channel abandonment was initiated from the Nilkumar River in the east and the Bura Torsa in the north of Balarampur and Tufangunj before 1764. Secondly, the abandonment of the Mara Torsa in the north-eastern and eastern portion of Coochbehar town, and the course of the Phulkoomar River in the downstream segment, occurred during the early 19th century. This was then followed by the abandonment of the Baniadaha River between 1886–87 and 1917. Finally, the Dharala River was abandoned between 1921 and 1968.
4. Among the delineated palaeo courses, the course of the Bura Torsa (the downstream section of the present course from Coochbehar up to the confluence with the Kaljani) has been perceived to be the oldest channel.
5. River capture and pivotal oscillation in the case of local avulsions has been the characteristic feature of the drainage development of the Torsa River.

All these particulars and criticalities regarding changes in the river course need careful study in order to predict the future possibilities, and are crucial in understanding the vulnerability potential of a certain region. Demarcation of a natural regime is a mandatory for environmental planning with a sustainable approach, as any further encroachment on any fluvial regime escalates the degree of vulnerability.

Disclosure statement

No potential conflict of interest was reported by the authors.

Author Contributions

Study design: U.D.S., S.B.; data collection U.D.S., S.B.; statistical analysis: U.D.S., S.B.; result interpretation U.D.S., S.B.; manuscript preparation U.D.S., S.B.; literature review: U.D.S., S.B.

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