



Assessing land erosion and accretion dynamics and river bank line shifting of upper reach of Hooghly river of West Bengal, India

Abhijit Paul¹ · Manjari Bhattacharji¹

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Abstract

River bank line shifting and channel migration due to river bank erosion and accretion causes inevitable geomorphic hazards in Gangetic West Bengal, India. Channel oscillation and associated river bank erosion-accretion is the widespread hydro-geomorphic phenomenon of the Bhagirathi-Hooghly river. In the present analysis, an attempt has been made to investigate the pattern of bank line shifting and river bank erosion-accretion dynamics of the 85 km long upper reach of the Hooghly river for the last 100 years with the use of geospatial techniques. The study is based on police station maps (1917–1921), topographical sheets (1954) and Landsat imageries of 1972, 1990, 2005 and 2020, which were collected from different sources. Sinuosity index, radius-wavelength ratio and bend-tightness index of different time periods have been computed for analyzing the temporal changes that occurred in the study reach. The result shows that the sinuosity index decreased from 1.95 in 1921 to 1.87 in 2020 and the areal extension of bank erosion and accretion decreases. This study has also developed a model for future prediction of river centerlines in the coming decades to identify future hazard zones. The overall channel migration of the upper reach of the Hooghly river indicates the oscillatory nature of the river channel. Channel widening, meander bend development and lateral movement of the channel are responsible for erosion and accretion of the bank. Therefore, the present analysis may be helpful for the identification and mapping of future vulnerable areas and make a plan for the lives of the people living near the bank line for their safety and sustainability.

Keywords Geomorphic hazards · Channel straightening · Geospatial techniques · Meander bend

Introduction

Migration of river channels and concomitant channel shifts across floodplains involves combination of erosion in the concave bank and concomitant deposition in the convex bank (Hickin and Nanson 1984; Charlton 2008). Erosion, deposition and inundation along meandering and braided rivers of the floodplains, are the most common hydro-geomorphic hazards (Lawler 1993). Erosion leads to loss of land, while depositional areas create incremental land areas. Therefore, hydro-geomorphologically, the former is less habitable and inhospitable, while the latter is favorable for human occupation. Bank erosion is controlled by various factors like

composition of bank materials, flow characteristics, riparian vegetation coverage, surface runoff and anthropogenic activities (Knighton 1998). Pattern of channel shifting, and concomitant morphological changes in different rivers, have been analysed using RS-GIS technology by different authors (Sarkar et al. 2012; Gogoi and Goswami 2014; Yang et al. 2015; Neog 2018; Singh et al. 2018; Hasanuzzaman and Mandal 2020). Planform changes with the help of historical maps and air photographs have been investigated by Gurnell et al. (1994). Khan et al. (2016a), Khan et al. (2016b), Khan et al. (2019) on the basis of their studies report that water discharge character, sediment budget, impact of small tributaries plays an important role for changing river dynamics in floodplain areas.

Increased human interference is the probable agent of active erosion in the Ganges river (Bhunja et al. 2016) because, intervention in the natural course of any river system causes unpredictable changes in the upstream and downstream areas. The hydro-geomorphic modifications and socio-economic impact of the Farakka Barrage Project in

✉ Abhijit Paul
abhijitpaul0703@gmail.com

Manjari Bhattacharji
manjari17_bhattacharji@rediffmail.com

¹ Department of Geography, Visva-Bharati, Santiniketan,
West Bengal 731235, India

both upstream and downstream areas have been studied by Banerjee (1999), Parua (2009), Rudra (2010, 2018), Islam and Guchhait (2017). The morphometric changes and land use/land cover change in the upstream of Farakka Barrage in pre and post barrage periods have been studied using remote sensing and GIS techniques Thakur et al. (2012), Mondal and Mandal (2018). Meander shift dynamics and its role in accentuation of flood and economic hardships of the Bhagirathi-Hooghly river between 1977 to 2017 has been assessed by Mandal et al. (2018). Islam et al. (2020) assessed the meander belt width of the Bhagirathi river caused by higher monsoon discharge, suspended surface sediment concentration, bed slope etc. The pattern of channel instability, bank erosion, channel geometry and migration cardinality of the Bhagirathi river have been studied by Islam and Guchhait (2013), Das et al. (2014) and Bag et al. (2019). They found that meander migration is very prominent and is reflected in the inconsistency of planform of the floodplain and erosion vulnerability. Chatterjee and Mistri (2013) analysed the nature and causes of bank erosion in Santipur block along the Hooghly river.

All of the above studies have been taken up in the Bhagirathi-Hooghly river. However, none of them have covered the themes of (spatio-temporal shifting of the bank lines, identification of erosion and accretion zones, measurements of their areal extents and impact of the hydrological regime on the changing channel dynamics) in the upper reach of the Hooghly river between Jalangi-Bhagirathi confluence (at Swarupganj in Nadia district) and Hooghly-Kunti confluence (at Kuntighat in Hooghly district).

The Bhagirathi-Hooghly river is the westernmost river system of the Ganga–Brahmaputra delta. It is bordered by the lateritic Rarh plain and the palaeo fan delta of peninsular rivers (Bagchi 1944; Bandyopadhyay 2007; Guchhait et al. 2016). Low elevation, gentle slope, meandering and migrating river channel, natural levees and oxbow lakes are the common geomorphological features of the region.

In the present study therefore, these themes have been studied with the help of the last 100 years database comprising police station maps (1917–1921), topographical sheets (1954) and Landsat imageries of 1972, 1990, 2005 and 2020. So, in the present study, effort has been made to measure and generate a record of river bank line shifting and erosion accretion dynamics. Future prediction of the channel centerline of the river has been attempted with a linear regression model. This item of enquiry in this densely populated area is very relevant. Therefore, the study will help for better understanding of the ground situation in planning for hazard management purposes.

Study area

The 85 km long stretch of the Hooghly river lies between Bhagirathi-Jalangi confluence and Hooghly-Kunti confluence. Jalangi river, a left-bank tributary, joins the river Bhagirathi at Swarupganj in Nadia district and the river Kunti, a right-bank tributary, meets the river Hooghly at Kuntighat in the district of Hooghly. Latitudinally the area extends from 23° 0' 53" N to 23° 24' 40" N and the longitudinal extension of the region is from 88° 19' 32" E to 88° 31' 04" E (Fig. 1). Bhagirathi-Hooghly river is one of the most important rivers in the Gangetic West Bengal. The river takes off from the Ganga near Mithipur in Murshidabad district and flows 500 km in the southward direction and falls into the Bay of Bengal at Gangasagar (Rudra 2010). The non-tidal part of the river up to Nabadwip is known as Bhagirathi, while the tidal part (280 km) of the river starts from Nabadwip, the confluence of Jalangi River, to the Bay of Bengal known as Hooghly (Garrett 1910; Rudra 2010). This 85 km long stretch of the Hooghly river traverses through five blocks (Nabadwip, Krishnagar-I, Santipur, Ranaghat-I and Chakdah) of Nadia district, three blocks (Purbasthali, Kalna-I, Kalna-II) of Purba Bardhaman district and one block (Balagarh) of Hooghly district. The river channel in this region is highly dynamic and characterized by avulsion, meandering and lateral migration. Bank erosion hazard is the most common phenomenon in this region, causing large-scale displacement of riparian communities, loss of crops, livestock, land property and human lives. In this study reach, two right bank tributaries, namely Khari at Dhatrigram and Behula near Somra Bazar, join with Hooghly river and one left-bank tributary, Churni river joins with Hooghly river near Shibpur in Ranaghat-I block of Nadia district. Topographically the area is characterized by low relief, sloping gently in south-east direction. Gangetic alluvium rich in calcium, potassium and magnesium covers the area. This region experiences subtropical climate with hot-humid summer and cool-dry winter. More than 75% rainfall occurs by the monsoonal rainfall from July to September (Islam 2016) and average annual rainfall is around 120 mm (Bag et al. 2019).

