ORIGINAL PAPER

Channel bar development and bankline migration of the Lower Padma River of Bangladesh

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Abstract

Bankline migration and erosion of banks are very common phenomenon in the Lower Padma River (LPR) of Bangladesh. Therefore, the current research focus on studies addressing issues about channel bar development; the interrelationship among number of bars, bars area, river width, braiding, and sinuosity indices; and its relation to bankline shifting using remote sensing (RS) and GIS techniques. Multi-dated Landsat images of 1977, 1989, 1999, 2014, and 2017 were taken into consideration for the research. The results reveal that the river area and the width of the river have been gradually increased at a rate of about 7.81 km^2 and 0.083 km per year, respectively, over the past 40 years. Contrary, the water area has been gradually decreased at a rate of about 1.66 km^2 $year^{-1}$. This is because the channel bar area of the LPR was gradually increasing as a result of bar formation, which is about 9.47 km^2 $year^{-1}$. About 192.73 km^2 and 327.70 km^2 lands eroded on the left and right banks, respectively, at a rate of 4.82 km^2 and 8.19 km^2 $year^{-1}$. In the past, the LPR course was less braided. But now it has become more braided due to the formation of many new bars within the river course. It is assumed that these factors intensified the bank erosion. Moreover, erosion rates have not always been the same on both banks and affected different parts of both banks of the river due to the different braiding intensities. The area of river, where more bars are present, creates more braiding, more sinuous, and finally causes severe erosion. Additionally, the bank sediments of the LPR are dominantly silty sand (loosely compact) and easily subjected to erosion. Moreover during monsoon huge water flows from the upstream naturally exert an additional effect on the bank. In summary, these random phenomena have changed the morphology of the LPR.

Keywords Padma River · Channel Bar development · Braiding · Bankline migration · Sustainable development

Introduction

The Ganges is one of the major and dynamic rivers in the world originating in the Gangotri glacier of the Himalayan (Hossain et al. 2005). The river is named Padma where it enters Bangladesh territory (Fig. 1). The river traverses through India nearly 2150 km (km) and in Bangladesh is nearly 366 km (Hossain et al. 2005). In Bangladesh the Padma River is joined by the mighty Jamuna (Lower Brahmaputra) near Rajbari and meets with the Meghna at

Chandpur (Allison 1998). The Padma–Meghna–Jamuna river systems supply every year about 1.2 billion tons of sediments from Himalaya and distribute this within the Bangladesh delta (Kudrass et al. 1998). Coleman 1969) also mentioned that every year about 2.5 billion tons of sediments are discharged by these river systems in Bangladesh. This high sediment discharge naturally exerts an effect on the sedimentation rates in the rivers (Anon 2014; Anon 2015; Khan 2015). The Padma River left the signature of its dynamism in the sur- roundings of the present course. Over time the river changes course with bank erosion and leaves the sediments in the older course. Due to bank erosion and shifting, neighboring com- munities and individuals had to relocate to new areas every few years as they lose their properties (Elahi et al. 1991; IRIN 2008; Islam and Rashid 2011). Some people have had to mi- grate several times. For instance, in the year 2018 there were significant river bank erosion of this river at Naria Upazilla, Sariatpur District (Ahamad 2018; Rahman 2018; Roy 2018;

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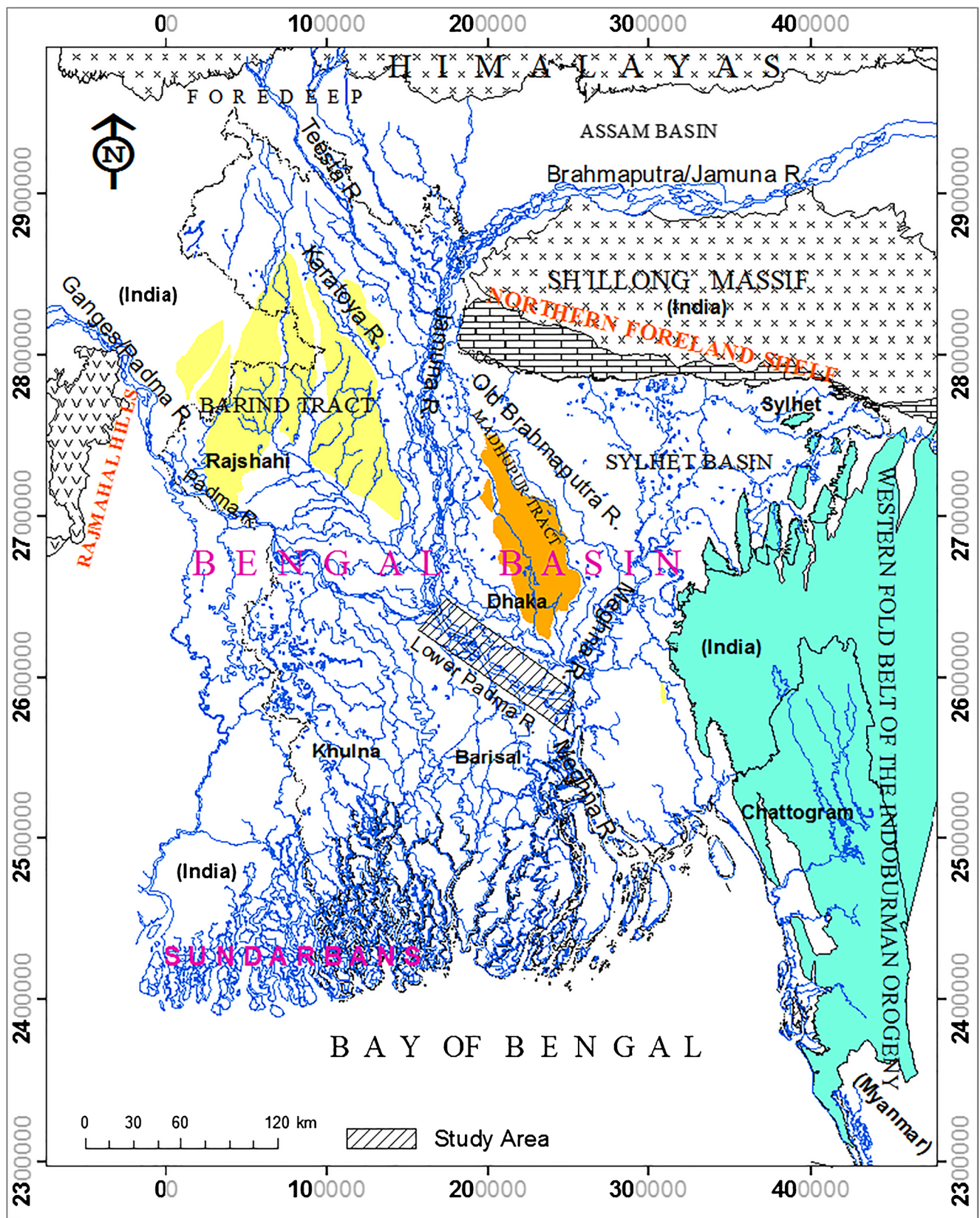
Fig. 1 Map representing the major physiographic provinces of the Bengal Basin, drainage system, and location of the study area

