



# Integrating subsurface stratigraphic records with satellite images to investigate channel change and bar evolution: a case study of the Padma River, Bangladesh

Shahreen Muntaha Nawfee<sup>1</sup> · Ashraf Dewan<sup>2</sup> · Towhida Rashid<sup>3</sup>

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## Abstract

Landsat data and stratigraphic records were employed to determine channel changes and bar evolution of a selected reach of the Padma River in Bangladesh. Analysis of multi-temporal images showed that the selected reach of the Padma River has undergone significant morphological changes since 1973. The mean width of the river has almost doubled, having increased from 5458 m in 1973 to 10,638 m in 2014. Bank erosion, totalling 281 km<sup>2</sup>, was more than double the accretion (123 km<sup>2</sup>), and the left bank experienced higher levels of erosion than the right bank. Analysis of the stratigraphy of the bar head, middle and tail sections revealed that erosion occurred in the head section, but that the middle section seemed to be stable, whereas accretion was estimated to be high in the tail section of the bar. Sedimentary facies analysis indicated that bar evolution is largely influenced by the variation of both water and sediment flows, as bar areas tend to accrete substantially following large floods. However, the erosion–accretion process of both bars and river banks appeared to be stable during the periods when the river experiences no major flooding. The relationship between bank erosion and bar area expansion showed a moderately positive correlation ( $r^2 = 0.64$ ,  $p = 0.016$ ), while a strong correlation was observed ( $r^2 = 0.80$ ;  $p = 0.008$ ) between channel width and area of the bar, suggesting that river width is highly influenced by bank erosion. This implies that the growth of bars within the reach is largely determined by materials flowing from bank failure.

**Keywords** Bar formation · River channel · Landsat · Stratigraphy · Padma River

## Introduction

Rivers are amongst the most dynamic geomorphic elements in nature. Channel change occurs when a river channel varies from one form to another (Winterbottom 2000). Such

variations can be attributed to the alteration in the input of water and sediment (Midha and Mathur 2014). Natural factors, such as climatic change and tectonic activities, have important roles in altering these inputs throughout the geological history; however, at present, most of these changes are intensified by human activities through dam construction, bank revetments, sand mining and deforestation amongst other things (Das et al. 2007). Leys and Werritty (1999), for instance, showed that changes in river width are associated with engineering works, such as bridge construction. Surian and Rinaldi (2003) have pointed out that river engineering influences morphological change, which further affects the environment and society. Thus, studies relating to morphological change can support effective management of rivers, in these cases.

Bangladesh is a riverine country, situated in the Ganges–Brahmaputra–Meghna (GBM) river basin. Rivers in this country, like other large alluvial systems in the world, exhibit high variations in flow and sediment load, driven by natural or anthropogenic factors (Gan and Baki 2012).

✉ Shahreen Muntaha Nawfee  
smnawfee@iub.edu.bd

Ashraf Dewan  
A.Dewan@curtin.edu.au

Towhida Rashid  
towhida\_rashid@du.ac.bd

<sup>1</sup> Department of Environmental Management, School of Environmental Science and Management, Independent University, Bangladesh (IUB), Dhaka 1212, Bangladesh

<sup>2</sup> Discipline of Spatial Sciences, School of Earth and Planetary Sciences, Curtin University, Bentley, Perth, WA 6102, Australia

<sup>3</sup> Department of Meteorology, University of Dhaka, Dhaka 1000, Bangladesh

River bank erosion occurs at extremely high rates on the major rivers, often resulting in population displacement, and loss of life and property (Sinha et al. 2010). These rivers are also characterized by the presence of numerous bars and islands, locally known as chars, which, like the river channel, show similar dynamism. In fact, it is the erosion and deposition pattern of the rivers that leads to the formation of islands and bars (Sarker et al. 2003).