Materials and methods

Preparation of database

The entire work has been carried out with the help of secondary databases collected from different sources. Geo-database files for the last 100 years (1921–2020) were

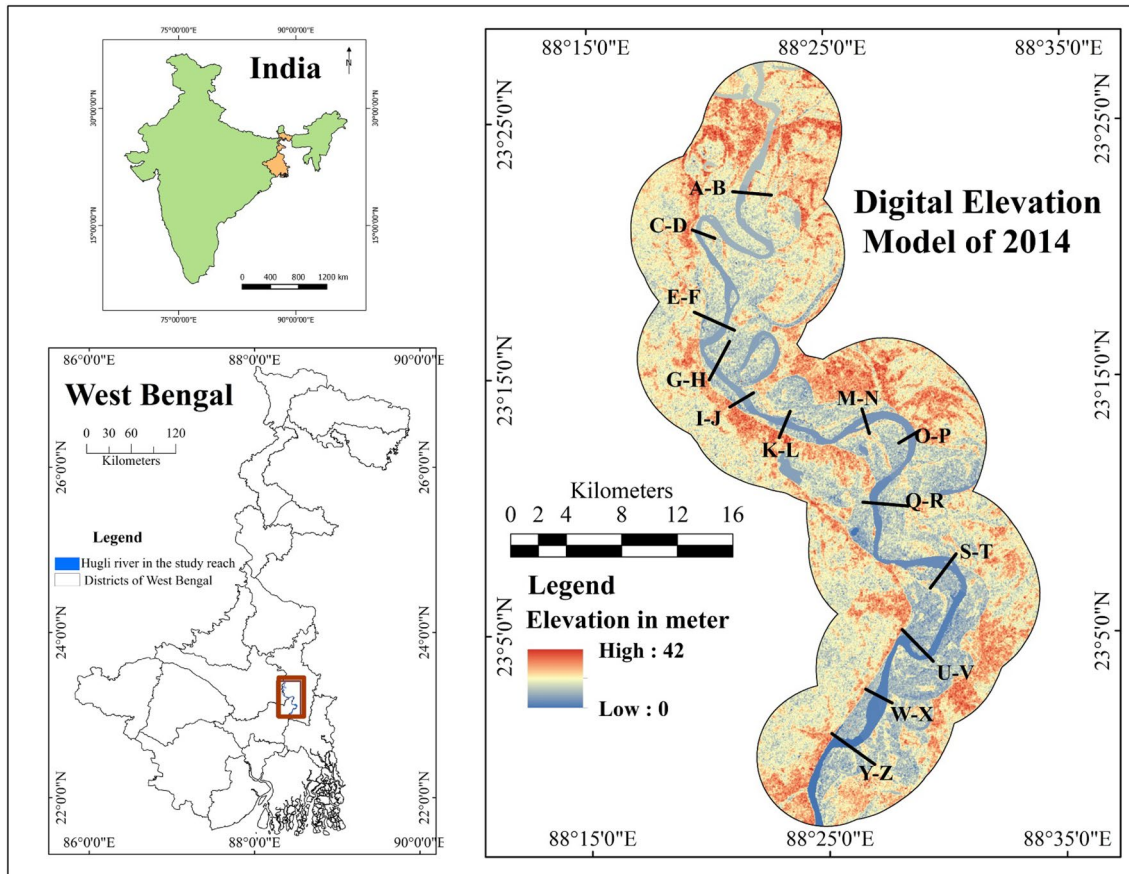


Fig. 1 Location map of the study area

prepared and the entire period was divided into different phases (1921–1954, 1954–1972, 1972–1990, 1990–2005 and 2005–2020). Police station maps, topographical sheets and satellite imagery were collected from various sources (Table 1). All the spatial datasets are rectified with the Universal Transverse Mercator (UTM) projection with 45 degree north latitude and World Geodetic Survey (WGS-84) datum. Police station maps of Krishnagar, Nabadwip, Santipur, Ranaghat and Chakdah (survey period 1917–21) were taken as the base map. US Army series topographical

sheets (NF 45-3, 45-4, NF 45-7 Series U502) of 1954 and satellite imageries of 1972 to 2020 were taken as the next layer for measurements.

Measurement of the magnitude of erosion and accretion

River channel of different time periods (1921–1954, 1954–1972, 1972–1990, 1990–2005 and 2005–2020) were mapped and superimposed. Thereafter, thirteen

Table 1 Data used in the study

	Satellite	Date	Spatial Resolution/ Scale	Source
Topographical maps and other maps	Police station maps of Krishnagar, Nabadwip, Santipur, Ranaghat and Chakdah	1917–1921	1:63,360	Bureau of Applied Economics and Statistics, Kolkata
Landsat Imageries (1972–2020)	NF 45-3, 45-4, NF 45-7 Series U502	1954	1:250,000	Army Map Service
	Landsat 1(MSS-148/44)	11.12.1972	60 m	USGS Earth Explorer
	Landsat 5 (TM-138/44)	14.11.1990	30 m	
	Landsat 5 (TM-138/44)	26.01.2005	30 m	
	Landsat 8 (OLI_TIRS-138/44)	18.02.2020	30 m	

cross-sections across these superimposed river channels were drawn to measure the rate of channel shifting and channel width (Fig. 1) using 'line tool' from 'measurement tool' in ArcGIS 10.5 software. The extent of erosion and accretion was measured for all the periods under investigation. River bank lines of 1921 and 1954 were superimposed to measure erosion and accretion in both banks during this period. Suppose the left bank of the river shifts towards the left, in that case, the zone between the left bank of the successive period is considered as an eroded area in the left bank, and if the right bank of the river shifts towards the right, then the zone between the right bank of the successive period is considered as an eroded area in the right bank. Suppose the left bank of the river shifts towards the right, in that case, the zone between the left bank of the successive period is considered as an accreted area in the left bank, and if the right bank of the river shifts towards the left, then the zone between the right bank of the successive period is considered as an accreted area in the right bank. The same processes were applied for the other periods (1954–1972, 1972–1990, 1990–2005 and 2005–2020).

Indices for measurement of channel planform changes

Sinuosity index, bend tightness index and radius-wavelength ratio have been used as the parameters of planform. There are several methods for identifying channel sinuosity (Brice 1964; Leopold et al. 1964; Leopold and Langbein 1966; Mueller 1968; Schumm 1985). In this study reach the Sinuosity index (SI) has been analysed following the methods of Brice (1964). The formula of the index is given in the equation below (Brice 1964)

$$SI = \frac{\text{Length of the channel}}{\text{Length of the meander belt axis}} \quad (1)$$

To understand the changing nature of the planform of the channel, radius of curvature, meander wavelength and average channel width along the meander loops have been measured. The radius of curvature of a particular meander bend is the radius of the best fit circle to the centerline of the bend. The Channel centerline is the line that passes inside the channel with equal distance from both the banks. Wavelength is the straight line distance from one bend to the next.

The radius-wavelength ratio is the ratio between the radius and the wavelength of a meander loop. It is a very important parameter to understand the geometry of the channel and intensity of the meander. The ratio is 1:4 for a sine generated curve and the greater the ratio, the more intense is the meander (Das 2014):

$$\text{Radius-wavelength ratio} = \frac{r_c}{\lambda}, \quad (2)$$

where r_c denotes the radius of curvature and λ is the wavelength of the channel (Charlton 2008):

$$\text{Bend-tightness index} = \frac{r_c}{w}, \quad (3)$$

where r_c represents the radius of curvature and w is the average channel width near the bend.

Prediction of bank line shifting by the linear regression model

Various researchers have used the linear regression method for predicting river bank line position to estimate the probable future risk zone of bank line shift (Das et al. 2012; Deb and Ferreira 2014; Bag et al. 2019). In this study, the river centerline position was predicted for the years 2030 and 2050 with the help of historical shifting values measured in the GIS environment. For this purpose river centerline position in 1921 was taken as the base year and the total study period was divided into five phases. Cross section-wise bank line shift were measured from the base year 1921–1954, 1921–1972, 1921–1990, 1921–2005 and finally 1921–2020. Centerlines of the river channels were created with the help of the 'collapse dual lines to centerline' tool in the ArcGIS environment. Finally, linear regression method was applied to compute the centerline position in 2030 and 2050. Cross section-wise regression values were calculated to assess the accuracy of the trend line (Bag et al. 2019). For accepting the predicted values, the prediction was made for the year 2020. It was seen that the predicted value and actual shifting value of the year 2020 do not differ much and it indicates the linear regression method is acceptable for the prediction analysis.

Results and discussion

Measurement of temporal changes of the river channel

Sinuosity index

The channel length is the distance of the channel from the source point to the mouth. Channel length was maximum (91.3 km) in 1954 and in 1972, it was 83.4 km in 1972 with a reduction of 7.9 km as there was a meander cut-off near the Srikrishnapur Char area in Nadia district. The sinuosity index was 1.96 in 1921 and 1.87 in 2020, while the value was maximum (1.99) in 1954, indicating a decreasing trend due to channel straightening (Fig. 2).

