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Planform Dynamics of the Chel River in the North Bengal Plain of Eastern India

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Abstract
In the present paper, an attempt to reconstruct planform changes of the river Chel over the period 1955-2017 has been made using Topographical sheets, multi-temporal Landsat images and supplemented by field work. The study has been carried out through an assessment of changes in channel morphology, sinuosity index variation, braiding index variation, and braid-channel ratio variation. The different types of morphological changes observed during the entire assessment period were: neck cut-off and consequent straightening of course, Changes in channel width, development and abandonment of anabranches, and shifting of meander bends. Computation of planform indices shows decreasing trends of Sinuosity and braiding index.

Keywords: Chel River, Channel Planform, Landsat, Channel morphology.

Introduction
Rivers are highly sensitive to environmental conditions (Eaton et al.,2010; Rozo et al.,2014), and especially alluvial channels are inherently dynamic in nature, responding to the variations in water and sediment inputs (Midha and Mathur,2014). Alluvial rivers can respond and readjust at a range of rates to the variations caused by water and sediment inputs, active tectonics, and human activities at a range of spatial and temporal scales (Sinha and Ghosh, 2012; Heitmuller, 2014). Natural or anthropogenic input alterations into the river systems results in changes in the planform/channel pattern, sinuosity, and braiding Index (Knighton, 1994). Any changes, whether natural or anthropogenic, can initiate a departure from a state of dynamic equilibrium (Winterbottom, 2000; Petts and Gurnell, 2005). This may, in turn, result in channel instability, causing changes in channel form and pattern (Yang et al., 1999; Surian and Rinaldi, 2003; Wellmeyer et al., 2005; Kummu et al., 2008; Yao et al., 2011; Gupta et al., 2013; Midha and Mathur, 2014).

Channel dynamics represent an integral component in the evolution of vast alluvial floodplains as well as a disturbance regime vital for floodplain patterns and maintenance of a high level of biodiversity (Midha and Mathur, 2014). Channel migration with bank erosion, accretion, and down-cutting is a natural phenomenon for an alluvial river. However, with the growth of the

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human population worldwide over the impact is evident. Humans are emerging as rather dominant factor than the natural ones. Developmental activities like reservoir construction, restricting the lateral movement of the river through embankments, sand and boulder mining, land use alterations, and infrastructure construction along the river banks have altered the natural geomorphological dynamics of the river (Gregory and Park,1974; Knighton,1989; Kondolf, 1997; Surian,1999; Surian and Rinaldi, 2003; Batalla et al., 2004; Vanacker et al., 2005; Wellmeyer et al., 2005). Channel instability cause damage to riverine infrastructure and also alteration of aquatic and riparian ecosystems. Thus, it poses challenges for engineers, scientists, and managers on how to best accommodate societal needs with the structure and processes of nature. Understanding the planform dynamics of river channels has important implications for maintaining biodiversity (Naiman et al., 1993; Hughes, 1997; Ward et al., 1999) and minimizing flood damage too (Holburt, 1984). Investigations of historical channel change provide insight into how stream channels respond to flood events. With this information, land and resource managers are able to make decisions that minimize social costs (e.g., flood damage to property) and maximize the ecological benefits of flooding (e.g., rehabilitating riparian vegetation and deterring the proliferation of exotic species) (Tiegs and Pohl, 2005). Driven by these objectives channel planform dynamics has been studied world over. Ollero (2010) assessed the channel dynamics and consequent floodplains changes in the middle Ebro River, Spain over 80 years and proposed feasible floodplain management solutions. Similarly, Tiegs and Pohl (2005) studied the response of the Colorado River's planform to the fluctuations in hydrology during the period 1976-2000 and thereby assisted land managers in figuring out an appropriate flow regime for proposed rehabilitation of native riparian vegetation. Within our country, Midha and Mathur (2014) have assessed the planform dynamics along a 6o kms reach of Sharda River during 1977 and 2001 in the Terai region of Northern India and established that the altered dynamics is threatening the future of critical wildlife habitats in Kishanpur Wildlife Sanctuary and North Kheri Forest Division in the state of Uttar Pradesh. Thus, an improved understanding of river channel change processes is imperative for improving river engineering and environmental management as well.

The Chel basin is a part of the region popularly known as 'Dooars', which is characterized by channel migration, flooding, and avulsion. It falls in the zone of transition between the dissected upper Himalayan hill surface and the lower gently rolling Teesta-Brahmaputra plains, and is popular for notorious incidents of channel avulsion and river capture activities (Chakraborty and Mukhopadhyay, 2014). Because of its straddle-like situation with two distinct physiographic units, the Chel basin has varied geomorphologic problems. The hilly terrain in the north, above an elevation of 350m, experiences rapid overland flow, erosion, and landslides, whereas its piedmont in the intermediate and alluvial plain in the south observes large-scale sediment deposition, rise in valley floor, and consequent shifting of channels (Lama and Maiti, 2019).

In the present paper, an attempt to reconstruct planform changes of the river Chel has been done over the period between 1955-2017 using Topographical sheets, multi-temporal Landsat images and supplemented by field work. Channel planform dynamics has been attempted to understand through changes in channel morphology, sinousity index variation, braiding index variation and braid-channel ratio variation.