Analysis of historical channel change is important to reduce future damage caused by floods and bank erosion and may help decision makers in developing appropriate strategies for river management (Tiegs and Pohl 2005), managing navigation, understanding changes in aquatic and riparian ecosystem (Li et al. 2007), improving river engineering and environmental management (Yao et al. 2011) and in developing ways to adapt to climate change (Sarker et al. 2013).

Understanding river channel and bar changes, both in time and space, in Bangladesh is particularly important, since a large number of people in this densely populated country live alongside the river or on river islands and depend on them for their shelter and livelihoods (Gan et al. 2013). Although the body of literature arising from river channel change studies is substantial worldwide, explicit understanding of the behaviour of large river systems in Bangladesh appears to be limited (Sarker et al. 2013).

The Ganges river system is one of the largest river systems in the world. Although only 4% (Gan et al. 2013) of its catchment lies in Bangladesh, this system has been of paramount importance for supporting the lives and the livelihoods of millions of people for millennia. Studies of paleogeographic maps (Rennel 1794 in ISPAN 1995a; Wilcox 1840 in ISPAN 1995a, b; Umitsu 1993; Goodbred and Kuehl 2000) show that the Ganges has shifted its course several times as a result of variation in water and sediment inputs. The flow of the Ganges through the present Padma channel commenced approximately in 1830, as the Brahmaputra (locally called the Jamuna River) diverted to the present course between 1790 and 1830 (ISPAN 1995a, b). The Padma River is the stretch of the Ganges system which starts from the meeting point of the Ganges with the Jamuna at Aricha and converges with the Meghna River in Chandpur district, which finally discharges to the Bay of Bengal.

Besides being morphologically active, the Padma River frequently contains both mid-channel and attached bars. The bar formation process is very complex and highly dynamic. Although the bars of the Padma are relatively more stable than those on the Jamuna (Sarker et al. 2003), they face rapid changes in their hydro-morphology during floods of large magnitude, and other bank erosion events. (ISPAN 1995a, b). Moreover, the presence of these large bars and islands is thought to influence the erosion–accretion process of the river system, making it more dynamic (Dewan et al. 2017).

Examination of how these bars have evolved constitutes part of the objectives of this study.

Many studies have shown that changes in water and sediment flow can lead to the changes in river channel morphology. For example, research on the Lower Colorado River (Tiegs and Pohl 2005) showed that the river width varies over time and space with fluctuations in discharge. In addition, a study on the Yangtze River (Li et al. 2007) revealed that an increase in discharge can lead to bank failure causing the width of the channel to increase. Furthermore, Yao et al. (2011) showed that sediments from bank failure contribute to bar development, while bank erosion was seen to have a strong association with the mean flow for the Yellow River in China. Therefore, analysing the flow variation of a river helps to understand its effect on channel and bar evolution.

The degree of river bank and bar changes varies from river to river and even from one reach of a river to another. Although a number of studies (Mount et al. 2013; Sarker et al. 2013; Gan et al. 2013) have focused on river bank erosion and accretion, a more detailed analysis of river bank changes in different reaches is required to enhance the existing knowledge base. Moreover, there is a lack of literature that simultaneously addresses the nature and amount of river channel changes and bar evolution. Most of the studies on the riverine bars of Bangladesh (e.g. Rahman and Rahman 2011) focus on the lives and livelihoods of the bar dwellers and the impact of flood, erosion and other hazards, but there is a paucity of information on bar morphology, stratigraphy and their relation to river channel morphology, as well as hydrology. Sinha et al. (2010) have particularly highlighted the significance of such studies, stating that an integrated approach can enhance our understanding of the process–form relationship of an alluvial system. Furthermore, study of the river channel and bars of the Padma is rare compared to the other reaches of the Ganges, despite the fact that this reach is highly dynamic and leads to population displacement (Dewan et al. 2017).