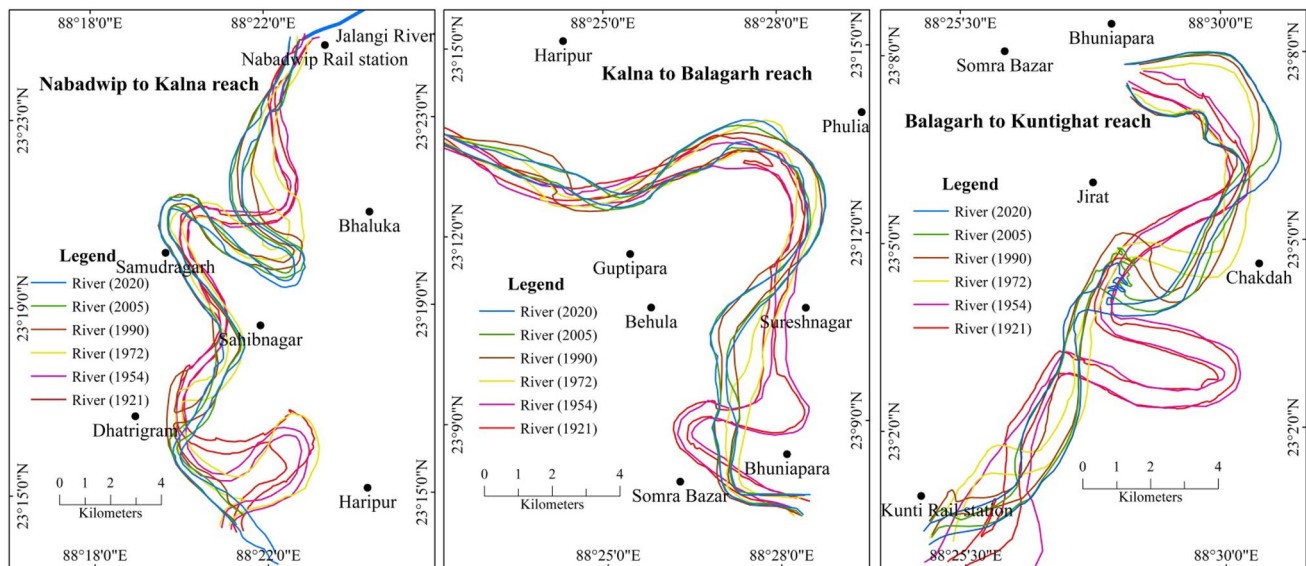


Fig. 2 Lateral movement of river bank line in different section of the study reach from 1921 to 2020

Shifting of river bank line

The mean maximum widening of the left bank implying erosion in the left bank in decreasing order, occurred in cross-sections U–V, followed by cross sections S–T and W–X, all located in the southern portion of the study area corresponding to the villages of Shibpur, Gournagar, Char Jirat. While mean maximum narrowing implying accretion along the same bank occurred in cross-section G–H (Gramkalna) followed by cross-sections A–B (Parmedia) located in the northern part of the study area and Q–R (Sureshnagar) located in the central part of the study area. Therefore, erosion and accretion is occurring along the left bank throughout the study area, erosion being dominant in the south and accretion in the northern portion (Fig. 3f). The mean maximum widening of the right bank implying erosion in the right bank in decreasing order, occurred in cross-sections A–B (Teghari), followed by cross sections G–H (Dhatrigram) located in the northern portion of the study area and Y–Z (Noasari Char) located in the southern portion; while mean maximum narrowing implying accretion along the same bank occurred in cross-section U–V (Char Jirat), Q–R (Char Sundalpur) located in the southern portion of the study area and E–F (Malatipur) located in the northern portion (Fig. 3f). Another significant observation is that there is no recurrence of maximum erosion and accretion along the selected cross sections except G–H (Dhatrigram) in the northern portion and Y–Z (Noasari Char) in the southern portion. In the former the recurrence period is after an average gap of 70 years while in Y–Z the recurrence of 34 years indicating thereby the latter is more vulnerable to erosion (Fig. 3a–e). The erosion pattern is also reflected in

the pattern of the bank line shift. There is a positive relation between erosion and bank line shift. For example, the cross section G–H (Dhatrigram) records the maximum area under erosion and bank line shift as well.

The overall sinuosity index of the channel has decreased during the observation period from 1921 to 2020. This decrease is however insignificant. Under normal circumstances rivers flowing over floodplains are characterized by series of prominent meanders and cut-offs. However, along the study reach there is an anomaly because only two cut-offs (near Krishnadebpur and Srikrishnapur-Char) and two prominent meander loops near Samudragarh are noted. It is plausible that the decrease in the SI could be due to the two major cut-offs. The authors predict that there will be a further decrease in the SI in future because the meander loops at Samudragarh is likely to develop into a cut-off. There are several meander loops but meander loops near Samudragarh located in the northern portion of the study area has been chosen for a detail analysis because of its location in the northern portion of the study area where right bank erosion is dominant and that forms the main theme of enquiry of the study. It is against this background that the meander loops at Samudragarh has been taken up for detail study.

Migration of the meander loop at Samudragarh

Samudragarh is located 8 km downstream of Bhagirathi-Jalangi confluence (Fig. 4). Unlike in the entire river stretch, here the Sinuosity index value increases between 1921 and 2020 along both meander loops. The SI increases from 1.53 in 1921 to 3.76 in 2020 (Fig. 5a) along the left

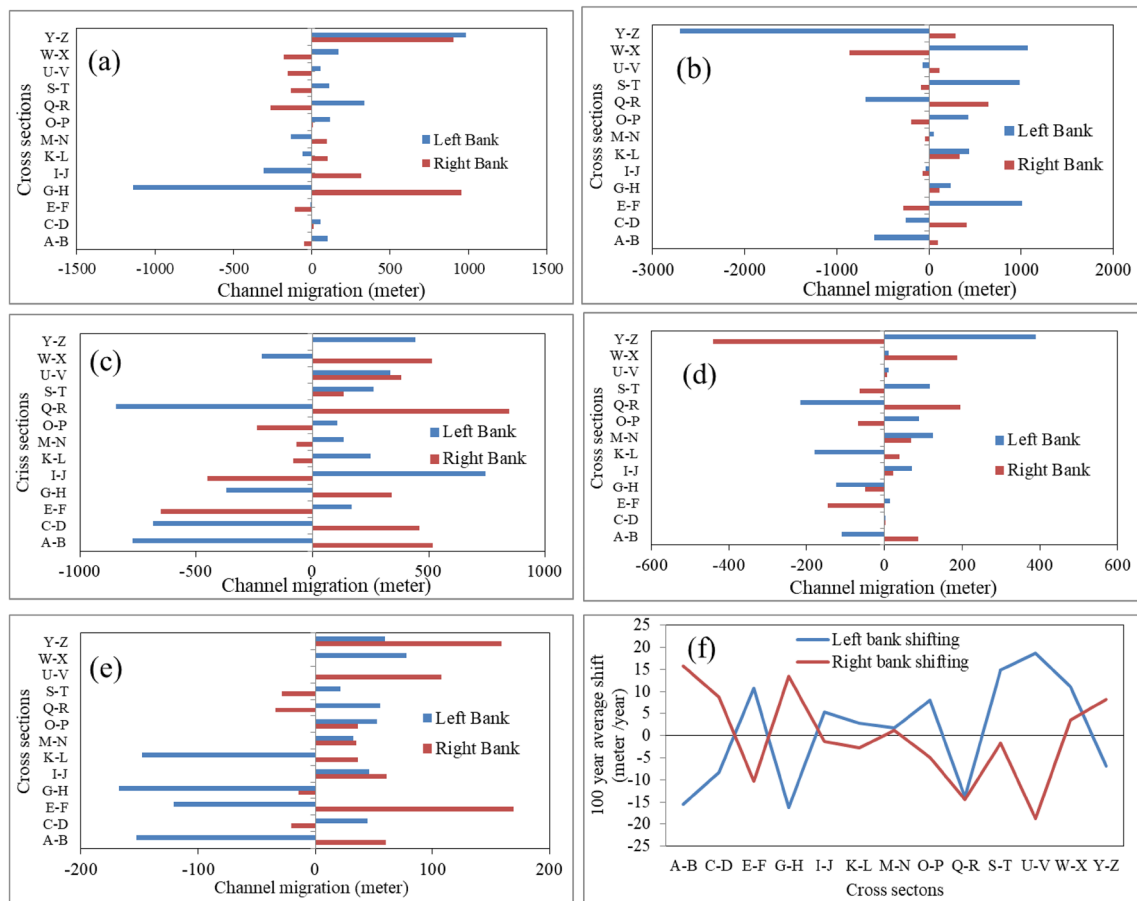


Fig. 3 Bank line shifting along different cross sections **a** 1921–1954, **b** 1954–1972, **c** 1972–1990, **d** 1990–2005 and **e** 2005–2020 and **f** 100 year average shift of bank line (Positive values (+) indicates channel widening and negative values (–) indicates channel narrowing)

bank meander loop and from 1.59 in 1921 to 3.54 in 2020 along the right bank meander loop (Fig. 5b).