Study Reach

Chel lies to the left of the river Tista after Lish and Gish and joins Neora to become Dharala Nadi at 88° 44' 13"E, 26° 41' 45.6"N, which ultimately merges with mighty Tista about 13kms downstream. The study area extends between 26° 41' 30" and 27° 5'15" north latitudes and longitudes 88° 37'00" and 88° 45' 15" east.

The study reach for the present chapter extends from near the confluence point of Manzing and Sukha Khola with Chel River near Putharjhora Tea Garden, near the mountain front below Gorubathan to the confluence Point of Chel River with Neora River (Fig. 1). The straight valley length of the reach is 20.93 km. But for the ease of description and understanding, the study reach was divided into three smaller reaches from north to south:
Reach-A (Putharjhora Tea Garden to Odlabari railway bridge)
Reach-B (Odlabari rail-road bridge to Nipuchapur Tea Garden)
Reach-C (Nipuchapur Tea Garden to Kranti)

The divisions of the reaches noted above were based on hard points located along the river. The first hard point was the Odlabari rail-road bridge, and the second hard point was near Nipuchapur Tea Garden, where channel migration during the entire assessment period of 62 years was observed to be negligible.

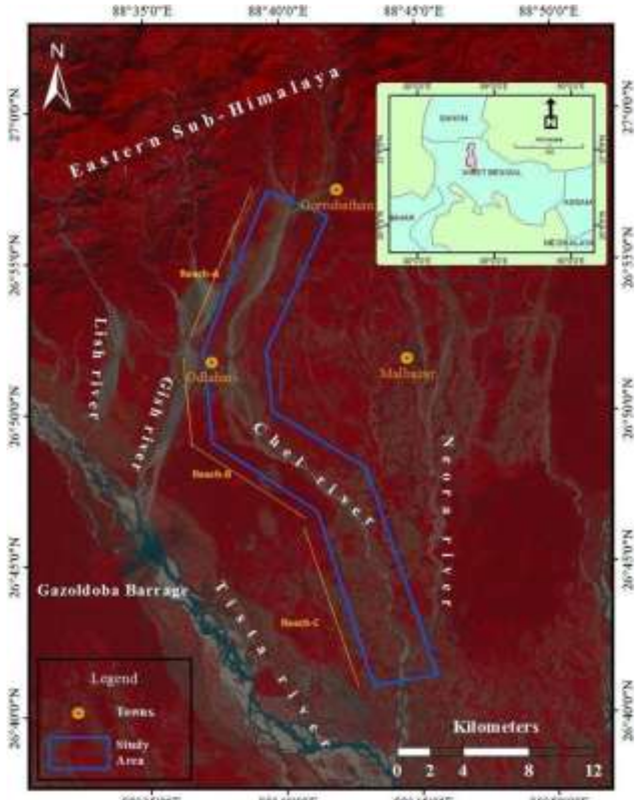

Fig. 1, Pan Sharpened Landsat 8 OLI/ TIRS image (1 December 2017, Path and Row-139/41) showing the study section of the river Chel (Map of part of North-East India showing location of Chel River basin in the inset).
Note: The image is a standard false colour composite where the red, green, and blue bands have been assigned Green, Red, and near-infrared colours, respectively.

Data and Methodology
Different methods applied for the fulfillment of objectives are discussed below.
Data and image processing
This study uses topographical maps and multi-temporal Landsat data to quantify and analyze the dynamics of the River Chel from 1955 to 2017. A single Landsat scene (Path/ Row: 139/41;

149/41 for 1976 image) covers the entire study area. Similarly, one US AMS Series –U502 topographical map also covers the entire study area. Whereas two sheets of Survey of India topographical maps (78B/9 & 78B/10) topographical maps cover the study area. Therefore, six Landsat scenes (1976, 1987, 1994, 2005, 2010, and 2017) were collected from the USGS site (http://earthexplorer.usgs.gov/). One 1: 250,000 scale U.S. Army corps of Engineers NG 45-8, Series –U502 topographical map (1955) was acquired from the University of Texas site (https://legacy.lib.utexas.edu/maps/india.html) and two 1:50,000 scale topographical maps(Map no.- 78 B/9 and 78B/10) surveyed during 1969-71 were obtained from the Survey of India (SOI). Therefore, the study will be confined to six epochs(1955-1970,1970-1976, 1976-1987,1987- 1994,1994-2005,2005-2010, and 2010-2017). There exists a large data gap from 1955 until 1970, from 1976 to 1987, and from 1994 until 2005. Variation in the length of epochs is due to the availability of topographical maps and cloud-free Landsat scenes. All the Landsat scenes were downloaded from the USGS through their data visualization tool GloVis. (Table 1). All the Landsat images were acquired for months of October to December as during this time of the year generally the region is cloud free being dry season and the discharge is sufficient to fill the main channel normal (non-flood water level of the river) and at the same time relatively constant from year to year (Fig. 2).

The ArcGIS (version 10.1; ESRI, Redlands, CA) software package has been used for the preparation of a GIS database relating to historical channel position and movement throughout the entire study period of 62 years. All the images were processed through ERDAS Imagine (v. 9.0) software and then were georeferenced based on the Universal Transverse Mercator (UTM) projection system (Northern hemisphere 45 zone and World Geodetic System (WGS) 84) manually using GCPs collected during a GPS survey. All the GCPs representing permanent features like road intersections, corners of large buildings, bridges, etc, were well distributed throughout the scenes, and the registration resulted in a Root Mean Square Error (RMSE) of <0.5 pixels. A first-order polynomial transformation with nearest neighbour resampling technique was applied to analyze channel planform dynamics of the river Chel from 1972 to 2017. Finally, each image was clipped using an area of interest (AOI) file derived from a vector dataset.