Researchers have used different approaches to study river channel changes and bar evolution. Over the past few decades, satellite images together with GIS (geographic information systems) have been used widely to study the rate of channel and bar changes around the world (Leys and Werriitty 1999; Harijan et al. 2003; Tiegs and Pohl 2005; Yueming et al. 2007; Das et al. 2007; Joeckel and Henebry 2008; Pati et al. 2008; Yao et al. 2011; Fisher et al. 2013; Henshaw et al. 2013; Sarker et al. 2013). These studies demonstrate that geospatial techniques are very useful in quantifying channel dynamics over space and time.

Until now, a number of studies have used two-dimensional maps and satellite data to study bank erosion and deposition of large rivers in Bangladesh (e.g. Gan and Baki 2012; Hosain et al. 2013; Dewan et al. 2017). Best et al. (2003) also determined changes in bar growth of the Jamuna River by

utilizing their sedimentary architecture. However, integration of stratigraphic records with satellite images to examine channel change and bar evolution appears to be very limited. This work aims to fill this void. We believe this study could greatly aid in the understanding of long-term dynamics of rivers and bar landforms, a topic which has received renewed interest in river basin management.

The objective of this study is therefore to quantify the nature of bar evolution and morphological changes of the Padma River in Bangladesh, by identifying the relationship between river channel changes and bar evolution. In addition, the influence of water flow on river channel and bar evolution was also examined.

## Description of the study area

The Padma River is the downstream continuation of the Ganges (which flows for 2526 km from its source at the Gangotri glacier in the Himalayas). The Padma flows for 108 km until it meets the Meghna River at Chandpur. It carries the combined discharge of the Ganges and Brahmaputra Rivers. The annual average discharge of the river is approximately  $30,000 \text{ m}^3/\text{s}^{-1}$ , and the bankfull discharge is about  $75,000 \text{ m}^3/\text{s}^{-1}$  (FAP 24 1996). The average slope of the river is 5 cm/km (Sarker et al. 2003). The annual average sediment load transported through the Padma system is 900 metric tons, of which 60% is transported as silt and clay and the remainder is bed material (Sarker et al. 2003). The planform of the river resembles a “wandering” pattern (Dewan et al. 2017).

This study concentrates on a 31-km stretch of the river Padma, which starts at approximately 4 km downstream of the Paturia-Daulatdia Ferry Route (Fig. 1). The selected reach lies between  $90.5^\circ$  and  $89.49^\circ\text{E}$  longitudes and  $23.45^\circ$  and  $23.33^\circ\text{N}$  latitudes. It is part of the active Padma floodplain. In this kind of physiographic region, many riverine bars form, and they are mainly made up of calcareous silts and sands (Rashid 1991). The reach under investigation has passed through three districts of Bangladesh. Along the left bank of the reach is the Harirampur *upazila* (sub-district) in Manikganj district, and along the right bank is Goalanda in Rajbari and Char Bhadrashan in Faridpur district.

The bar chosen for stratigraphic analysis is the largest bar in the study reach (Fig. 1). It is approximately  $124 \text{ km}^2$  in plan area during dry season. The head of the bar is located about 9 km downstream of the Paturia-Daulatdia ferry terminal. It covers portions of two districts in Bangladesh.

## Materials and methods

### Image acquisition and preprocessing

To analyse channel and bar dynamics of the selected reach of the Padma River, multi-date Landsat data were used. In total, nine Landsat images, representing 1973, 1980, 1984, 1989, 1995, 2000, 2005, 2011 and 2014, were obtained from Earth Explorer (<http://earthexplorer.usgs.gov/>). The variation of temporal range amongst the eight periods was because of unavailability of cloud free images at regular intervals. However, all images were from the same season (i.e. the dry season) and also from the same month of the year, as is the standard practice in previous works. The same-season data allow for better detection of changes in fluvial dynamics (Rozo et al. 2014) as water level variation is minimal during the dry season (Gan et al. 2013). The images were subjected to radiometric and geometric corrections. Topographic maps of the study area were used to correct the images geometrically, and an image-based method was employed for radiometric correction (Chavez 1996). It may be noted that Landsat multispectral scanner (MSS) data from 1973 to 1984 (Table 1) with a spatial resolution of 60 m was resampled to 30 m, using the nearest neighbour method, in order to match the spatial resolution of Landsat TM/ETM+/OLI data after 1984, for appropriate comparisons between image acquisition years. The Universal Transverse Mercator (UTM) coordinate system (46N) was used as the reference system.