Conceptually the impact of increasing sinuosity index should be reflected in a decreasing trend in the meander bend tightness index. This is found to be true in the analysis of this index along Hooghly river at Samudragarh where the bend tightness index along the left bank meander loop shows a decreasing trend during the entire observation period and along the right bank meander loop a steep decline in the tightness index up to 1990 followed by insignificant rise (Fig. 5c, d). All this indicates a gradual progress towards the development of a cut-off which could lead to straightening of the river in this stretch and a consequent decrease in the overall sinuosity of the river. Indications of the development of cut-offs can also be inferred from the relation between bend tightness index and radius wavelength ratio (Fig. 5c, d). Higher the radius wavelength ratio lower will be the bend tightness index and higher will be the probability of the development of a cut-off. Assessment of the relation between r_c/λ ratio and r_c/w shows that the likelihood of the development of cut

off is higher in the left bank meander loop compared to that of the right bank meander loop.

Amounts of bank erosion and accretion in the study reach

Critical assessment of the areas under erosion and accretion along both the banks for all the study periods show that the average area under erosion measures less than 2 km². Therefore, erosion zones or pockets measuring more than 2 km² are considered deviations from the average. Therefore, these pockets of erosion measuring more than 2 km² have been taken into consideration for identification of erosion zones of concerned.

Erosion and accretion dynamics during 1921–1954

During this period, area under erosion in the right bank was more than in the left bank (Fig. 6a; Tables 2, 3); the annual rates being 0.345 km² and 0.328 km² respectively (Fig. 6b). Correspondingly, areas under accretion was

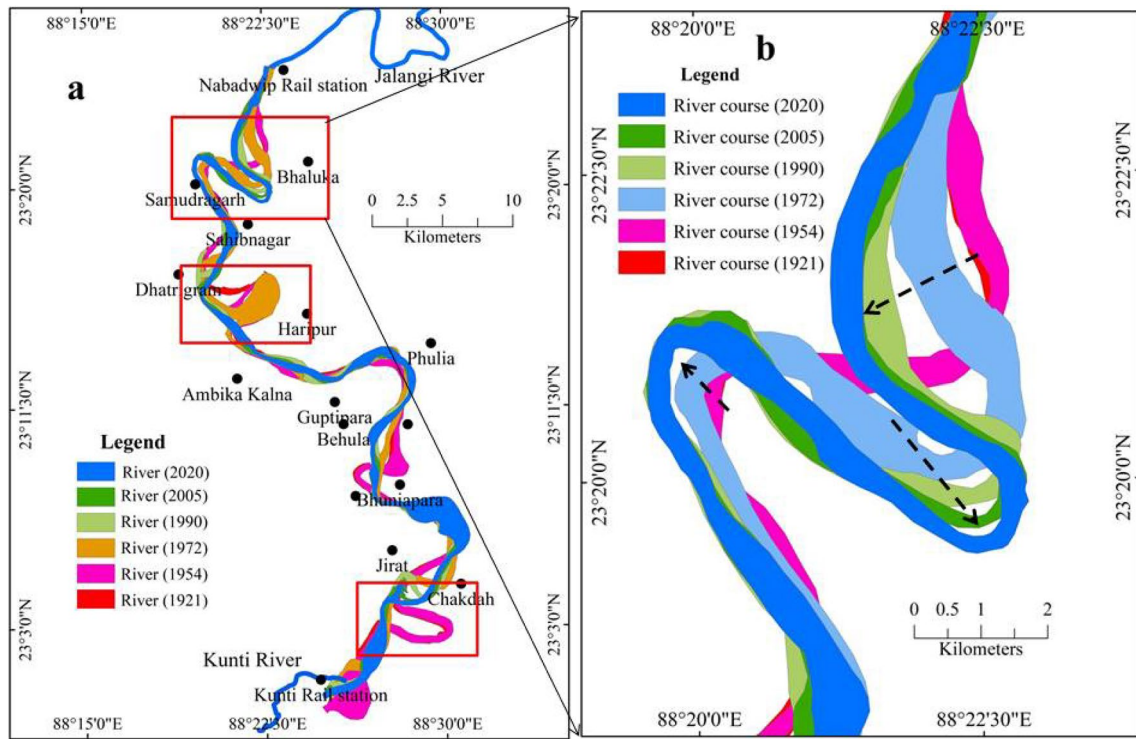


Fig. 4 a Channel pattern of Hooghly river in the study area with meander loops. b Lateral movement of meander loop near Samudragarh area

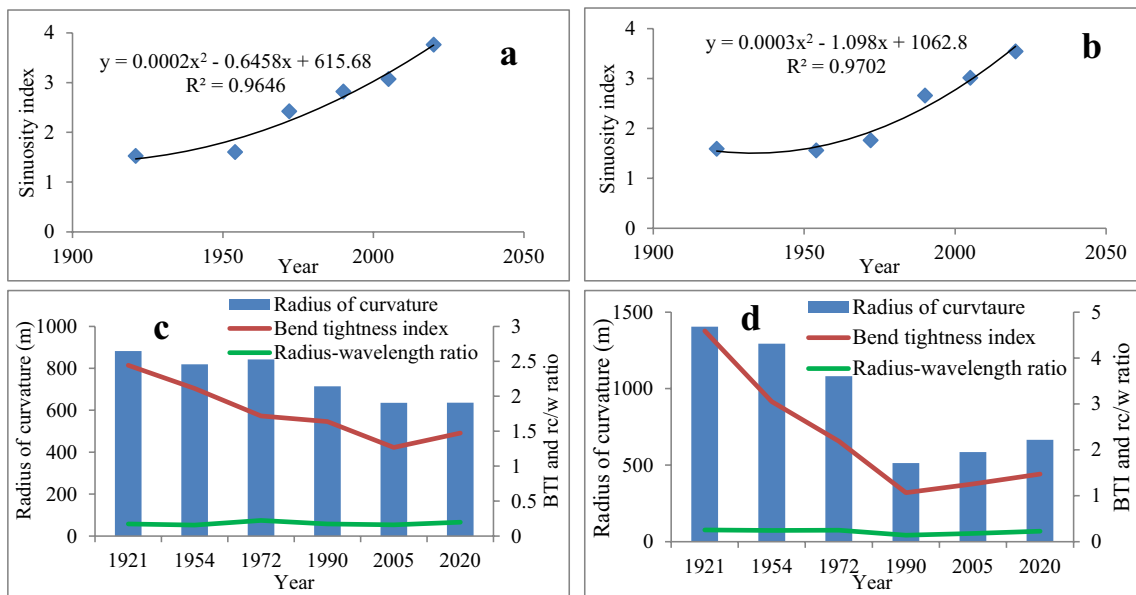


Fig. 5 a Sinuosity index of left bank loop. b Sinuosity index of right bank loop. c Radius of curvature, bend tightness index and radius-wavelength ratio of left bank loop and d radius of curvature, bend tightness index and radius-wavelength ratio of right bank loop

more in the left bank (6.9 km²) and vice versa (Fig. 6a; Tables 4, 5). The annual rate of accretion in left and right banks is 0.209 km² and 0.191 km² respectively (Fig. 6b). As far as the threshold value of erosion zone

(2 km²) is concerned, it is noted that only one pocket of erosion along the left bank measuring more than 2 km² is noted and in the right bank there are two such pockets in the southernmost part of the study reach near

Fig. 6 **a** Amount of bank erosion and accretion along the left and right bank of the study reach of Hooghly river in different periods. **b** Rate of bank erosion and accretion along the left and right bank of the study reach of Hooghly river in different periods