Table 1, Map sources used in the study

Types of Data	**Publisher**	**Map/ Index No.**	**Survey Year**	**Scale**	**Spatial Coverage**		
Edition-2 Army Map Service (AMS) Series- U502	**US Army Corps Engineers**	**NG 45-8**	**compiled in 1955 from half-inch series, 1: 126.720, SOI, 1930-33**	**1:2,50,000**	**Jalpaiguri and Kochbehar District**		
Topographical Maps	**Survey of India**	**78 B/9 and 78 B/10**	**1969-71**	**1:50,000**	**Darjiling, Jalpaiguri, and Dinajpur District**		
Satellite Images	**Satellite/ Sensor**	**Path/ Row**	**Date of Acquisition**	**Resolution (Metre)**	**Projection**	**WRS Type**	**Bit Depth**

	Landsat 1-5 MSS	**149/41**	**30.11.1976**	**60**	**UTM/WGS 1984**	**1**	**8**
	Landsat 4-5 TM	**139/31**	**31.12.1987**	**30**	**UTM/WGS 1984**	**2**	**8**
	Landsat 4-5 TM	**139/31**	**18.12.1994**	**30**	**UTM/WGS 1984**	**2**	**8**
	Landsat 4-5 TM	**139/31**	**13.10.2005**	**30**	**UTM/WGS 1984**	**2**	**8**
	Landsat 4-5 TM	**139/31**	**14.12.2010**	**30**	**UTM/WGS 1984**	**2**	**8**
	Landsat 8 OLI/TIRS	**139/31**	**01.12.2017**	**30 (15m for PAN)**	**UTM/WGS 1984**	**2**	**16**

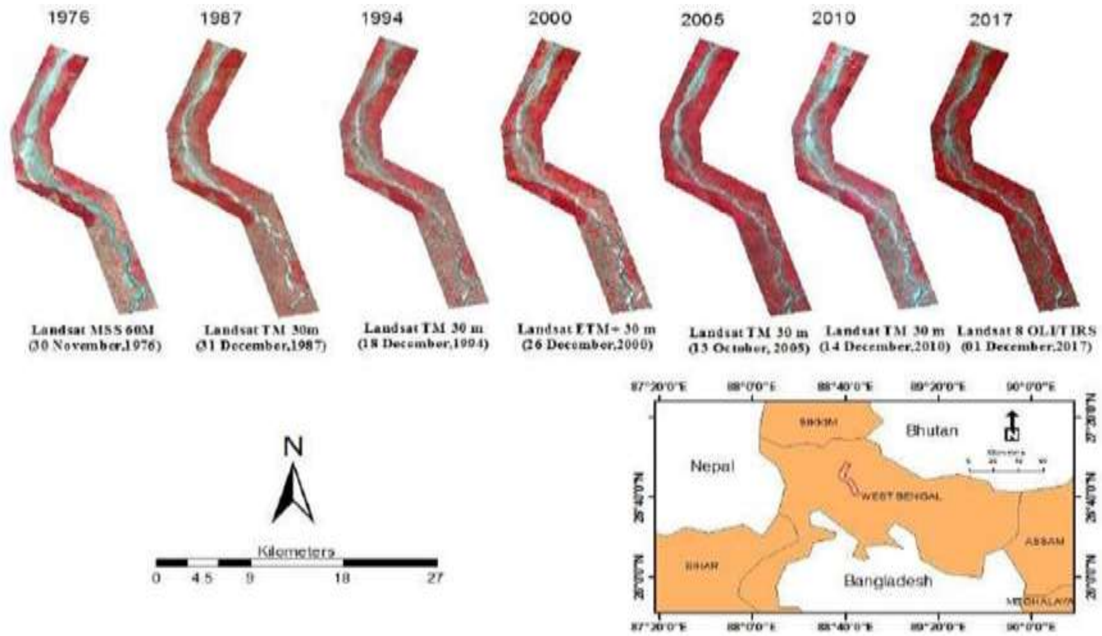

Fig. 2, Temporal Landsat images used in the study showing morphological changes over time.

Delineation of channel boundary

For assessing various channel characteristics mentioned above, channel boundary delineation is imperative. Now, the channel boundary has been delineated from both topographical maps and Landsat images. A bunch of previous studies demonstrate the availability of techniques ranging from manual digitization to automatic digitization to extract river boundaries from

Landsat images. Here, an automatic technique for extracting river banks was attempted, but the idea had to be dropped due to unreliable results caused by similarities in the spectral reflectance of several riverine features. Studies done in other parts of the world (Yang et al.1999; Gupta et al. 2013) have similarly found manual digitalization superior to the automatic digitization for delineation of river bank from Landsat multispectral data. So manual digitization technique was preferred over the automatic one, and the channel boundaries were digitized from each Landsat image, using a combination of bands (1-6-7), which has been found by Yang et al. (1999), an effective band combination to display river channels at normal water level.