Fig. 2 Erosion by the River Padma and washing away (Ahamad 2018) **a** concrete structures at Naria. Erosion by the River Padma and washing away (Roy 2018) **b** a three-storey building at Naria. Erosion by the River Padma and washing away (Rahman 2018) **c** Naria Upazila Health Complex building. **d** Commercially important Mulfatganj Bazar. **e** Bangladesh Water Development Board is dumping sandbags along the bank of the Padma to prevent erosion at Mulfatganj Bazar. **f** Locals form a human chain demanding effective steps to protect the Naria from erosion

Fig. 2). More than 5000 families, about 300 business offices in the 200-year-old Mulfotganj Bazar, two government primary schools, 10 mosques, several temples including 100-year old Das Para Ram Mandir, a part of the Naria upazila health complex, a school for special children, and the Naria-Kederpur Road were all devoured by river bank erosion (Ahamad 2018; Rahman 2018; Roy 2018). Proper land use planning taking into account local geo-information from the menace of erosion and depositional behavior of the river would save lives and property insuring the development of people in the area and creating a positive impact for the national economy of Bangladesh. This requires an interdisciplinary approach linking engineers, earth scientists, and social scientists concerned with environmental economics, planning, and societal and political strategies, in order to fully evaluate the economic and social validity of different options for different timescales. Remote sensing (RS) and GIS techniques have been used to study channel characteristics and planform dynamics of different rivers in different parts of the world (Yang et al. 1999; Li et al. 2007; Das et al. 2007; Gao et al. 2013; Midha and Mathur 2014; Langat et al. 2019; Quanwen et al. 2019). Keeping in views its distinct advantages, the present study used remotely sensed data to prepare various derivatives maps and to find out the characteristics of the Lower Padma River (LPR) in Bangladesh (Fig. 1). Several studies have also used these techniques to study channel change, bank migration, and morpho-dynamics of the Padma and Jamuna rivers in Bangladesh (Rahman and Alam 1980; Ashworth et al. 2000; Yeasmin and Islam 2011; Gan and Baki 2012; Gan et al. 2013; Laha and Bandyapadhyay 2013; Mount et al. 2013; Sarker et al. 2014; Dewan et al. 2017; Ety and Rashid 2017; Sarma and Acharjee 2018). Previous research on the Padma River focused on bar area expansion, river bank erosion, its impact, changing morphometry, and vulnerability analysis (Rahman and Alam 1980; Islam and Rashid 2011; Yeasmin and Islam 2011; Gan and Baki 2012; Gupta 2012; Gan et al. 2013; Laha and Bandyapadhyay 2013; Rahman 2013; Das et al. 2014; Ety and Rashid 2017; Dewan et al. 2017; Nawfee et al. 2018; Anon 2018; Saleem et al. 2019). There is still little effort on studies addressing issues about channel bar

development; the interrelationship among number of bars, bars area, river width, braiding, and sinuosity index; and its relation to bankline shifting by using RS and GIS techniques. Therefore, the present research takes an initiative to study these object of the LPR and its relation to bankline shifting by using RS and GIS. This research will help to understand

the river characteristics and future protective plan for sustainable development of the area.

Regional setting

The Bengal Basin occupies a major part of Bangladesh, West Bengal of India, and the off-shore part of the Bay of Bengal. Structurally, it is bounded to the west by the Rajmahal Hills; to the east by the Western Fold Belt of the Indo-Burman Orogeny; to the north by the Himalayan Foredeep, the Shillong Massif, and the Assam Basin; and is open in the south of the Bay of Bengal (Morgan and McIntire 1959; Guha 1978; Khandoker 1989; Alam et al. 1990; Reimann 1993; Nandy 2001; Khan 2002; Fig. 1). The Bengal Basin was formed during the early Tertiary period as the Indian Plate broke away from the Gondwanaland in the Late Cretaceous and moved toward the north and collided with the Eurasian Plate and subsequently with the western part of the Burmese Sub-plate. Drifting of Indian Plate during Late Cretaceous-Late Eocene (Curray and Moore 1974a, b) and collision with Eurasia and Burma raised extensive Himalayan and Indo-Burmese Ranges with the formation of the Bengal Basin. The tectonic activity of the basin has influenced reverine sediment distribution of all parts of the margin. Tectonically, the LPR area falls under Faridpur Trough tectonic element of the Bengal Basin (Alam 1972; Guha 1978; Khandoker 1989; Reimann 1993). The area experiences a humid tropical monsoon climate. Monsoon starts in June and lasts up to October. The winter season begins at the end of November and continues until late February. The summer season prevails between March and May. The Padma River is a relatively young that formed approximately 200 years ago (FAP 4 1993). Initially, it maintained its course through the Ganges along the Arial Khan River but, during a major avulsion between 1830 and 1857, it broke through the Chandina Alluvium to join the Meghna near Chandpur (FAP 16 1995). The total catchment area of the river is 1.7 million km^2 and includes the combined catchments of the Ganges and Brahmaputra (Nippon Koei Co. Ltd. 2005).

Materials and methods

Data acquisition and preparation

Multi-dated Landsat images representing of 1977, 1989, 1999, 2014, and 2017 were collected from the website http://glovis.usgs.gov covering the dry period (winter season/post monsoon) and used for this study (Table 1). Imagery collected during dry period is suitable for analysis, i.e., land-water boundary, channel bar statistics, braiding, and sinuosity indices, as it is a common practice in previous works (Gan et al. 2013; Rozo et al. 2014). However, the variation of temporal range among the considered periods happened because of unavailability of cloud-free images at regular intervals. Resolutions of images are 60 m (m), 30 m, 30 m, and 30 m, respectively. It is worthy to state that Landsat multispectral scanner (MSS) data from 1977 with a spatial resolution of 60 m was resampled to 30 m using the nearest neighbor technique by Erdas imagine 2010 in order to match the spatial resolution of Landsat TM/ETM+/OLI data of 30 m resolution. All the images were georeferenced in WGS 84 UTM Zone 45°N and 46°N projection system. Required processing of images like layer stack, mosaic, image enhancement, and geoprocessing was done in Erdas imagine 2010 and Arcmap 10.

Delineating river course, erosion, deposition, bankline, and channel bars

The visual image interpretation was carried out using indicative and deductive analysis of various image elements (tone, texture, pattern, shape, size, and terrain elements like landform, drainage, erosion, and landuse) (Agarwal and Garg 2000) to delineate the LPR course, its erosional and depositional pattern, channel bar development, and bankline shifting, as it is viewed as a standard practice in previous works (Agarwal and Garg 2000; Islam et al. 2011; Rashid et al. 2015a; Rashid et al. 2015b; Alam and Islam 2017; Rashid et al. 2018a; Rashid et al. 2018b). Demarking the

Table 1 Landsat imagery used in this work

Satellite aensor	Year	Date	Frame	No. of band	Data type
MSS	1977	February 8, 1977	147/44	3	Ver1.0
		February 9, 1977	148/43		
		February 9, 1977	148/44		
TM	1989	November 11, 1989	138/43	4	Ver1.0
			138/44		
ETM+	1999	November 24, 1999	137/44	7	L1G
L8 OLI TIRS	2014	January 25, 2014	137/44	11	L1T
L8 OLI TIRS	2017	February 19, 2017	137/44	11	L1T

land-water boundary using Landsat image is a challenging task. To overcome this situation, a combination of different Landsat bands (Yang et al. 1999) and a soil-vegetation limit approach (Gurnell 1997) were employed to identify the land-water boundary. Previous studies (Winterbottom 2000; Yang et al. 1999) suggest that these approaches are highly effective to distinguish river planform, resulting from varying water levels within a channel. The channel bars were identified based on its contrasting tone with the dark river, its shape, and its association with the river. The banks of the river were identified based on its contrasting tone with the dark river. A *river bank* is the land along the edge of a *river*. Arcmap 10 was used for digitizing the images. Point mode method was used to digitize.