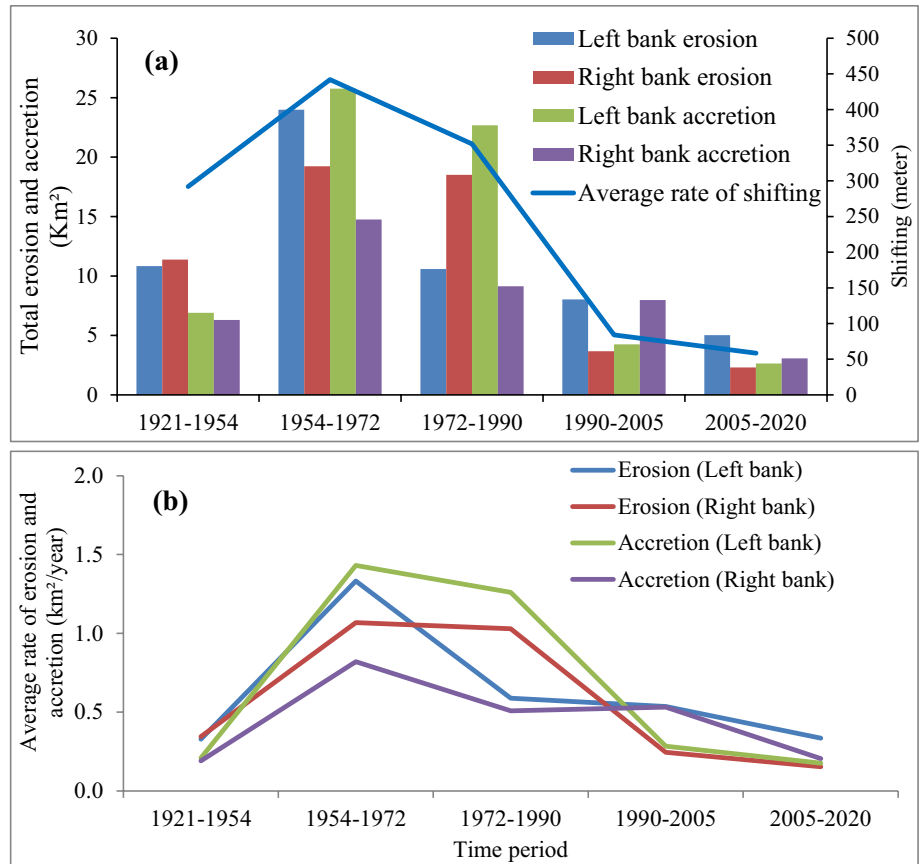


Table 2 Erosion zones in the left bank (north to south) of the study area in different periods

	Total erosion in km ² and average erosion in km ² /year				
	1921–1954	1954–1972	1972–1990	1990–2005	2005–2020
North to South	1.044	0.458	2.028	0.157	0.629
	0.023	4.165	0.803	0.572	0.130
	0.176	3.386	2.489	0.178	0.326
	0.079	0.322	0.318	0.225	0.184
	1.414	1.544	0.420	0.779	0.552
	1.702	0.909	1.233	0.236	0.160
	0.404	2.352	1.508	0.502	0.409
	0.319	1.392	1.785	0.644	0.201
	1.704	6.712		0.241	0.103
	3.965	2.744		1.476	0.068
				1.771	0.643
				1.096	0.790
				0.075	0.706
			0.074	0.121	
Total	10.831	23.984	10.584	8.028	5.023
Average	0.328	1.332	0.558	0.535	0.335

the Kunti-Hooghly confluence. The process of erosion in this area may be attributed to channel widening (Fig. 7a); while accretion zones are noted in the middle reach of the study area near Dhatrigram, Haripur (Fig. 8a). Erosional

and accretional processes along the channel are an outcome of channel migration and meander bend development along the different sections of the study reach.

Table 3 Erosion zones in the right bank (north to south) of the study area in different periods

	Total erosion in km ² and average erosion in km ² /year				
	1921–1954	1954–1972	1972–1990	1990–2005	2005–2020
North to South	0.304	3.150	5.050	0.969	0.053
	0.014	1.054	2.937	0.168	0.507
	0.161	5.156	2.275	0.015	0.188
	3.066	0.105	0.100	0.073	0.072
	1.212	0.065	0.294	0.127	0.208
	1.632	2.056	0.200	0.315	0.150
	0.070	0.925	3.972	0.054	0.084
	0.246	0.102	0.516	0.415	0.106
	4.672	5.286	0.631	0.030	0.318
		1.329	2.538	0.281	0.275
			1.223	0.345	
Total	11.375	19.227	18.512	3.670	2.306
Average	0.345	1.068	1.028	0.245	0.154

Table 4 Accretion zones in the left bank (north to south) of the study area in different periods

	Total accretion in km ² and average erosion in km ² /year				
	1921–1954	1954–1972	1972–1990	1990–2005	2005–2020
North to South	0.028	1.708	4.276	1.362	0.150
	0.038	0.196	2.590	0.110	0.207
	0.011	0.281	9.010	0.584	0.305
	0.015	0.133	0.124	0.716	0.295
	0.020	0.822	0.563	0.418	0.212
	3.773	0.240	3.545	0.341	0.198
	1.890	0.037	1.120	0.540	0.239
	0.068	0.465	1.445	0.086	0.268
	1.057	3.768		0.096	0.513
		0.375			0.254
	10.009				
	10.009				
	7.727				
Total	6.900	25.762	22.672	4.254	2.640
Average	0.209	1.431	1.260	0.284	0.176

Erosion and accretion dynamics during 1954–1972

In the previous period of observation, erosion was less in the left bank and more in the right bank. During this period of observation reversal of the situation is noted. Erosion in the left and right bank was increased by 121% and 69% respectively from the previous period (Fig. 6a, Tables 2, 3). In case of accretion, it was 273% and 134% increase in the left and right bank respectively from the previous period (Fig. 6a, Tables 4, 5).

Number of erosion pockets measuring more than 2 km² in both left and right banks increased during this period of observation in villages of Parmedia, Bankar Dhopadi, Krishnadebpur, Durgapur, Char Gournagar, Gosair Char located along the entire study reach (Fig. 7b). Accretion

zones along the right bank are also found along the entire stretch but zones of maximum accretion along the left bank were found only in the southern section of the study reach (Fig. 8b); implying thereby the process of erosion is spatially dominant. Increase in the areas under erosion and accretion in both the banks during this observation period is attributed to the development of meander bends and their lateral migration. A significant portion of this process in the southern section of the area is due to the cut-off at Srikrishnapur Char in Chakdah block of Nadia district.

Erosion and accretion dynamics during 1972–1990

In this observation period erosion rate in the left and right bank was decreased by 56% and 4% respectively from the

Table 5 Accretion zones in the right bank (north to south) of the study area in different periods

	Total accretion in km ² and average erosion in km ² /year				
	1921–1954	1954–1972	1972–1990	1990–2005	2005–2020
North to South	0.085	0.518	2.803	0.148	0.189
	0.201	2.161	1.001	0.530	0.369
	0.029	1.717	0.819	0.030	0.205
	0.106	0.959	0.564	0.369	0.271
	0.076	0.113	0.059	1.595	0.274
	0.028	1.541	0.137	0.146	0.233
	0.094	0.054	0.593	0.544	0.166
	0.142	2.300	0.808	0.035	0.122
	2.181	2.733	0.240	0.095	0.055
	0.039	2.662	2.118	0.627	0.150
	0.022			0.342	0.785
	0.792			0.104	0.148
	0.823			0.219	0.101
	1.090			2.086	
	0.591			1.108	
Total	6.297	14.757	9.140	7.977	3.070
Average	0.191	0.820	0.508	0.532	0.205

previous period (Fig. 6a, Tables 2, 3); the annual rates being 0.588 km² and 1.028 km² respectively (Fig. 6b). In case of accretion, it was 12% and 38% decrease in the left and right bank respectively from the previous period (Fig. 6a; Tables 4, 5).

Erosion zones measuring more than 2 km² area in both left and right banks were found in the same villages as in the previous period of observation (Parmedia, Bankar Dhopadi, Krishnadebpur) located along the entire stretch of the study area (Fig. 7c). Erosion zones measuring more than 2 km² are only two along the left bank while there are 5 such pockets along the right banks indicating higher erosion rates in the right bank. Maximum accretion in the left bank was found in the northern and middle parts of the study reach, while along right bank it is noted in the northern section alone (Fig. 8c). Lateral migration of the river towards the south-west in the northern section and towards the west in the southern section of the study area happens to be the principal cause of erosion and accretion.