Now there is some difference of opinion in defining the channel- bank limit among the geoscientists. Nicoll and Hickin (2010) digitized the channel outlines of confined meandering rivers at 23 locations in Alberta and British Columbia, Canada to understand planform geometry and channel migration using a strict geomorphologic approach wherein boundary of water limit was taken as edge of the channel because this boundary is clearly visible in multispectral Landsat image. However, this approach cannot be used in my study area having low discharge and braiding nature of flow. Almost in entire study reach, the channel cross sections are broad and shallow. So, a small change in water level can therefore give misleading large changes in the positions of the channel boundaries. To avoid this problem, channel bank limits were defined using a non- morphological variable, namely soil-vegetation limit. This method of defining channel bank limits was adopted by Lawler (1993), Gurnell (1997); Yang et al. (1999), Tiegs and Pohl (2005), Dewan et al. (2017) etc. Soil- vegetation limit approach presume that river channel limit is an elongated area wherein stream flow occurred with sufficient frequency, energy and duration to prevent the incidence of vegetation, and therefore 90% of this area is either bare soil or water (Gurnell, 1997; Yang et al., 1999, Tiegs and Pohl, 2005). This method effectively overcomes the problem of inconsistencies in channel planform delineation due to varying water levels (Gurnell, 1997). Due to its simplicity and practicality, this method has been used successfully and widely in different climatic regions of the world (Lawler, 1993, Gurnell, 1997; Yang et al., 1999, Tiegs and Pohl, 2005, Midha and Mathur, 2014, Dewan et al., 2017). Author performed digitization of channel boundary on-screen from each Landsat image at 1:5000. Finally, a georeferenced spatial dataset, representing Channel banklines, for each topographical map and Landsat image was created (Fig. 5.5). Bhunia et al. (2016) have used single sensor Landsat-Thematic Mapper (TM) of 1989,1999,2005 and 2010 to show the channel dynamics of a reach of river Ganga in the southern Vaishali district of Bihar. They argue that observing images of common projection minimizes the error due to temporal changes.

Channel planform dynamics

Channel planform dynamics has been attempted to understand through changes in channel morphology, sinousity index variation, braiding index variation, and braid-channel ratio variation.

Channel morphology dynamics

In order to understand morphological changes, a map showing reach wise temporal morphological changes from 1976-2017 was prepared (Fig.4). Further a combined configuration map was also prepared by superimposing temporal vector files showing epochal changes (during 1955-2017) in the channel location (Fig.5). These two maps were used to assess the changes in morphology by visual inspection. A typology mainly based on the methods proposed by Goswami et al. (1999) for planform changes was established (Midha and Mathur (2014). It helped as a reference to classify the observed geomorphological changes.

Sinuosity, Braiding Intensity, and Braid-Channel Ratio

Detailed study on planform dynamics has been attempted through the application of several Channel planform indices, namely Sinousity Index, Braiding Index, and Braid-Channel Ratio. Sinuosity, Braiding Index and Braid-Channel Ratio have been calculated only for the period 1976- 2017 from Landsat Images. Computation of these parameters from topographical maps was avoided as they display poor details on channel morphology. Changes in channel Braiding Index was computed adopting method given by Brice (1964). Whereas measurement of changes in channel Sinousity Index and Braid-channel Ratio was achieved through Friend and Sinha's method (1993). Each index has been discussed and calculated below;

Sinousity Index has been calculated following Friend and Sinha's method (1993). Accordingly, the sinuosity index, P, is defined as

$P= Lcmax/LR,$(1)

Where LR is the overall length of the channel-belt reach measured along a straight line, and Lcmax is the mid-channel length of the same reach, or the mid-channel length of the widest channel, where there is more than one channel. Sinousity Index in fact is a measure of bending of a river. Lower value of it implies the channel is near to straight course and higher values shows more sinuous course.

There are mainly three indices for estimation of Braiding index, viz. Braiding Index (BI) by Brice, Braiding Parameter (Bo) by Rust and Braid-Channel Length ratio (B) by Friend and Sinha. I have employed braiding index (BI) by Brice, 1964 as:

$BI= 2(\Sigma Li)/Lr$ (2)

Where Li is the length of all the islands and/or bars in the reach, and Lr is the length of the reach measured midway between the banks of the channel belt (Brice, 1964).

Braid-channel ratio (B) has been measured following Friend and Sinha, 1993 using the relation:

$B=Lctot/Lcmax,$ (3)

Where Lctot is the sum of the mid-channel lengths of all the segments of primary channel in a reach, and Lcmax is the mid-channel length of the widest channel through the reach.

A higher value of braid-channel ratio means higher braiding of the river which means multiple numbers of channels. In fact, greater braid index implies an unstable river condition. The lowest value of Braid-Channel ratio is 1 that implies a single channel flow with no mid-channel bars.

Results

Channel Morphological dynamics

The different types of morphological changes observed during the entire assessment period were: neck cut-off and consequent straightening of course; Changes in channel width; development and abandonment of anabranches; and shifting of meander bends.

A meander bend was observable at the very beginning of assessment period (i.e., in 1955) near Kranti in the Reach-C. In the next 15 years, it's observable that the meander's intensity has increased further (Fig. 3 A) in 1970 and by 1976 we see a complete neck cut-off (Fig. 3 B). Thus, the river has straightened its course by abandoning the meander loop. Notably, this straightening has decreased the length value by 1.94 km in the Reach-C and by 2.10 km in the overall length of the river during the period 1970-1976 (Table 2).