Determination of river morphology, erosional and depositional pattern, bankline shifting, and bar characteristics

Arcmap 10 was used for erosional and depositional pattern, channel bar development, and bankline shifting analysis. Assessment of erosion and deposition of both banks, polygons of two particular years were taken (superimposing) using the union method of Analysis tool. Channel bar development, its statistics, width of the river at different times, and statistics of the bankline shifting were calculated by using Microsoft Office Excel 2007 and Arcmap 10. The channel bar formation and the changing characteristics of the bars of the LPR were analyzed by using the standard deviation (SD) values of the bars at different times (Table 2; Fig. 4). The braiding intensity of the LPR was calculated by using Germanoski and Schumm (1993) braiding index and, Hong and Davies (1979) channel length sinuosity indices. These indices are widely accepted throughout the world in case of morphological characterization for any river (Egozi and Ashmore 2008). Along with the whole LPR, the river was also divided into five segments (Fig. 3e) and the braiding and sinuosity index of these segments calculated. Statistical analysis was performed for the river among number of bars (N_b), average widths, braiding index (BI), and sinuosity index (P_T) of the river along with different segments using SPSS version 20. Pearson correlation matrix was selected for the mutual relationship and association analysis in order to identify the degree of association of different parameters (Stigler 1989) . The channel widths from both banks of this river at different times of different cross sections were measured perpendicular to the two banklines at the same fixed geographical points by using the measure tool in Arcmap 10, as it is viewed as a standard practice in previous works (Ety and Rashid 2017). Seven cross sections were drawn in different parts of the river course (Fig. 8). The river width's standard deviations (SD) were calculated for different times on the basis of river widths at different cross sections (Table 10). The river center points from both banks of this river at different times of different cross sections were pointed out perpendicular to the two banklines at the same fixed geographical points by using the line construction tool in Arcmap 10 (Fig. 8). On the basis of these center points, river center lines at different times were drawn (Fig. 8) to delineate the shifting of center lines of the river to both banks at different times.

Results and discussion

Channel bar formation of the river

Channel bars are located within the stream courses and composed of loose coarser-grained lag deposits with fines at top (Reineck and Singh 1980). Sometimes it may be covered by vegetation. Many channel bars exist in the LPR channel. Many of them are only exposed during the late winter and summer, particularly small and new channel bars. Normally, the older and larger channels bars are always exposed. The bars are elongated, semi-circular, and pointed down-stream. Bar areas range from 1 to 150 km^2 in size. Every year new bars are formed in the channels of the LPR due to upstream sedimentation. The satellite images of different years reveal that many bars have shifted or changed their position, modified their shape, or are completely removed by erosion (Figs. 3 and 5). In this research the channel bar formation and the changing characteristics of the bars of the river were analyzed by using the SD values of the bars at different times (Table 2; Fig. 4). In statistics, SD is a measure that is used to quantify the amount of variation or dispersion of a set of data values (Mitchell 2005). A standard deviation close to 0 indicates that

Table 2 Channel and bar statistics of the Lower Padma River from 1977 to 2017

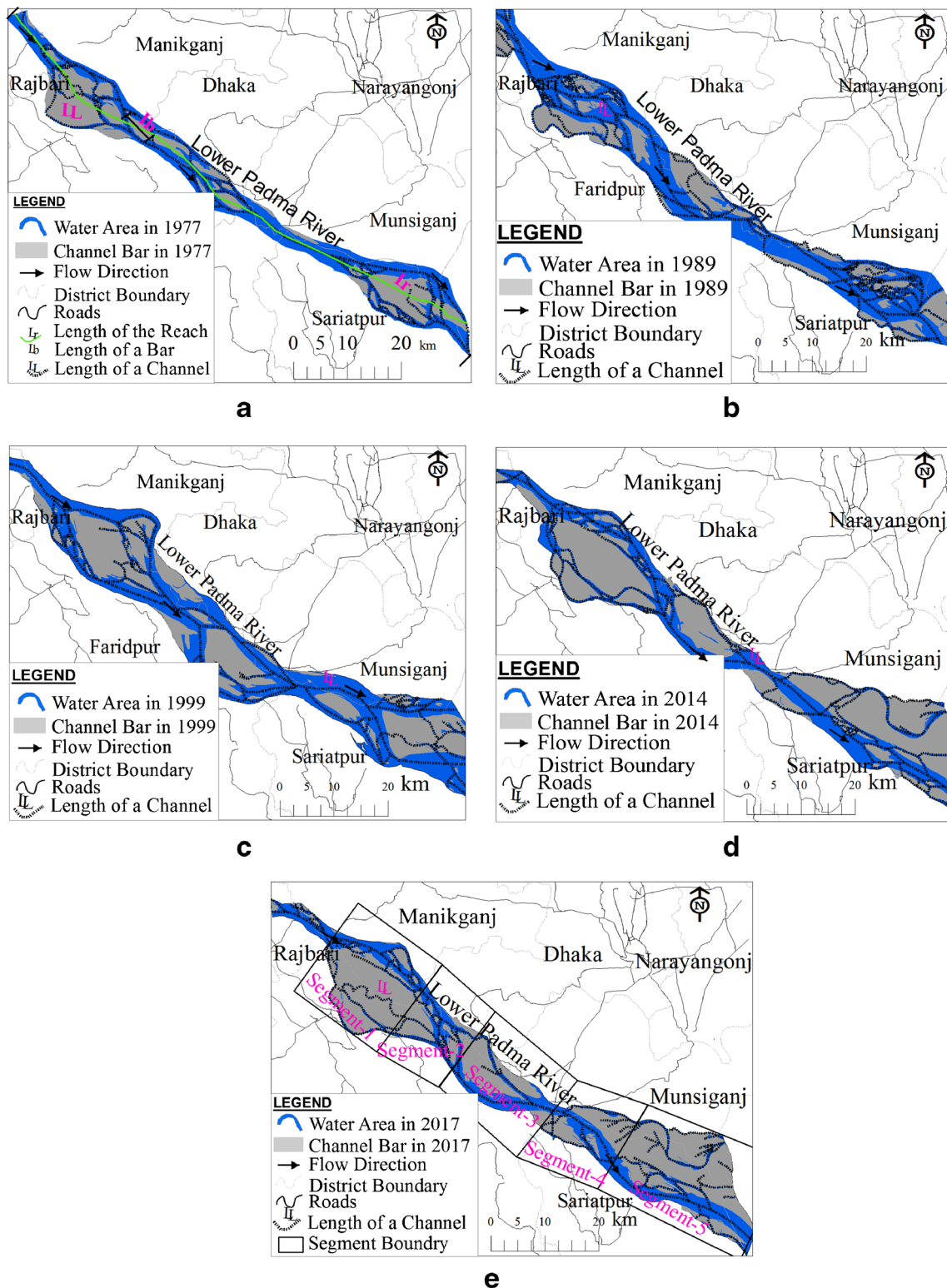| Year	Total bar	Bar area (km^2)	Bar mean area (km^2)	Bars standard deviation (STD)	River area (km^2)	Largest bar area (km^2)	Water area (km^2)
1977	45	250	5.55	10.86	630	59	380
1989	123	288	2.34	6.74	877	46	589
1999	64	413	6.45	14.44	1008	82	595
2014	103	572	5.55	17.76	976	123	404
2017	64	609	9.52	29.36	985	176	376