### Delineating bankline and channel bars

To extract the river channel and bars (attached and in channel), continuous polygons were drawn using head-up digitizing. To effectively identify the boundary between the river channel and floodplain, individual images were displayed with a band combination of 1, 6 and 7 for TM and ETM + data, as suggested by Yang et al. (1999), but for MSS images, bands 4, 3 and 2 were used. To maintain accuracy, digitizing was done at a constant scale of 1:3000 and a single operator performed the whole process. The use of 1:3000 digitizing scale is one of the major strengths of this study, since smaller scale digitizing is superior in capturing data related to riverbanks (Rozo et al. 2014). Finally, georeferenced digitized polygons, representing the river channel and bars, were also constructed for each year.

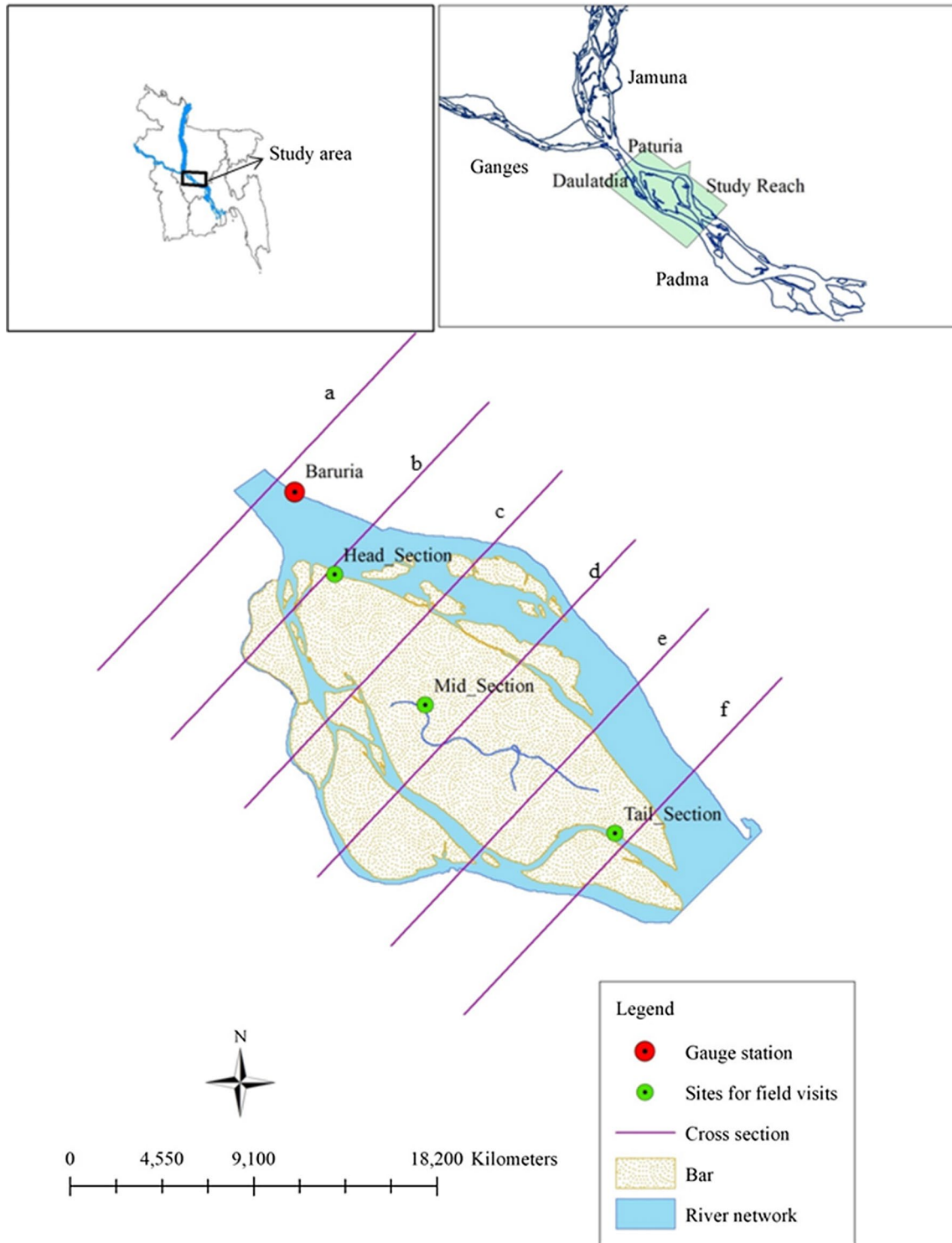


Fig. 1 Location of study area

**Determination of river channel and bar characteristics**

The width of the river (distance between the two banks)

was determined at six cross sections for each of the images acquired (Fig. 2). Each cross section was taken at 5-km intervals, and set at 90 degrees to the valley direction (Hossain et al. 2013). The mean channel width was then

**Table 1** Attributes of Landsat images used in this study

Sensor	Year	Image acquisition month	Resolution (m)
MSS	1973	February 1973	60 × 60
MSS	1980	February 1980	60 × 60
MSS	1984	February 1984	60 × 60
TM	1989	February 1989	30 × 30
ETM+	1995	February 1995	30 × 30
TM	2000	February 2000	30 × 30
TM	2005	February 2005	30 × 30
TM	2011	February 2011	30 × 30
OLI	2014	February 2014	30 × 30

**Fig. 2** Exposed soil section

calculated from the sum of the width values obtained for each cross section.

The digitized polygons, representing the river channel for different years, were superimposed to estimate the erosion and accretion pattern. A total of eight epochs [1973–1980 (7 years); 1980–1984 (4 years); 1984–1989 (5 years); 1989–1995 (6 years); 1995–2000 (5 years); 2000–2005 (5 years); 2005–2011 (6 years); 2011–2014 (3 years)] were used for the selected reach. Total erosion and accretion during the entire study period (1973–2014) was also measured. The locations of bankline shifts were identified to determine whether they underwent erosion or accretion. Depending on the type of bank movement, erosion was defined when