The Chel River experienced several episodes on contraction, expansion, osilation and straightening during the assessment period of 62years as shown by the channel configuration maps of the seven periods between 1955 and 2017 (Fig.4 & 5).

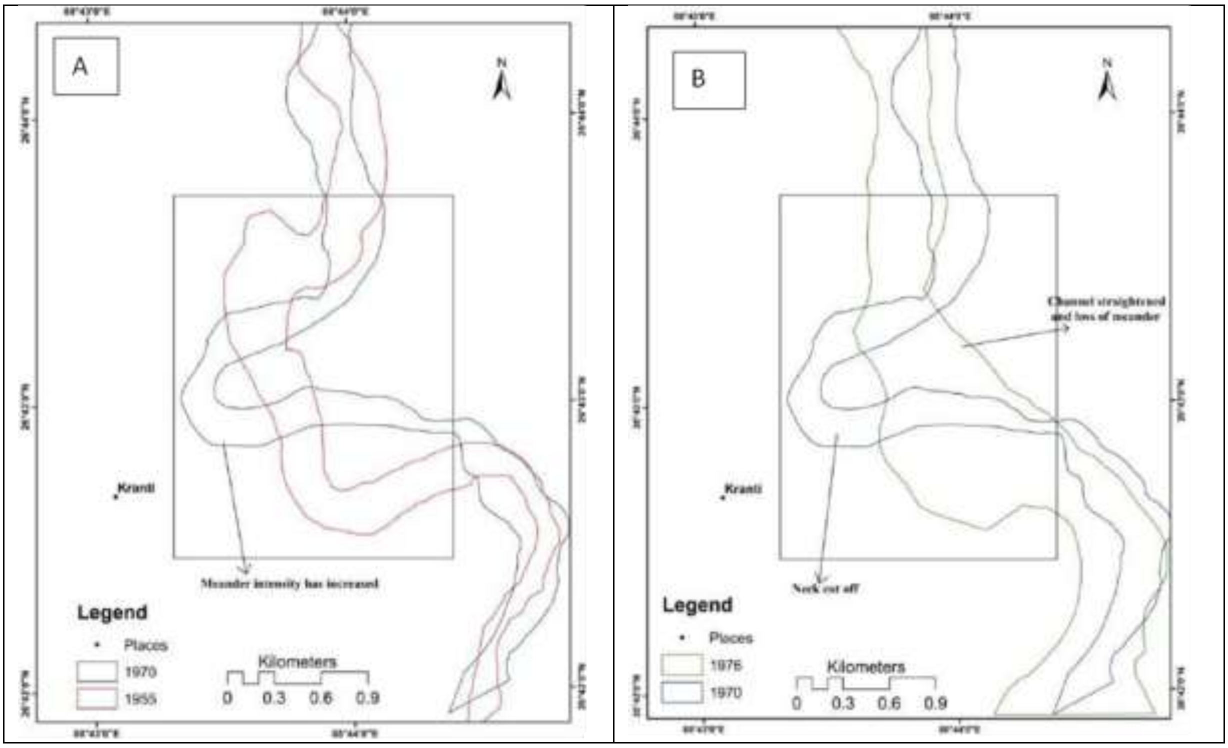

Fig. 3, Channel polygons of 1955, 1970 and 1976 illustrating the episode of channel straightening through neck cut-off in Reach-C of the Chel River.

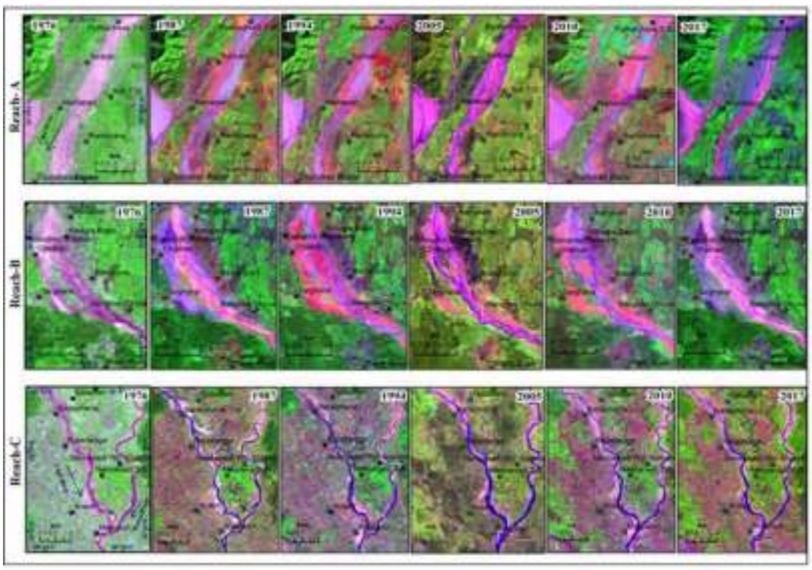

Fig. 4, Reach-wise morphological changes over time.