Fig. 3 River and channel bars at different times **a** 1977, **b** 1989, **c** 1999, **d** 2014, and **e** 2017

the data points tend to be very close to the mean (also called the expected value) of the set, while a high standard deviation indicates that the data points are spread out over a wider range

of values (Mitchell 2005). In the current research the river area indicates the river total area, which includes bar area and water area (water area indicates the area occupied by water). Two

Fig. 4 Statistical result of channel bar development of the Lower Padma River from 1977 to 2017: **a** River area, **b** water area, **c** number of bars, **d** bar area, **e** bar mean area, **f** bar standard deviation, and **g** largest bar area
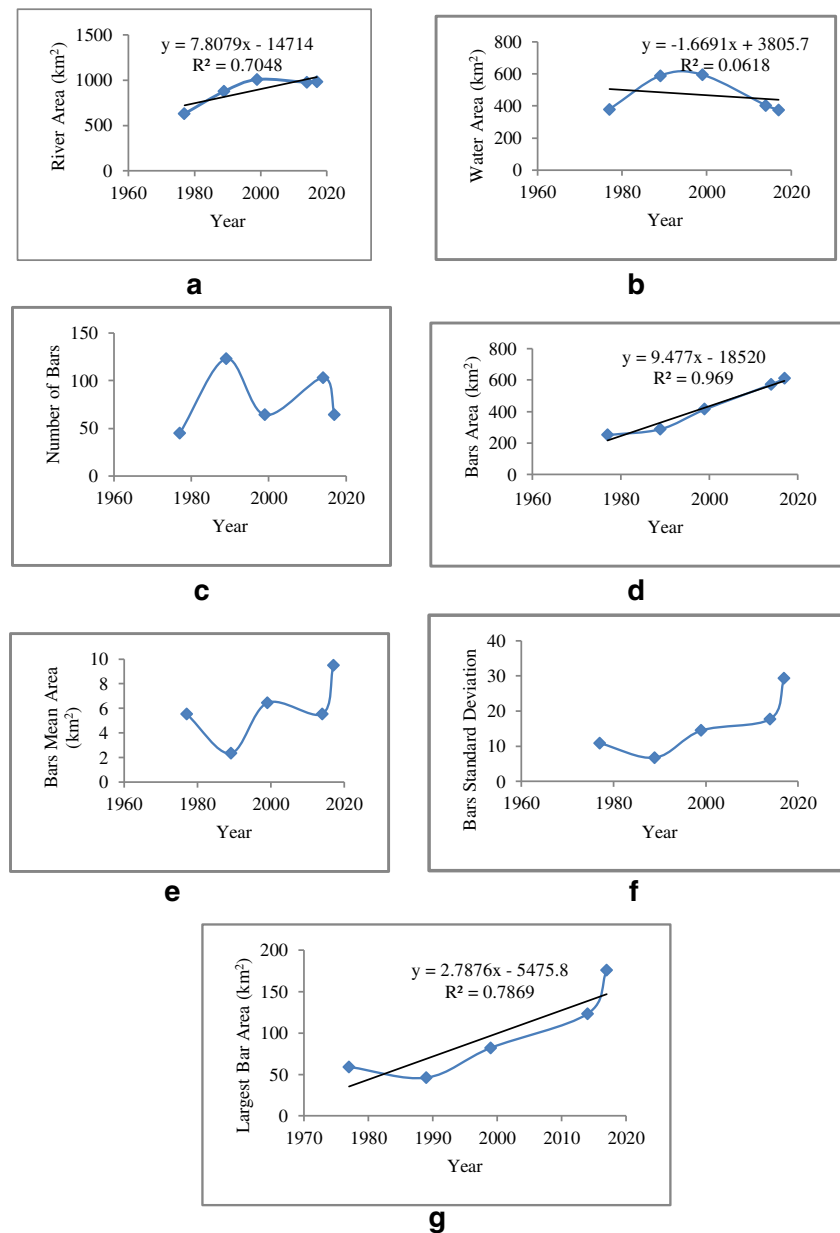

types of bars are distinguished here: small bar and large bar. Small bars are relatively small in size (area near to or less than the bars mean area), whereas a large bar occupied an area that deviated from bar mean area or larger than the bar mean area.

The numbers of bars of the LPR were increased from 1977 to 1989, while the mean area of bars and standard deviation were decreased. This likely owes to the 1988 major flood event (Dewan et al. 2003) in the area, which cause severe erosion of the existing bars and simultaneously formed numerous bars in the channel. Consequently, it decreased the mean area of the existing bars. The differences among the number of large bars and small bars were also decreased. The value of standard deviation indicates the same view. In 1999 the number of bars decreased, while the mean area of

the bars increased. It indicates that many small bars were joined together and transformed to large bars by additional sedimentation in the channels every year and many small bars also destroyed by erosion. The standard deviation of the bars was also increased but the increasing rate was remarkably high. Similar phenomenon was also noticed in 2017. Correspondingly, many small bars were also destroyed by erosion. Reciprocal trend was observed in 2014. However, the standard deviation of the bars was increased. This indicated that many small bars were formed but the numbers of large bars were also further increased concurrently. The image interpretation also reveals that many bars, which were developed earlier, are destroyed totally by the next image year (Figs. 3 and 5).

Fig. 5 Number of bars in different times at different cross sections (see Fig. 8 for cross section locations)
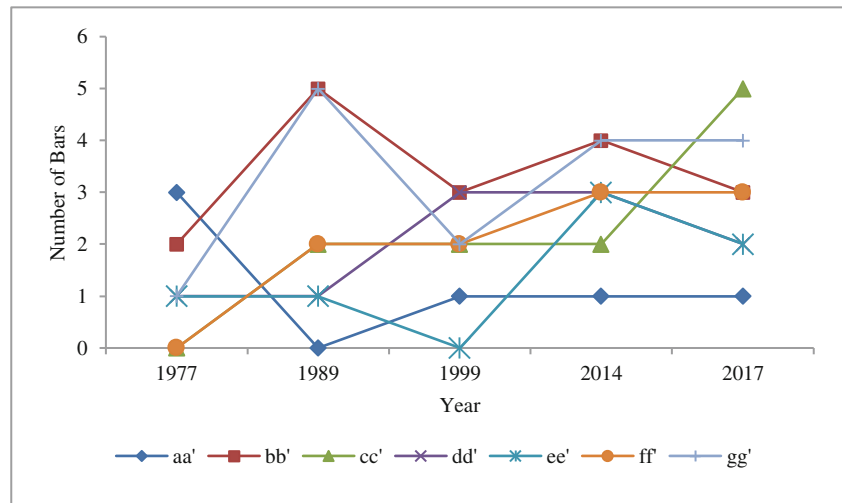
The analysis implies that the river area of the LPR has progressively increased at a rate of about 7.81 km^2 year^{-1} (Fig. 4a). Although the river area is expanding, the water area has been gradually reduced at a rate of about 1.66 km^2 year^{-1} (Fig. 4b). This is due to the increasing of channel bar area by channel bar development of this river. The study reveals that the bar area of this river has been enlarged at a rate of about 9.47 km^2 year^{-1} (Fig. 4d). During this time period many bars have converted to large bars from small bars and many small bars were also destroyed by erosion.