Erosion and accretion dynamics during 1990–2005

Erosion and accretion in both left and right banks show a significant decrease in comparison to the previous two periods. Erosion in the left and right bank was decreased by 24% and 80% respectively from the previous period (Fig. 6a, Tables 2, 3); the annual rates being 0.535 km² and 0.245 km² respectively (Fig. 6b).

There was a significant increase in the number of erosion pockets in the left bank, but their areal extents were insignificant. In case of accretion, it was 81% and 13%

decrease in the left and right bank respectively from the previous period. The annual rate of accretion in the left and the right bank was 0.284 km² and 0.532 km² respectively (Fig. 6b; Tables 4, 5). Maximum erosion in the left and right banks was found in the southern section of the study reach (Fig. 7d). Maximum accretion in the left bank was found in the northern portion of the study reach, while maximum accretion in the right bank was found in the middle and southern section of the study reach (Fig. 8d).

Erosion and accretion dynamics during 2005–2020

The areal extensions as well as the rate of erosion and accretion in both the banks decreased in this period (Fig. 6a). Erosion was decreased by 37% in both left and right bank from the previous period. The annual rates being 0.335 km² and 0.154 km² respectively (Fig. 6b; Tables 2, 3). However, the numbers of erosion pockets have increased in the last two observation periods in both the left and right banks, but their areal extents were very insignificant (Fig. 7e). In case of accretion, it was 38% and 62% decrease in the left and right bank respectively from the previous period. The annual rate of erosion in the left and the right bank was 0.176 km² and 0.205 km² per annum respectively, (Fig. 8e; Tables 4, 5).

From the analysis of the spatial extent of erosion and accretion in the observed study periods, the following observations are noted. Left bank erosion is dominant in the southern portion of the study area while right bank erosion is dominant in the northern portion of the study area. Accretion in the left bank is dominant in the northern portion of the study area while accretion in the right bank is dominant

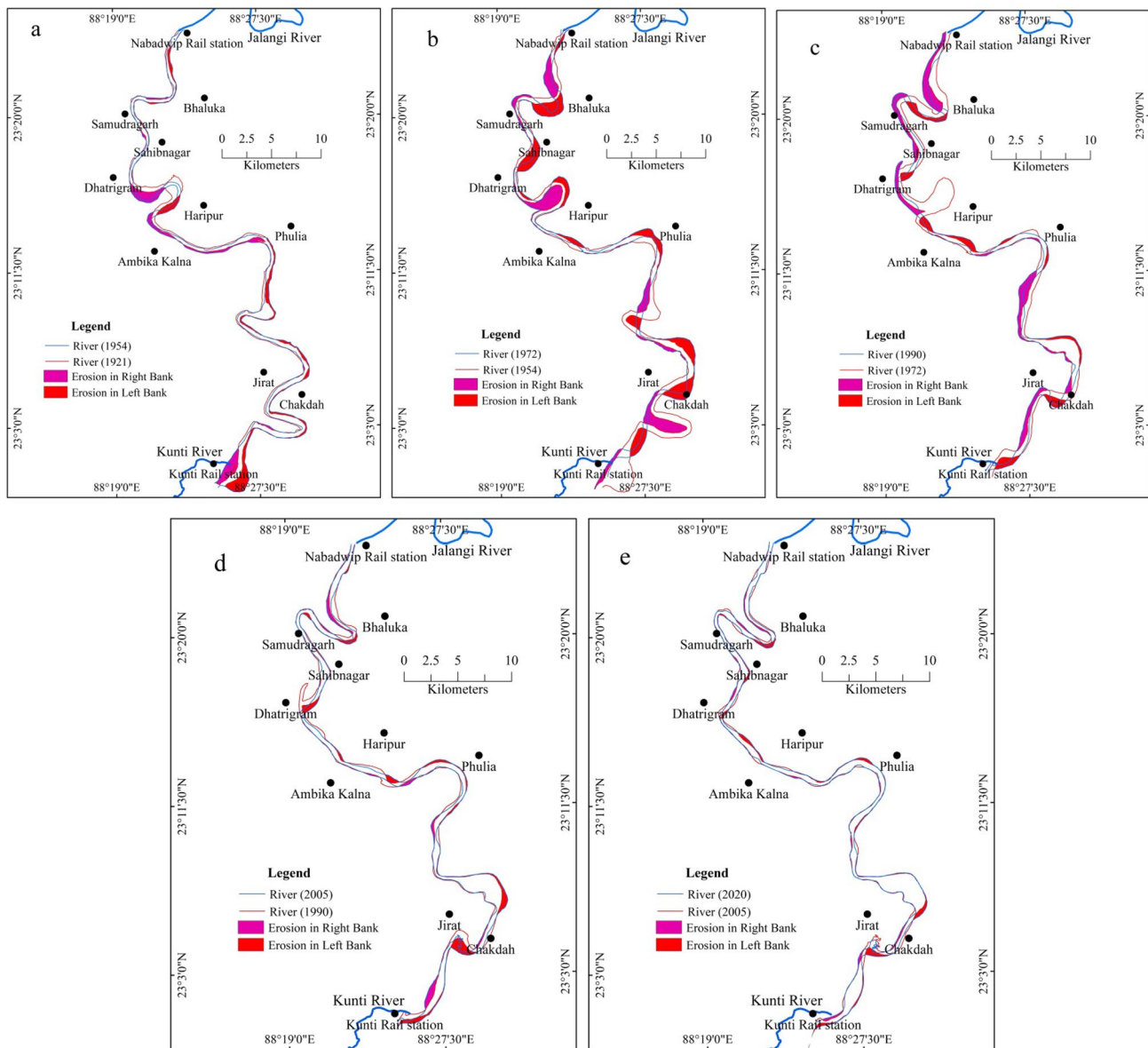


Fig. 7 Extent of erosion along the left and right bank of different study periods. **a** Land erosion during (1921–1954). **b** Land erosion during (1954–1972). **c** Land erosion during (1972–1990). **d** Land erosion during (1990–2005). **e** Land erosion during (2005–2020)

in the southern portion of the study area. The vulnerable areas of erosion in the left banks are Gram Kalna, Parmedia, Bankar Dhopadi, Krishnadebpur, Noasari Char, Char Jirat, Satkulia, Durgapur. On the other hand the vulnerable areas of erosion in the left banks are Char Jajira, Raninagar, Piari-nagar, Rasulpur Char, Char Gournagar, Mahisunra, Gosair Char, Gournagar (Table 6).

Villages vulnerable to erosion during 1954–1972 and 1972–1990

The trend of recurrence of erosion is also reflected in the recurrence of bank lines shifts because the villages with

recurrence of bank erosion in both banks correspond to the cross-sections having maximum bank line shifting (Fig. 6a). Area under erosion and accretion is higher in the second and third observation periods (1954–1972 and 1972–1990) compared to the other observation periods.

Channel centerline shift using LR model and assessment of future hazard zones

Prediction of channel centerline will help to plan and draw judicious management of erosion hazard. Linear regression is widely used to describe the relationship of a continuous outcome measure to one or more explanatory or predictor