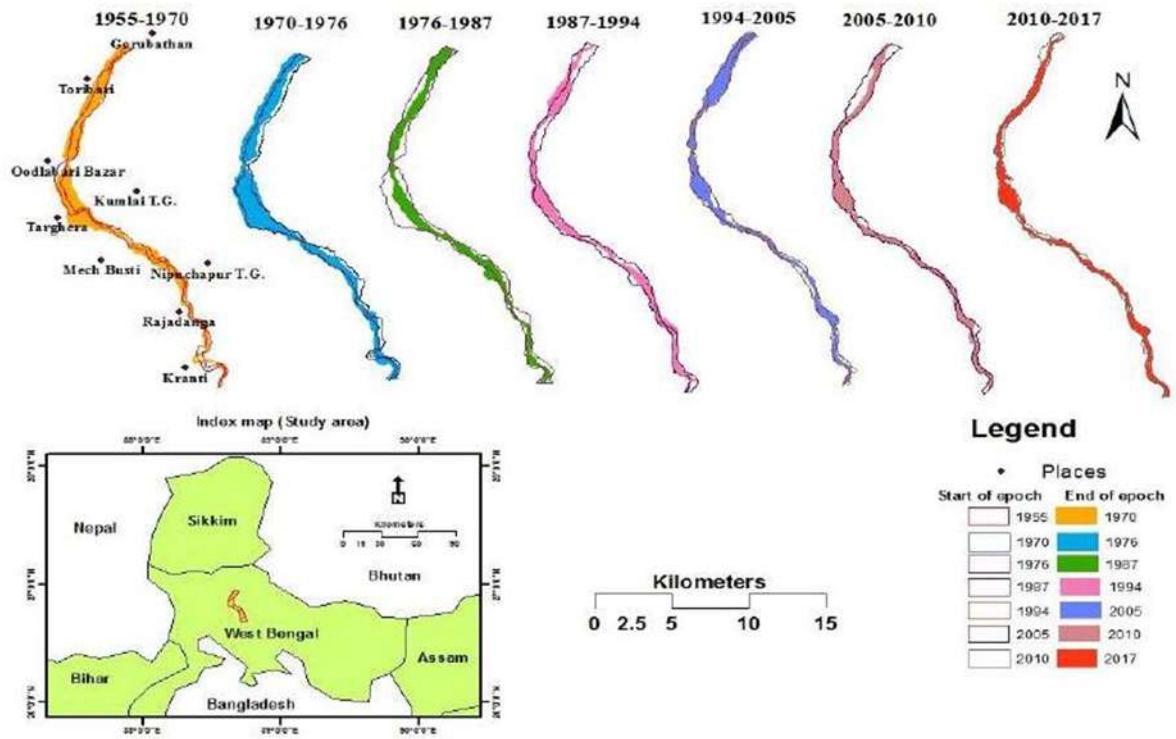

Fig. 5, Channel configuration maps of the Chel River, showing epochal change in channel location. Channel at the start of the epoch is shown by a hollow polygon, and at the end with solid fill.

Table 2, Reach-wise temporal channel length changes from 1955 to 2017 (values in the parentheses indicate percentage change from the previous year).

Reach	**Length(km)**							
	1955	**1970**	**1976**	**1987**	**1994**	**2005**	**2010**	**2017**
A	10.59	10.4 (-1.8)	10.49 (+0.87)	10.54 (+0.48)	10.87 (+3.13)	10.61 (-2.39)	10.75 (+1.32)	10.9 (+1.4)
B	13.73	12.53 (-8.74)	12.28 (-2)	11.99 (-2.36)	12.08 (+0.75)	12.2 (+1)	12.16 (-0.33)	12.25 (+0.74)
C	13.17	12.94 (-1.75)	11 (-14.99)	11.07 (+0.64)	10.87 (-1.8)	11.15 (+2.58)	10.62 (-4.75)	10.44 (-1.69)
Total	37.49	35.87 (-4.32)	33.77 (-5.85)	33.6 (-0.5)	45.9 (-36.6)	33.96 (-26.01)	33.53 (-1.27)	33.59 (-0.18)

Sinuosity, Braiding Intensity, and Braid-Channel Ratio

Computation of planform indices reveals the fact that there are visible trends of decreasing sinuosity and BI of river Chel. Decreasing trend of channel width has already been established in the earlier paragraphs. This decreasing trend in channel width, sinuosity and braiding index seems to be due to construction of embankment and channelization. There are good number of documented evidences of decreasing width, sinuosity and BI in other parts of the world which validates the fact that channel narrowing begins rapidly after channel confinement.

The sinuosity index and Braid-Channel Ratio values has been computed for each segment or reach of the river for a period of 41 years (from 1976 to 2017) and it reveals the fact that sinuosity values are generally low and constant but Braid-Channel Ratio values are comparatively much variable and horizontally much scattered (Table 3 and Fig.8). Friend and Sinha (1993) have used the similar indices for the study of measuring channel morphological variability of Gandak, Burhi Gandak and Bagmati River of India. A river will be of straight pattern when B=1 and P=1 because a reach with a single channel with no braids will have a value of 1 for B and will be equal to Sinousity value (P). The horizontally elongated shape of plotted points in a scatter diagram with Braid-Channel ratio values along the abscissa and Sinuosity values along the Ordinate, suggests braided channel pattern, whereas vertically elongated shape points towards the meandering channel pattern (Fig. 6).