Braiding intensity of the river

There are three indices for estimation of the braiding intensity of a braided river: (1) bar dimensions and frequency (Brice 1960, 1964; Rust 1978; Germanoski and Schumm 1993), (2) the number of channels in the network (Howard et al. 1970), and (3) the total channel length in a given river length (Hong and Davies 1979; Mosley 1981; Friend and Sinha 1993). In the present work the Braiding intensity of the LPR at different times is calculated (Table 3) by using Germanoski and

Schumm (1993) index BI = 2 L_b/L_r + N_b/L_r, where L_b (Fig. 3a) is defined as the sum of twice the length of all islands and (or) bars, L_r (Figs. 3a, and 8) is length of the reach measured along the centre line of the river, and N_b is the total number of bars per reach length. A river is called braided when its braiding index is more than 1.5 (Sarma and Acharjee 2018). The channel length ("sinuosity") indices of this river at different times computed (Table 4) by Hong and Davies (1979) proposed index P_T = L_L/L_r, where L_L (Fig. 3a) is the total length of channels and L_r (Figs. 3a and 8) is the length of the reach measured along the centre line of the river. The braiding and sinuosity indices of this river changed with time. The river was divided into five segments (Fig. 3e), and the braiding and sinuosity indices of these segments were calculated (Tables 5 and 6). The braiding and sinuosity indices are also not similar in different segments throughout this river. This indicates that the braidings are not similar along the course of this river.

Erosion and deposition of the river

Earlier the LPR course in the researched area was less braided (Fig. 3; Table 3). Due to the formation of many new bars

Table 3 Braiding index and its matrix of the Lower Padma River in different times

Year	2 L_b	L_r	2 L_b/L_r	N_b	L_r	N_b/L_r	BI$_B$
1977	331.46	104	3.19	45	104	0.43	3.62
1989	533.86	110	4.85	123	110	1.12	5.97
1999	459.68	109	4.22	64	109	0.59	4.80
2014	597.82	114	5.24	103	114	0.90	6.15
2017	550.1	113	4.87	64	113	0.57	5.43

Table 4 Sinuosity index and its matrix of the Lower Padma River in different times

Year	L_L	L_r	P_T = L_L/L_r
1977	383	104	3.683
1989	687	110	6.245
1999	486	109	4.459
2014	534	114	4.684
2017	565	113	5.000

Table 5 Braiding index and its matrix of different segments of the Lower Padma River

Segment	$2 L_b$	L_r	$2 L_b/L_r$	N_b	L_r	N_b/L_r	BI_B
Segment-1	96.28	16.2	5.94	14	16.2	0.86	6.81
Segment-2	91.12	13.46	6.77	20	13.46	1.49	8.26
Segment-3	78.24	18.66	4.19	6	18.66	0.32	4.51
Segment-4	74.24	17.28	4.30	9	17.28	0.52	4.82
Segment-5	182.48	27.68	6.59	29	27.68	1.05	7.64

within the river by huge sedimentation from the upstream and gradually increasing of bar area within the channel, the river gradually converted to more braids. Braided channels marked by successive division and rejoining of the flow around channel bars (Reineck and Singh 1980). The main channel is divided into several courses, which meet and re-divide. Channel bars, which divide the stream into several channels at low flow, are often submerged during high flow. Williams and Rust (1969) reported that the braided bars are sometimes themselves dissected into smaller bars and shallower channels. The braided rivers are characterized by wide channels, and continuous shifting of sediments and position of the channels (Reineck and Singh 1980). Leopold and Wolman (1957) demonstrated that braided channels develop on steeper slopes. Steeper slopes cause larger sediment transport and bank erosion. These are contributing factors of braiding. High sediment transport and low threshold of bank erosion are essential condition for braiding. If discharge is high and banks are weak, braiding is common. Nonetheless, there is no unique solution to managing the braided rivers (Sarma and Acharjee 2018). Balancing the sustainable development of such a dynamic braided river is a complex task (Piegay et al. 2006). During rainy season the runoff of the Ganges-Brahmaputra river system is enormous (170,000 m^3/s) (Kudrass et al. 1998) with huge sediment supplies. Saleem et al. (2019) carried out regression analysis between bank erosion and mean annual flow, peak discharge, and mean flood flow of the LPR, and they stated that two of the three independent variables

Table 6 Sinuosity index and its matrix of different segments of the Lower Padma River

Segment	L_L	L_r	P_T
Segment-1	128	16.2	7.90
Segment-2	85	13.46	6.32
Segment-3	53	18.66	2.84
Segment-4	78	17.28	4.51
Segment-5	185	27.68	6.68

were significantly associated with bank erosion. However, they did not consider the morphological characteristics of the river. A morphological characteristic of any river is one of the important characteristics of bankline migration (Reineck and Singh 1980). Present research carried out an attempt about the channel bar development and bankline migration of the LPR in Bangladesh. Here another mighty river, the Jamuna, braided in nature, confluences with the Padma River near Gualando Ghat at Rajbari District, Bangladesh, and the morphological characteristics of this river totally changed after the confluence with the Jamuna River. In case of the LPR, spanning from after the confluence with the Jamuna River upto the confluence with Meghna River near Chandpur District, it is braided in nature (Tables 3 and 4) according to braiding and sinuosity indices (Sarma and Acharjee 2018). Dewan et al. (2017) also carried out through regression analysis among bank erosion rates, annual average discharge, and mean flood flow, and they found that bank erosion is significantly correlated with annual average discharge for the Padma ($r^2 = 0.628$). Although, Dewan et al. (2017) carried out about the morphological characteristics of the Padma River and they stated that the river was more of straight in nature with some meandering loops at a few locations. However, this statement is applicable for whole Padma River. The present study only considers the LPR in Bangladesh. The study implies that the LPR is braiding in nature rather than meandering (Tables 3 and 4). Therefore, development of less braided to more braided channel of the LPR and random channel bar formation are one of the major causes of bank erosion of this mighty river. Additionally, the bank sediments of the river are dominantly silty sand (loosely compact) (CEGIS 2004; Patwary et al. 2014) and easily subjected to erosion. Therefore, bank erosion is very common on both banks of the LPR course (Fig. 6; Table 7).