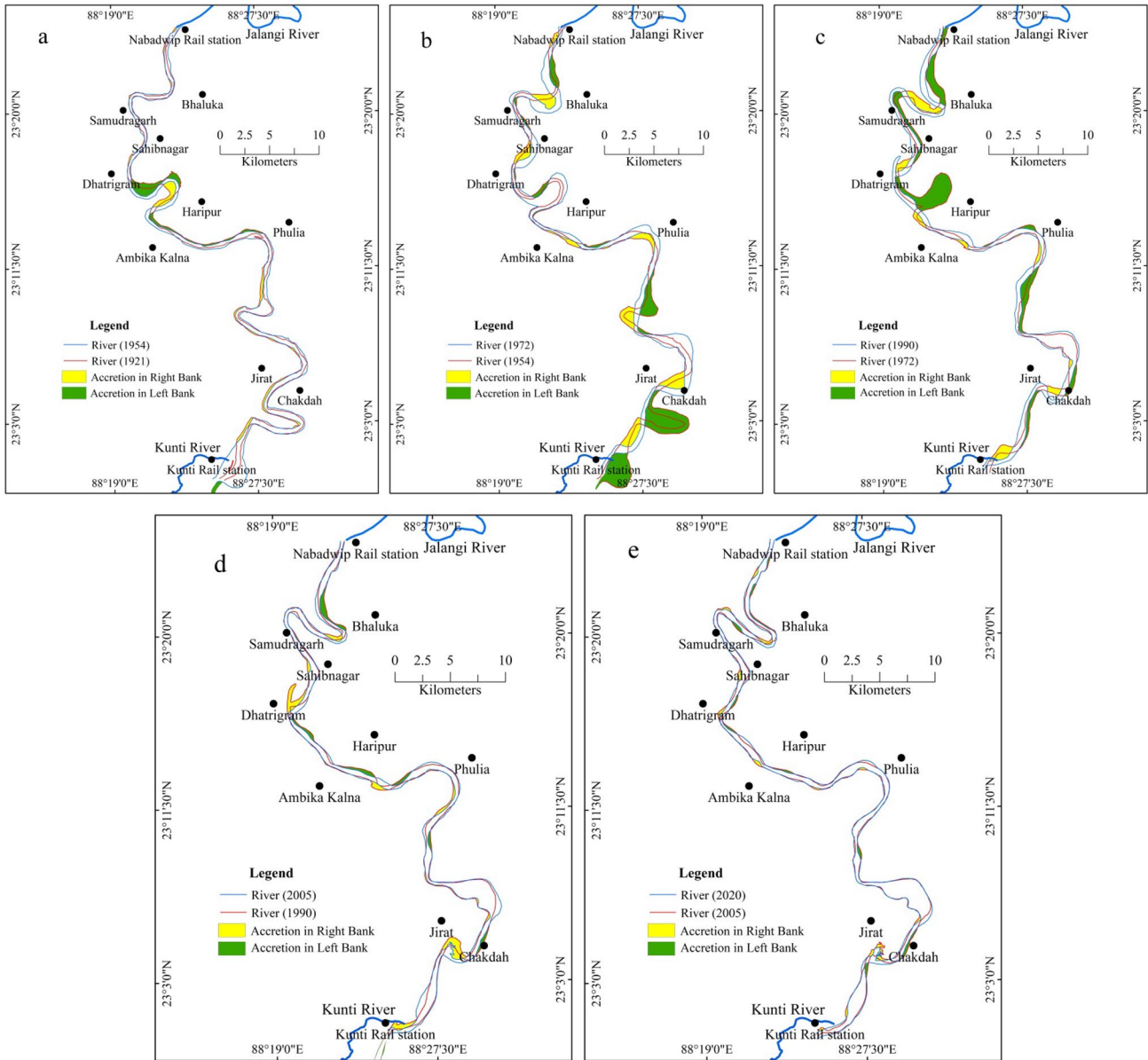


Fig. 8 Extent of accretion along the left and right bank of different study periods. **a** Land accretion during (1921–1954). **b** Land accretion during (1954–1972). **c** Land accretion during (1972–1990). **d** Land accretion during (1990–2005). **e** Land accretion during (2005–2020)

Table 6 Villages vulnerable to erosion during 1954–1972 and 1972–1990

Recurrence of erosion in areas measuring > 2 km ²	Left bank villages	Right bank villages
3	Gram Kalna, Parmedia, Bankar Dhopadi, Krishnadebpur, Naosari Char	Char Jajira, Rani-nagar, Piarinagar, Rasulpur Char
2	Char Jirat, Satkulia, Durgapur	Char Gournagar, Mahisunra, Gosair Char, Gournagar

measure (Boscardin 2010). This is a modeling technique to predict a dependent variable from one or more independent variables (Kumari and Yadav 2018). Deb and Ferreira (2014) and Bag et al. (2019) have assessed different cross-sectional position of the midline of river using linear regression model for the estimation of future erosion and accretion zones at different critical areas. All the rivers of deltaic plains do not maintain a linear pattern of shifting; the river under consideration is not an exception. From the assessment, it is observed that in 50% of the cross-sections (A–B, C–D, G–H in the northern portion), O–P, (Q–R, S–T and U–V in the southern portion) have a linear trend of river centerline shift with high r^2 values (> 0.8) (Table 7). Cross-sections E–F, I–J, M–N have moderate regression values and other cross-sections have low regression values showing moderate to low linear shifting trends. Because of this the future trends along these cross sections is difficult to predict and hence have not been taken into consideration. Here, with the help of the linear regression method, the predicted values for the years 2030 and 2050 were calculated for the cross-sections with high regression values and mapped in the GIS environment (Fig. 9). The reason behind this mapping is to find out the future vulnerable areas in the study reach and make a plan for the lives of the people living near the bank line for their safety and sustainability. The green points represent the predicted river centerline in 2030 and the red points represent the river centerline in 2050.

The predicted descending order of the maximum shift of centerline towards the left is along the cross sections U–V (Char Jirat), S–T (Shibpur, Ghol Nadia, Parniamatpur in Ranaghat block) and O–P (Malipota, Phulia, Pumlia in Santipur block). Along the right bank the descending order of the maximum shift is along cross sections A–B (Chak Rahatpur), Q–R (Arazi Guptipara, Char Sundalpur, Abdulpur in Balagarh block), C–D (Samudragarh, Jalahati, Jaluidanga in Purbasthali block) and G–H (Krishanadebpur, Dhatrigram, Mirzabati, Bhabanipur in Kalna-I block). The range of shift along the left bank is 674 m and along the right bank it is 403 m. Comparison of the contemporary

erosion vulnerable zones and the predicted vulnerable zones show that only two of the present vulnerable zones (Char Jirat and Krishnadebpur) will continue to vulnerable in 2030 and 2050. The remaining erosion zones will not be vulnerable to erosion in future. The aforesaid region will experience river bank erosion hazards in the near future. With the help of the future assessment of erosion-prone areas, plans should be taken to overcome the situation in these areas.

Impact of changing hydrological regime on channel dynamics

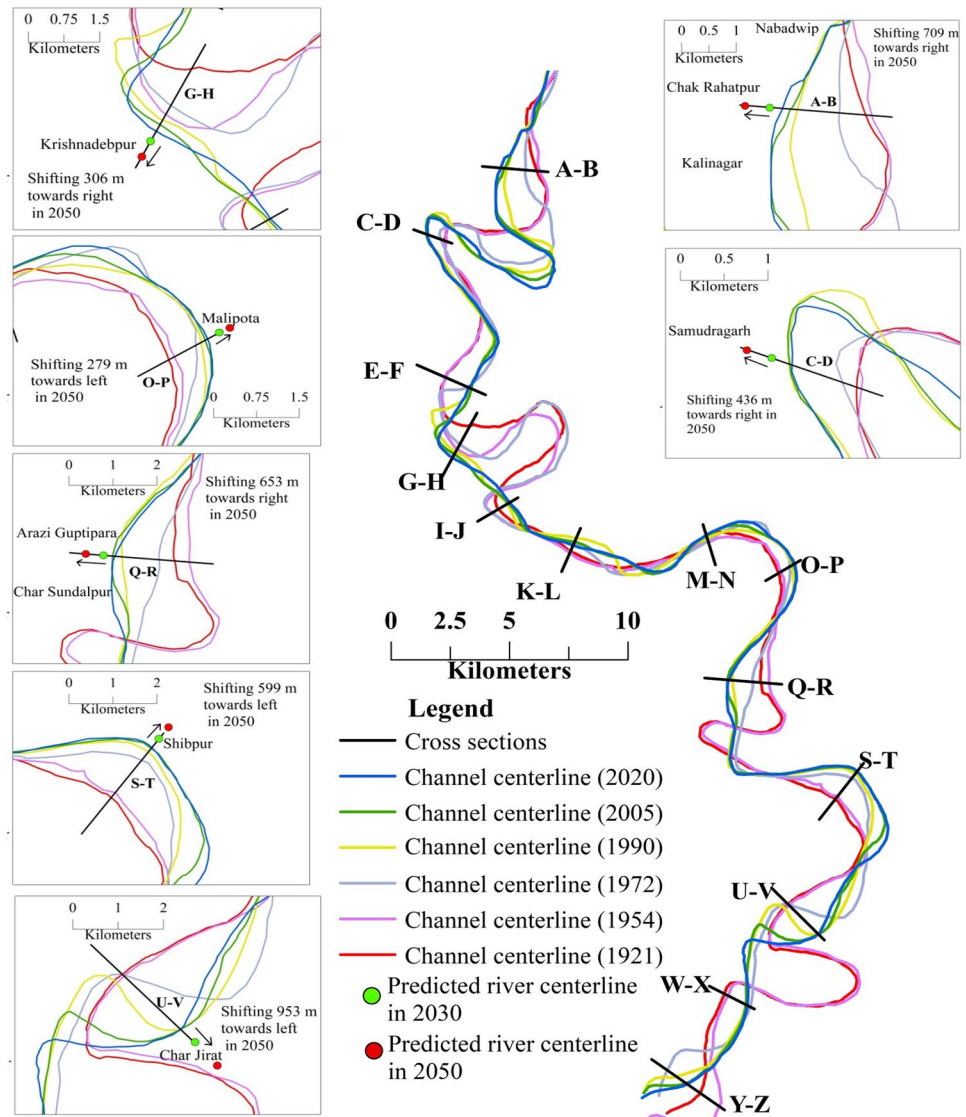
Variation in the hydrological regime plays an important role in changing the channel characteristics of any river. Various researchers have analysed the role of controlled hydrology over the changing channel dynamics and meander geometry (Gadgil and Guha 1994; Friedman et al. 1998; Nilsson 2005; Marren et al. 2014). From 1905 to 1913, there was very little discharge in Jangipur, Berhampore and Katwa gauge stations, but the discharge increases in the monsoon period in all these stations (Table 8) (Hirst 1915).