In the present study, the plotting of Segment or Reach wise braid-channel ratio against the sinuosity index (Fig.7) exhibits that sinuosity values are less variable as compared to braid-channel ratio values. The lowest sinuosity value of 0.9 has been observed during 2010 in Segment-B whereas the highest sinuosity value of 1.48 has been observed during 2017 in Segment-C. Similarly, the lowest braid-channel ratio value of 0.96 is observed during 2005 in the Segment-C whereas the highest braid-channel ratio value of 2.27 is observed during 1976 in Segement-B (Table 4.2.10). Overall, the horizontally scattered points suggest of moderately braided channel pattern of the river (Fig. 7). The values of braid-channel ratio have consistently decreased since its highest mark of 2.27 in 1976 to lowest value of 0.96 in 2005 and then by 2017, the values in each segment became near 1 which is suggestive of the fact that Chel river is gradually transforming itself from a braided channel to a straight one. The recent years clustering of points which otherwise were scattered horizontally and elongated further confirms the transition of channel form from braided to straight. The Reach wise plotting of points suggests that Segment- B is the most braided reach followed by Segment-A and Segment-C. Segment-C has always been a near straight reach throughout the assessment period of 41 years (Fig. 8).The consideration of Sinousity and Braiding Index for the entire study reach of Chel River reveals the fact that channel configuration dynamics led to an overall decrease of braiding index by 20.6% and a negligible increase of sinuosity index by 4.5% in 41 years i.e., from 1976 to 2017 (Table 4 & Fig.9).

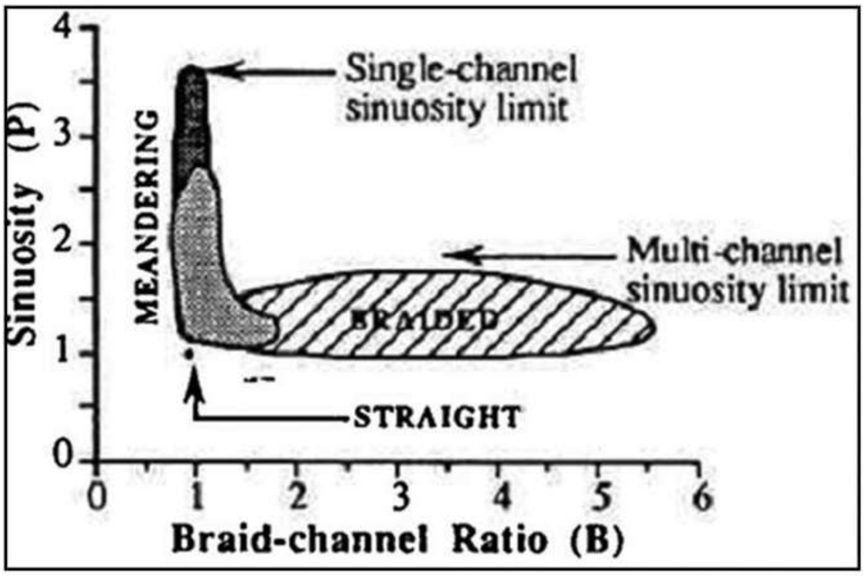

Fig. 6, Determination of channel pattern based on Sinousity (P) and Braid-channel Ratio (B), Friend and Sinha,1993.

Table 3, Reach-wise temporal dynamics in planform

Reach	year	Lctot (km)	Lcmax (km)	Li (km)	Lr (km)	Sinousity Index (P)= Lcmax/LR	Braiding Index, Brice 1964 (B)=2(?Li)/Lr	Braid-channel ratio, B= Lctot/ Lcmax
	1976	16.18	11.23	8.26	10.45	1.07	1.58	1.44
	1987	14.19	11.6	7.08	10.46	1.11	1.35	1.22
A	1994	12	11.83	8.83	10.8	1.1	1.64	1.01
	2005	22.1	11.66	14.13	10.6	1.1	2.67	1.89
	2010	14.23	11.73	4.04	10.7	1.1	0.76	1.21
	2017	13.76	11.8	5.25	10.84	1.1	0.97	1.17
	1976	26.1	11.5	9.69	12.24	0.94	1.58	2.27
	1987	24.23	11.49	8.73	11.98	0.96	1.46	2.11
B	1994	16.01	11.61	8.82	12.04	0.96	1.46	1.38
	2005	22.32	12.32	10.96	12.2	1.01	1.8	1.81
	2010	21.29	11.21	12.67	12.7	0.9	2.01	1.9
	2017	17.5	11.53	7.4	12.23	0.94	1.21	1.52
	1976	19.71	14.84	6.69	10.9	1.36	1.23	1.33
	1987	15.34	15.34	1.65	11.29	1.36	0.29	1
C	1994	13.98	13.98	7.6	10.81	1.29	1.4	0.98
	2005	14.82	14.82	5.75	11.26	1.32	1.02	0.96
	2010	15.51	15.51	4.68	10.52	1.47	0.89	1
	2017	15.46	15.46	6.77	10.46	1.48	1.29	1

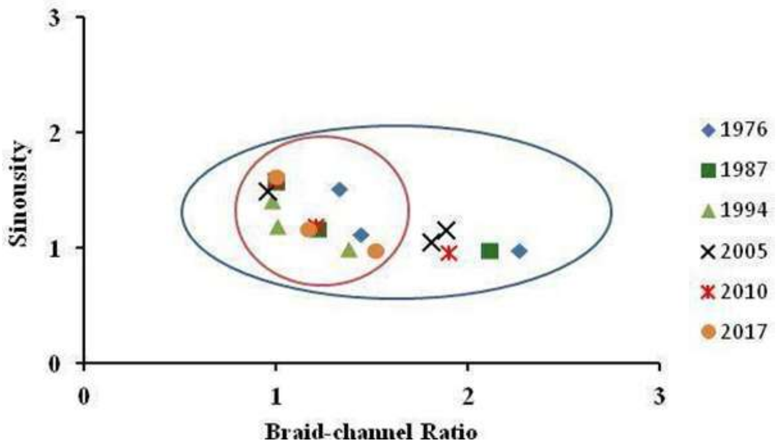

Fig. 7, Temporal variability of Sinousity(B) and Braid-channel Ratio (P) of River Chel.