The analysis exposed that from 1977 to 1989 about 66.82 km^2 and 136.35 km^2 of lands were eroded on the left and right banks of the LPR at a rate of about 5.56 km^2 and 11.36 km^2 year^{-1}, respectively (Table 7; Fig. 7). During the period from 1989 to 1999 the eroded lands were about 108.62 km^2 and 124.5 km^2 at a rate of about 10.86 km^2 and 12.45 km^2 year^{-1}. The erosion rate was increased on the left bank, while on the right bank the situation was more or less similar in respect of earlier period. Afterwards, during the period from 1999 to 2014, the erosion was dramatically decreased on both banks. About 15.62 km^2 and 91.41 km^2 of lands were eroded on the left and right banks, respectively, at a rate of about 1.04 km^2 and 6.10 km^2 year^{-1}. Consequently, from 2014 to 2017, the erosion was again increased on both banks of the river, while on the right bank the increasing rate was more than on the left bank. About 7.25 km^2 and
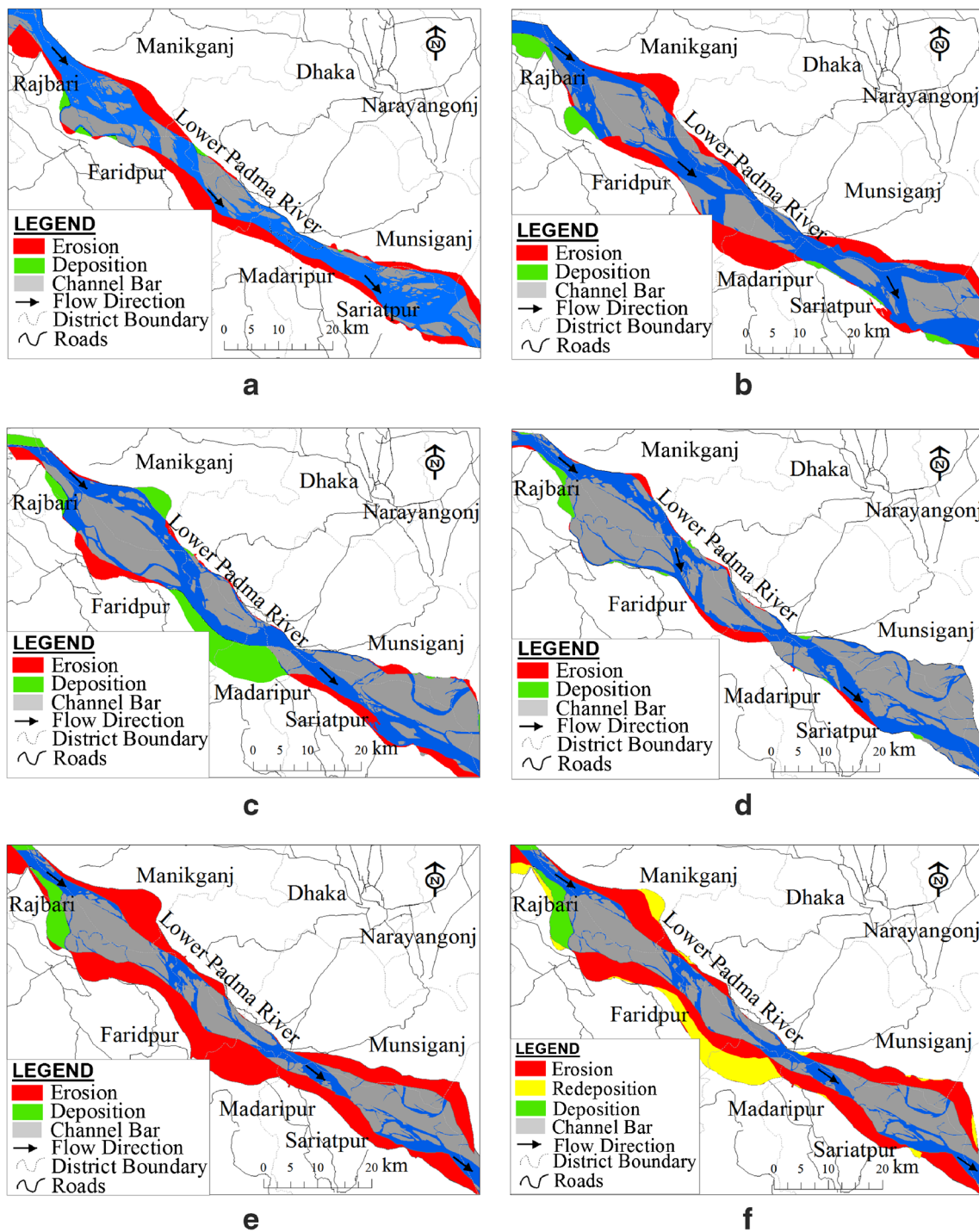
Fig. 6 Erosion and deposition map of the Lower Padma River in different time duration: **a** 1977–1989, **b** 1989–1999, **c** 1999–2014, **d** 2014–2017, **e** 1977–2017, and **f** 1977–2017

30.69 km² of lands were eroded on the left and right banks, respectively, at a rate of about 2.42 km² and 10.23 km² year⁻¹. Over the past 40 years, about 192.73 km² and 327.70 km² lands eroded on the left and right banks, respectively, at a rate of 4.82 km² and 8.19 km² year⁻¹ (Table 7). Therefore, erosion

was higher on the right bank than on the left bank over the past 40 years. During that period about 11 km² and 37.90 km² lands also accreted on the left and right banks, respectively, at a rate of 0.28 km² and 0.95 km² year⁻¹ (Table 7). In the same period about 20.88 km² and 107.19 km² lands again

Table 7 Statistics of erosion and deposition of both banks of the Lower Padma River in different period

Duration (Year)	Erosion left bank (km²)	Erosion rate left bank (km² year⁻¹)	Deposition left bank (km²)	Deposition rate left bank (km² year⁻¹)	Redeposition left bank (km²)	Erosion right bank (km²)	Erosion rate right bank (km² year⁻¹)	Deposition right bank (km²)	Deposition rate right bank (km² year⁻¹)	Redeposition right bank (km²)
1977–1989	66.82	5.56	1.77	0.15	*	136.35	11.36	7.33	0.61	*
1989–1999	108.62	10.86	–	–	*	124.5	12.45	55.05	5.51	*
1999–2014	15.62	1.04	35.56	2.37	*	91.41	6.10	121.23	8.08	*
2014–2017	7.25	2.42	3.2	1.07	*	30.69	10.23	20.43	6.81	*
1977–2017	192.73	4.82	11	0.28	20.88	327.70	8.19	37.90	0.95	107.19

*Not calculated

redeposited on the left and right banks, respectively. The study also discloses that the erosion rates were not always same on both banks of the river. Sometimes erosion was more prominent on the left bank when the situation was reverse on the right bank. Saleem et al. (2019) also indicated that erosion and deposition vary both spatially and temporally on both banks of the LPR. They stated that from 1911 to 2015 the right bank eroded more than the left bank of the river. An estimated of total 1749 km² of lands were eroded from 1911 to 2015 of which 807 km² were on the left bank, while 942 km² were on the right bank. The annual average bank erosion rate over their study period (1911–2015) was about 17 km² year⁻¹. Although, Nawfee et al. (2018) stated that the left bank of the LPR experienced higher levels of erosion than the right bank. However, in their study, they did not consider the whole LPR. They only consider one particular area of the LPR (Nawfee et al. 2018). Hence, their study cannot reflect the LPR characteristics as a whole. Therefore, the present

research will add another dimension about morphological characterization, channel bar formation, and its relation to bankline migration of any tropical rivers in the world, and finally, it will be helpful to take future protective plan from erosion and bankline shifting for any tropical river throughout the world.