Before Farakka Barrage Project, the amount of discharge was not so devastating. From 1915 to 1972, the average minimum and maximum discharges were 9.24 cumec and 1718.62 cumec, respectively (Table 9). The maximum and minimum water level in that period also shows a slightly decreasing trend. From 1973 to 1985, the maximum discharge rate of the station Jangipur, Berhampore and Purbasthali has been shown (Fig. 10). Here, the maximum discharge after construction was not significantly increased. It remains constant for the station Jangipur, Berhampore and Purbasthali gauge stations, but the discharge rate of Purbasthali was always high compared to other stations. The maximum discharge scenario of all the gauge stations does not depict Farakka Barrage's impact over the hydrological regime, but a substantial increase in average discharge for all these gauge stations portrays the increasing lean period discharge in Bhagirathi (Islam and Guchhait 2017). On average, before the Farakka Barrage

Table 7 Cross-section wise centerline prediction by linear regression analysis, positive values (+) indicates left ward shifting and negative values (–) indicates right ward shifting, shifting values represents in meter

Cross section	Centerline shifting (Base year 1921)					Predicted Shifting for the year 2020	Prediction		R^2
	1954	1972	1990	2005	2020		2030	2050	
A–B	91.36	–348.65	–874.22	–1125.27	–1510.12	–1538.33	–1764.34	–2247.57	0.99
C–D	41.28	–134.45	–422.49	–695.45	–877.85	–880.98	–1024.29	–1314.48	0.99
G–H	–1006.85	–903.2	–1324.96	–1456.55	–1617.32	–1582.31	–1709.36	–1923.52	0.87
O–P	221.12	546.15	678.07	701.83	923.74	907.80	1012.089	1202.48	0.93
Q–R	142.23	–362.15	–785.39	–947.66	–1356.84	–1352.80	–1573.07	–2009.01	0.98
S–T	182.56	687.12	748.41	1311.12	1538.37	1527.07	1734.774	2137.30	0.95
U–V	68.36	11.57	341.4	1824.15	1837.4	1825.62	2151.765	2790.61	0.80

Fig. 9 The future position of centerline of Hooghly river in 2030 and 2050 at the selected cross-sections



Period, the discharge's inconsistency primarily depended on the monsoon rainfall and discharge was seasonal. Parua (2009) indicated that after Farakka Barrage's commissioning, the water dispute between India and Bangladesh emerged. The water-sharing treaties in 1977 and 1996 triggered the variable discharge in India and Bangladesh on a 10-day scale from January to May, mainly from March to May (Parua 2009). The increasing average discharge after the Farakka Barrage Project significantly indicates the high lean period discharge. It has increased the bank erosion by piping actions triggered by pore water movement inside the bank following a high flow event. In the pre-Farakka period, the low water level could not reach the piping level in the dry season. Still, after the Farakka Barrage period, water level fluctuation triggered the piping actions (Islam and Guchhait 2017). The increased lean period discharge from the feeder canal after FBP also plays

a vital role in meander bend development, channel oscillation, and overall channel dynamics.

Conclusion

The study has analysed the changing nature of bank line shifting, lateral migration and erosion accretion dynamics of the upper reach of the Hooghly river for the last 100 years using remote sensing and GIS techniques. The study shows that the river has experienced lateral migration and channel shifting in the study reach affecting the livelihood of the riparian communities severely. Alluvial rivers change their channel morphology easily to adjust themselves and the Hooghly river in this reach proves the phenomena firmly as the river has passed through a series of erosion and accretion by lateral migration. Incidents

Table 8 Average discharge (cumec) through Bhagirathi in pre-Farakka period (1905–1913) at Jangipur, Berhampore and Katwa gauge stations

Year	Month	Date	Jangipur (Entrance)	Berhampore	Katwa
1905	February	1st to 15th	–	30.98	58.62
	August	16th to 31st	3952.75	–	4607.29
1906	February	10 to 15th	–	–	54.57
	September	16th to 30th	518.85	–	1933.22
1907	February	1st to 15th	–	–	22.68
	September	1st to 15th	1071.65	–	1088.98
1908	March	1st to 15th	2.49	–	556.43
	August	–	–	–	–
1909	February	16th to 28th	2.07	11.36	25.4
	August	16th to 31st	–	2791.39	–
1910	March	1st to 15th	2.41	7.65	26.82
	August	–	–	–	–
1911	February	1st to 15th	117.94	44.83	–
	August	16th to 31st	1617.85	–	4320.44
1912	February	1st to 15th	8.13	–	13.25
	August	16th to 31st	1236.4	–	–
1913	February	16th to 23rd	4.64	9.51	18.01
	August	–	–	30.98	58.62

Source: Hirst (1915)

Table 9 Water level and discharge through Bhagirathi at Jangipur

Year	Minimum water level (m)	Discharge (cumec)	Maximum water level (m)	Discharge (cumec)	Time span (days)
1915	15.05	3.1	21.4	2554	190
1920	16.86	5.8	20.7	1892	150
1926	14.42	3.6	19.96	1317	175
1930	14.92	13.3	21.26	2109	170
1935	14.94	1.6	21.43	2053	138
1940	14.88	4.6	20.69	2006	165
1945	15.1	25	21.22	1572	178
1950	15	20.1	20.86	1927	136
1955	14.39	18.2	20.97	1472	191
1960	14.73	17.1	20.85	1773	156
1965	13.52	1.1	19.18	1409	142
1970	14.48	3.7	19.45	1306	122
1972	14.63	2.9	18.91	952	84
Average		9.24		1718.62	

Source: Parua (2009)

of erosion and accretion in the concave and convex bank play a crucial role in the floodplain alluvial river channel development. The analysis results indicate that the amount of erosion and accretion in left and right banks go hand in hand. In this reach, maximum erosion and accretion were observed in the second study phase (1954–1972) while the minimum erosion and accretion were observed in the final study phase (2005–2020). The overall sinuosity was gradually decreased from 1.95 in 1921 to 1.87 in 2020.

The channel centerline migrates linearly in most cross sections in the total study period, and around 50% cross sections show a highly linear migration trend. The prediction of the centerline for the year 2030 and 2050 using linear regression method identify the future vulnerable zones in the study area. The overall channel migration of the upper reach of the Hooghly river indicates the oscillatory nature of the river channel. The analysis will be helpful for the identification and mapping of future vulnerable areas in

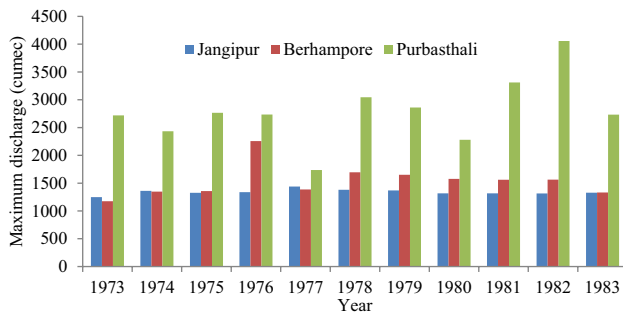


Fig. 10 Maximum discharge (Cumec) at Jangipur, Berhampore and Purbasthali gauge stations from 1973 to 1985

the study reach and make a plan for the lives of the people living near the bank line for their safety and sustainability.

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Availability of data and material Topographical sheets are available in the website of Army map service. Satellite imageries of different periods used for change analysis were downloaded from USGS Earth Explorer website. Data from other sources have been described appropriately.

Code of availability Not applicable.

Declarations

Conflict of interest Authors declare that there is no such conflict of interest regarding the results and data. We also disclose that all the ethical standards have been maintained for this research.

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