the channel moved towards land over the period of observation. Similarly, accretion was defined as riverward movement. Moreover, changes along the left and right banks were separately measured using the method suggested by Yao et al. (2011). For the calculation of the annual rate of river bank erosion/accretion, the number of years in each epoch was considered. To compute erosion–deposition of the bars within the study reach similar method was used.

### Stratigraphic analysis

In study area, there are a number of mid-channel bars; however, we have chosen only the largest bar (Fig. 1) for stratigraphic analysis. Locations that underwent major morphological changes during the study period were marked on the images, prior to field work. Amongst those locations, three sites were chosen for detailed investigation (Fig. 1), given the constraints on resources. These sites represented the head, middle and tail sections of the bar. Choosing sites from three distinct portions of the bar was assumed to provide representative information on the stratigraphy of entire bar.

For stratigraphic analysis, sedimentary layers were exposed at the eastern side of the bar head and western side of the bar tail sections (Fig. 2). To expose a site fully, in the bar head and tail, soil was excavated with the help of a hammer, until any presence of water was detected. The head section was exposed to 2.92 m below the surface, while the tail section was exposed to 3.89 m. After exposing each section, the different layers of sediment were identified and their depths were measured. Subsequently, the lithostratigraphic units were carefully examined using the following criteria:

1. The lamination pattern;
2. Presence of rootlets, detritus and burrows;
3. Soil texture;
4. Presence of erosional or depositional features.