India built a barrage on the river Padma in 1975, some 18 km from the India–Bangladesh border at Farakka to divert the flow of water from Bangladesh to India (Crow et al. 1995; Adel 2013; Miah 2003). It leads to lessening the water discharge of the Padma River in Bangladesh part; subsequently, it enhances channel sedimentation in the upper parts of the river rather than it is deposited into the more downstream to the Bay of Bengal and decreases the depth of the river especially in the dry season (Adel 2004; Anon 2017; Anon 2014; Khan 2015). Moreover, many subaquas small bars (these bars always submerged under water) are also formed in the channel bed, which also obstruct the water flow (Anon 2014; Anon 2017). In addi-

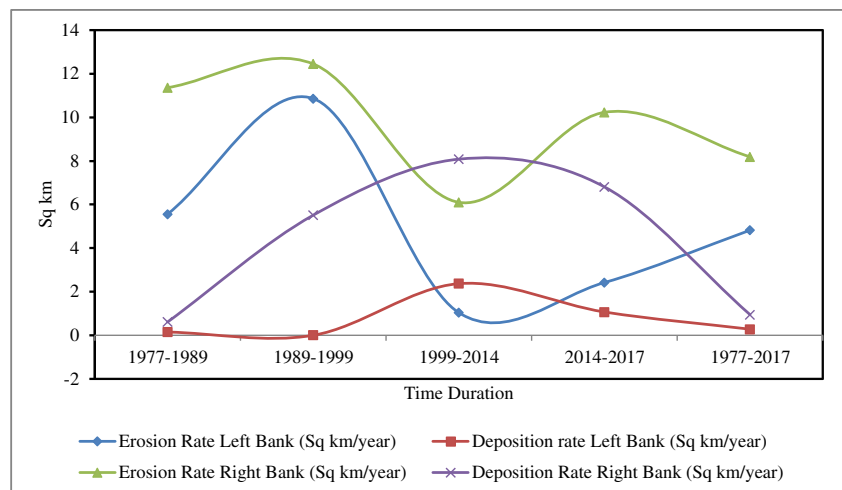**Fig. 7** Erosion and deposition rate of both banks of the Lower Padma River at different times

Table 8 Mutual correlation matrix of different parameters of the Lower Padma River from 1977 to 2017

	N_b	BI	P_T	Average width	Bar area
N_b	1				
BI	.943*	1			
P_T	.874	.786	1		
Average width	.144	.448	0.00	1	
Bar area	.042	.339	.095	.748	1

*Correlation is significant at the 0.05 level (2-tailed)

tion, these subaquas bars in the channel are not allow to carry and transport excess water receiving from the upstream during wet season which ultimately causes bank erosion.

Correlation matrix analysis

Correlation study (Table 8) implies that the braiding index is significantly correlated with number of bars ($r = 0.943^*$, $\alpha \leq 0.05$). Similar, to braiding index, sinuosity index is also positively correlated with number of bars ($r = 0.874$, $\alpha \leq 0.05$). Braiding index and sinuosity index are also positively and strongly correlated ($r = 0.784$, $\alpha \leq 0.05$). It indicates when more bars are present that creates more braiding, more sinuosity, and finally causing more bank erosion. Since erosion is an inherent characteristic of any braided river (Reineck and Singh 1980). The bar statistics and erosion rates at different times of this river also support this statement. In 1989 and 2014 the numbers of bars were increased from the earlier time (Table 2), and after that the erosion rates of both banks of this river were also increased (Table 7). The data also show that the river width and bar area are significantly correlated ($r = 0.748$, $\alpha \leq 0.05$). The positive correlation indicates that the river width is highly influenced by bank erosion. Nawfee et al. (2018) also found positive correlation between river width and bar area of this river. However, the bar area and the number of bars are insignificantly correlated ($r = 0.042$, $\alpha \leq 0.05$). This indicates that bar area does not depend on the number of bars. Correlation study has also been carried out at different segments of the LPR (Table 9). In case of different segments braiding index also shows positive correlation with number of bars ($r = 0.857$, $\alpha \leq 0.01$). Similar to

braiding index, sinuosity indices are also significantly correlated with number of bars ($r = 0.973^{**}$, $\alpha \leq 0.01$). Braiding index and sinuosity index are also significantly correlated ($r = 0.724$, $\alpha \leq 0.01$). It also indicates that the area of river where more bars are present creates more braiding and more sinuosity.

Bankline migration

The satellite images from 1977 to 2017 have been visually interpreted to identify river width and bankline migration of the LPR at different times (Figs. 8 and 9; Table 10). The river width has been measured perpendicular to the two banklines at the same fixed geographical points. Seven cross sections have been drawn in different parts of the river course. These are aa′, bb′, cc′, dd′, ee′, ff′, and gg′ (Fig. 8).

In cross section aa′ the width of the river follows an increasing trend from 1977 to 1999, and after that it was a decreasing trend (Table 10). But the overall trend is a decreasing one at a rate of 0.018 km per year (Fig. 9). In case of cross section bb′, the width of the river continuously follows an increasing trend at a rate of about 0.26 km year^{-1} (Table 10; Fig. 9). In cross section cc′ the river width follows increasing trend from 1977 to 1999, and after that it was a decreasing trend (Table 10). However, the overall trend is an increasing one at a rate of 0.03 km year^{-1} (Fig. 9). In cross section dd′ the river width was also gradually increased from 1977 to 1999, and after that it has been decreased. But in the overall result, the width of the river in this section has been increased at a rate of 0.05 km year^{-1} (Fig. 9). In cross sections ee′ the river width was increased from 1977 to 1999 but after that slightly decreased. In cross sections ff′ and gg′ the widths of the river have been gradually increased from 1977 to 2017 at a rate of 0.11, 0.10 km year^{-1}, respectively (Table 10; Fig. 9). The analysis shows that the average width of the river follows an increasing trend from 1977 to 1999, but after that it was a decreasing one from 1999 to 2014 and again increased from 201 to 2017 (Table 10; Fig. 10). As a whole, the river width shows an increasing trend at a rate of 0.083 km year^{-1} over the past 40 years (Fig. 10). The river width's standard deviations (SD) have been calculated for different times on the basis of river widths at different cross sections (Table 10). The SD indicates that the river width at different parts of its course were not same. Then after 1989 the variations of river widths at different parts were intensely deviated.

An attempt has been made to delineate the river center point from both banks of the LPR at different times of different cross sections (Fig. 8). On the basis of these center points, river center lines at different times have been drawn (Fig. 8). The center lines of the river not uniformly shifted to both banks at different times. In any given year these lines shifted to the left bank at some parts of its course and also shifted to the right bank at other parts along its course. This indicates
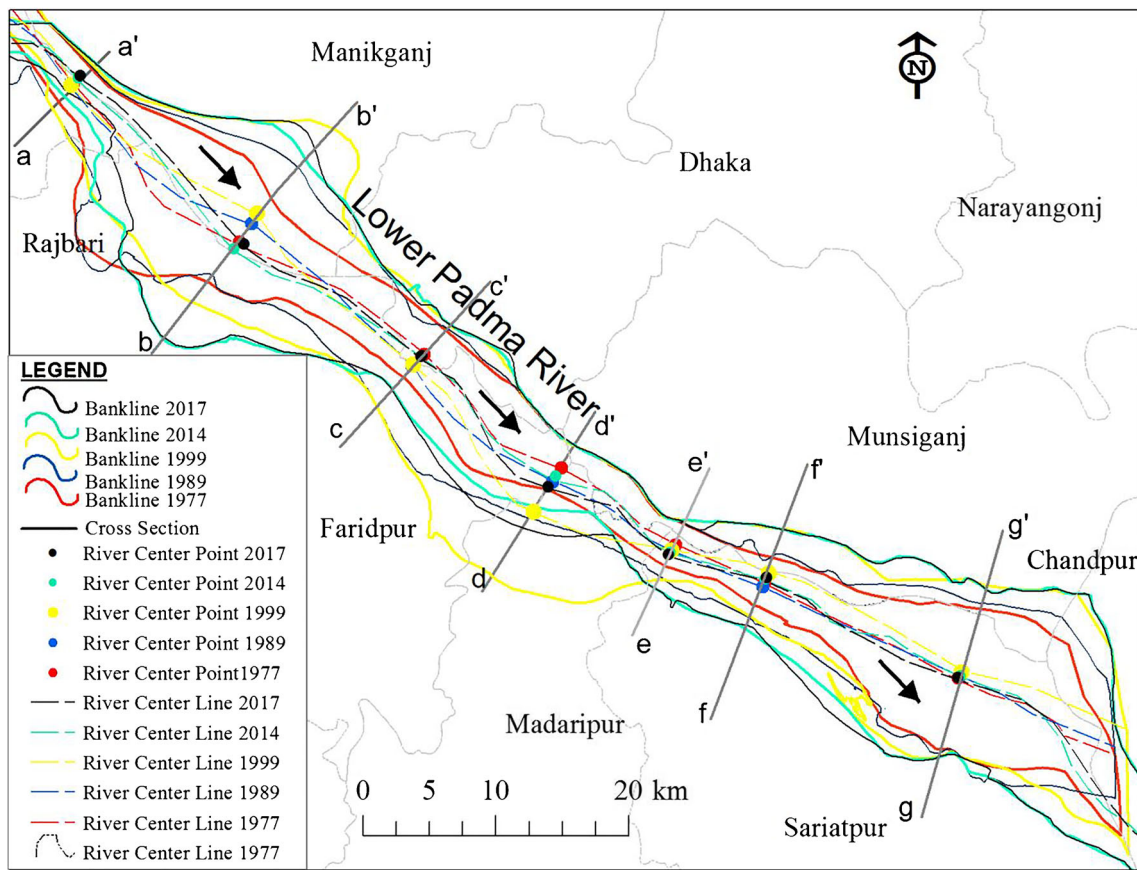
Table 9 Mutual correlation matrix of different parameters of different segments of the Lower Padma River in 2017