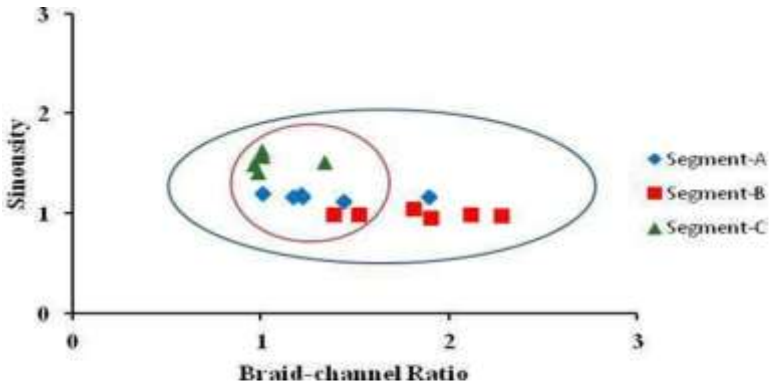

Fig. 8, Reach-wise temporal variability of Sinousity (B) and Braid-channel Ratio (P) of River Chel.

Table 4, Temporal variation in Sinousity and Braiding Index values of entire study reach from 1976- 2017 (values in the parentheses indicate percentage change from previous year).

Year	Sinuosity Index	Braiding Index
1976	1.12	1.46
1987	1.14(+1.8%)	1.03 (-29.5%)
1994	1.12 (-1.8%)	1.5 (+45.63)
2005	1.14 (+1.8%)	1.83 (+22%)
2010	1.16 (+1.8%)	1.22 (-33.33%)
2017	1.17 (+0.9%)	1.16 (-4.92%)
Overall % change	(+4.5%)	(-20.6%)

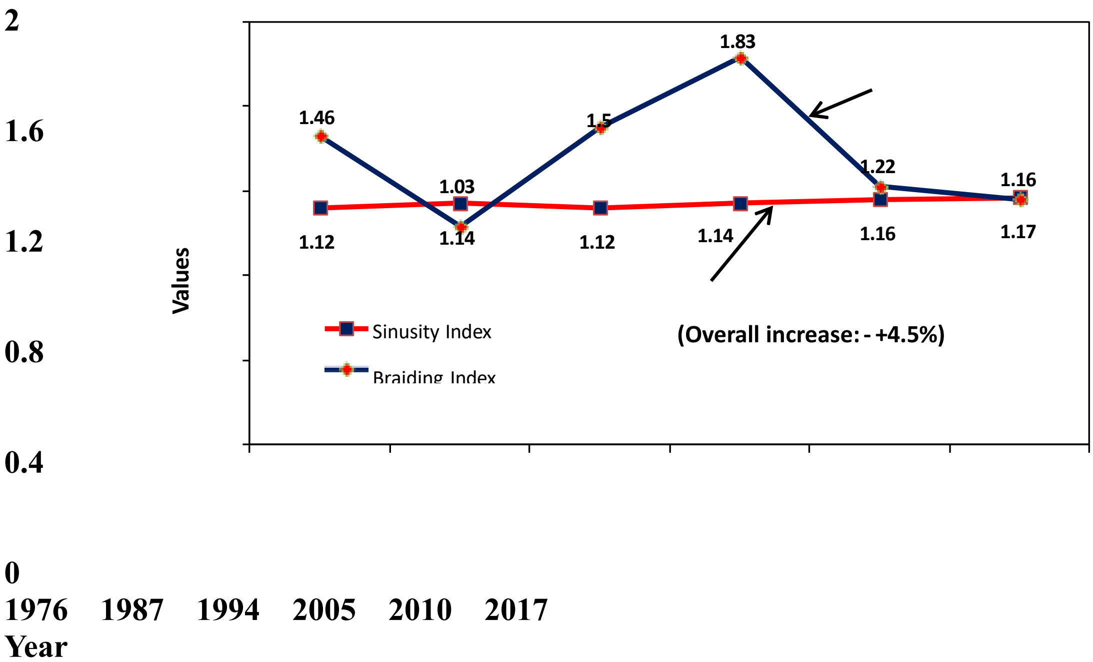

Fig. 9, Variation in Sinousity Index and Braiding Index values from 1976 to 2017 in the Chel River.

Findings

The different types of morphological changes observed during the entire assessment period were: neck cut-off and consequent straightening of the course; Changes in channel width; development and abandonment of anabranches; and shifting of meander bends.

Computation of planform indices shows decreasing trends of Sinuosity and braiding index.

The decreasing trend in channel width, BI, and sinuosity seems to be due to heavy extension of embankments.

Conclusion

The paper considerably establishes the fact that the Chel River has undergone various phases of planform changes during the assessment period of 62 years from1955-2017. The significant changes observed were increased instability in terms of channel widening, an increasing number of neck cut-offs, occurrences of avulsions, decreasing sinuosity, and braiding intensity.

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