	N_b	BI	P_T
N_b	1		
BI	.857	1	
P_T	.973**	.724	1

**Correlation is significant at the 0.01 level (2-tailed)

Fig. 8 Bankline, river center points, river center lines, and different cross sections of the Lower Padma River of different times

that the erosion rates were not always same on both banks as well as at different parts along both banks of the river. This is due to the formation of channel bars and the position of bars in the river. The area of river where more bars are present creates more braiding, more sinuosity, and finally more erosion. This

phenomenon has randomly changed the morphology of the river and its course. The river, which was less braided, now altered to more braid and therefore causes more erosion. Moreover, during monsoon huge water flows from the upstream naturally apply an additional effect on the channels.

Fig. 9 River widths and trend lines with equation of the Lower Padma River at different cross sections of different times
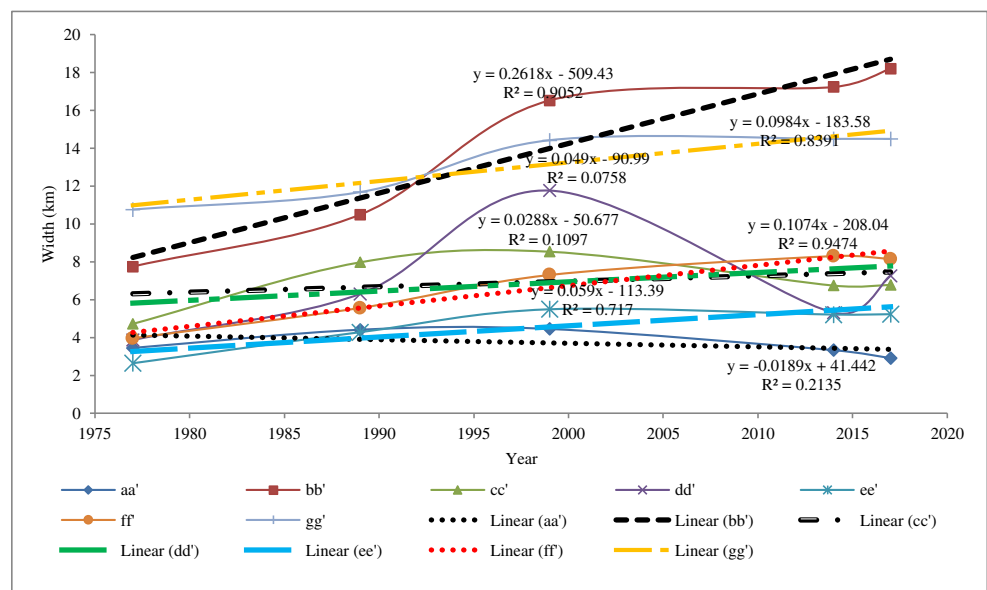
Table 10   River width (km) of the Lower Padma River at different cross sections of different times

Cross section	Year				
	1977	1989	1999	2014	2017
aa′	3.41	4.41	4.45	3.33	2.91
bb′	7.75	10.49	16.52	17.23	18.20
cc′	4.72	7.97	8.53	6.74	6.78
dd′	3.87	6.30	11.76	5.31	7.27
ee′	2.64	4.28	5.49	5.21	5.23
ff′	3.96	5.56	7.30	8.30	8.14
gg′	10.76	11.68	14.42	14.49	14.49
Avg	5.30	7.24	9.78	8.66	9.00
Max	10.76	11.68	16.52	17.23	18.20
Min	2.64	4.28	4.45	3.33	2.91
STD	2.91	2.92	4.57	5.21	5.40

But due to the presence of channel bars, these are hampering the normal water flow. Therefore, it needs more space to pass the water and consequently bank erosion.

Conclusion

Bank erosion is common in the Lower Padma River (LPR) of Bangladesh. The another mighty river of Bangladesh, the Jamuna, braided in nature, confluences with the LPR near Gualando Ghat at Rajbari District and the morphological characteristics of the LPR totally changed after the confluence with the Jamuna River. Though, the upper part of this river is a meandering in nature. However, in case of the LPR, spanning from after the confluence with the Jamuna River upto the confluence with Meghna River near Chandpur District, it is braided in nature rather than meandering, according to braiding and sinuosity indices. Therefore, bankline migration and erosion of banks are very common of this river, as bank erosion is common features of any braided river. Moreover, huge water flow and sediments from the upstream and soft bank sediments enhance the bank erosion. Although, earlier researches did not emphasized the morphological characteristics of the LPR for bankline migration. The study also discloses that the erosion rates were not always same on both banks as well as at different parts along both banks of the river. This is due to the formation of channel bars and the position of bars in the river. The area of the river where more bars are present creates more braiding, more sinuous, and finally causing severe erosion. This phenomenon has randomly changed the morphology of the river and its course. The river, which was less braided, now changes to more braid and therefore causes more erosion. However, still there is no unique solution to manage braided rivers. The management depends on the stage of geomorphological evolution of the river, ecological dynamics and concerns, and human needs and safety. For sustainable solutions, the government authorities may consider the cost-benefit aspects of their options, and the needs and desires of society. Some of the strategies for achieving this could be (1) river training by constructing a concrete embankment for reducing erosion at a reach scale, thereby reducing bank erosion, and (2) increase dredging activities for maintaining the river main course during rainy season and dredged sediments dispersed to other suitable areas. Therefore, the present research will add another dimension about morphological characterization of the LPR like channel bar development; the interrelationship among number of bars, bars area, river width, braiding, and sinuosity indices; and its relation to bankline shifting so far, and finally, it will be helpful to take future protective plan from erosion and bankline shifting of this mighty river.

Fig. 10   Average (with trend line and equation), maximum and minimum widths, and widths standard deviation of the LPR of different times

$y = 0.0838x - 159.46$
$R^2 = 0.6373$

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