Details were then logged on graph paper, and photographs were taken for each unit. Sediment samples were collected from each unit in airtight bags for further analysis in the laboratory. Sediments were examined for colour using Munsell Soil colour charts, and the grain size distribution of the soil was determined by hydrometer method.

Due to high population density and greater depth of section, an alternative strategy was used to examine the stratigraphy for the middle section of the bar. In this section, a wash bottle method was used as it allowed the collection of sediment from a greater soil depth (Fig. 3). Sediments were collected at approximately 1.5-m intervals until a hard rock layer was reached at 27.43 m depth from surface. Soil texture was then determined from sediments samples obtained from field, using the hydrometer method.

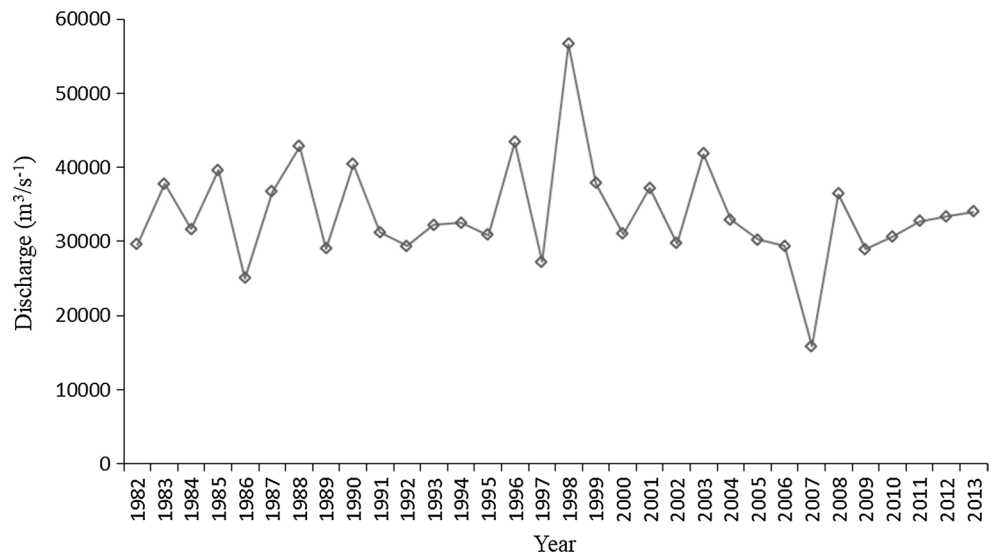


**Fig. 3** Sediment sample collection at the middle section of the bar by wash bottle method

### Hydrological analysis

Daily discharge data, between 1982 and 2013, were obtained from the Bangladesh Water Development Board (BWDB). The records were specifically from the Baruria gauge station (Station ID: SW91.9L) (Fig. 1). Mean annual discharge was then calculated (Fig. 4). To determine any impact of flow variation on bar and channel characteristics, the Pearson correlation coefficient was used at the 95% significance level.

**Fig. 4** Variation in water flow at Baruria gauge station between 1982 and 2013

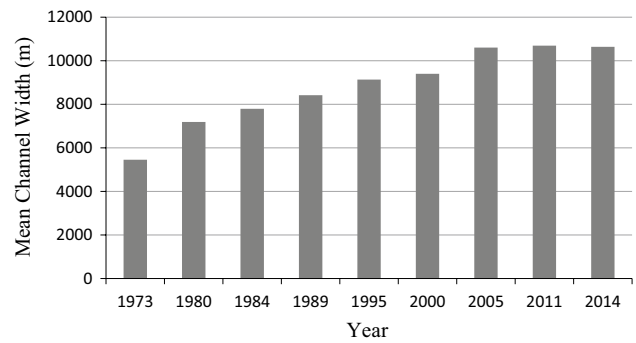


## Results

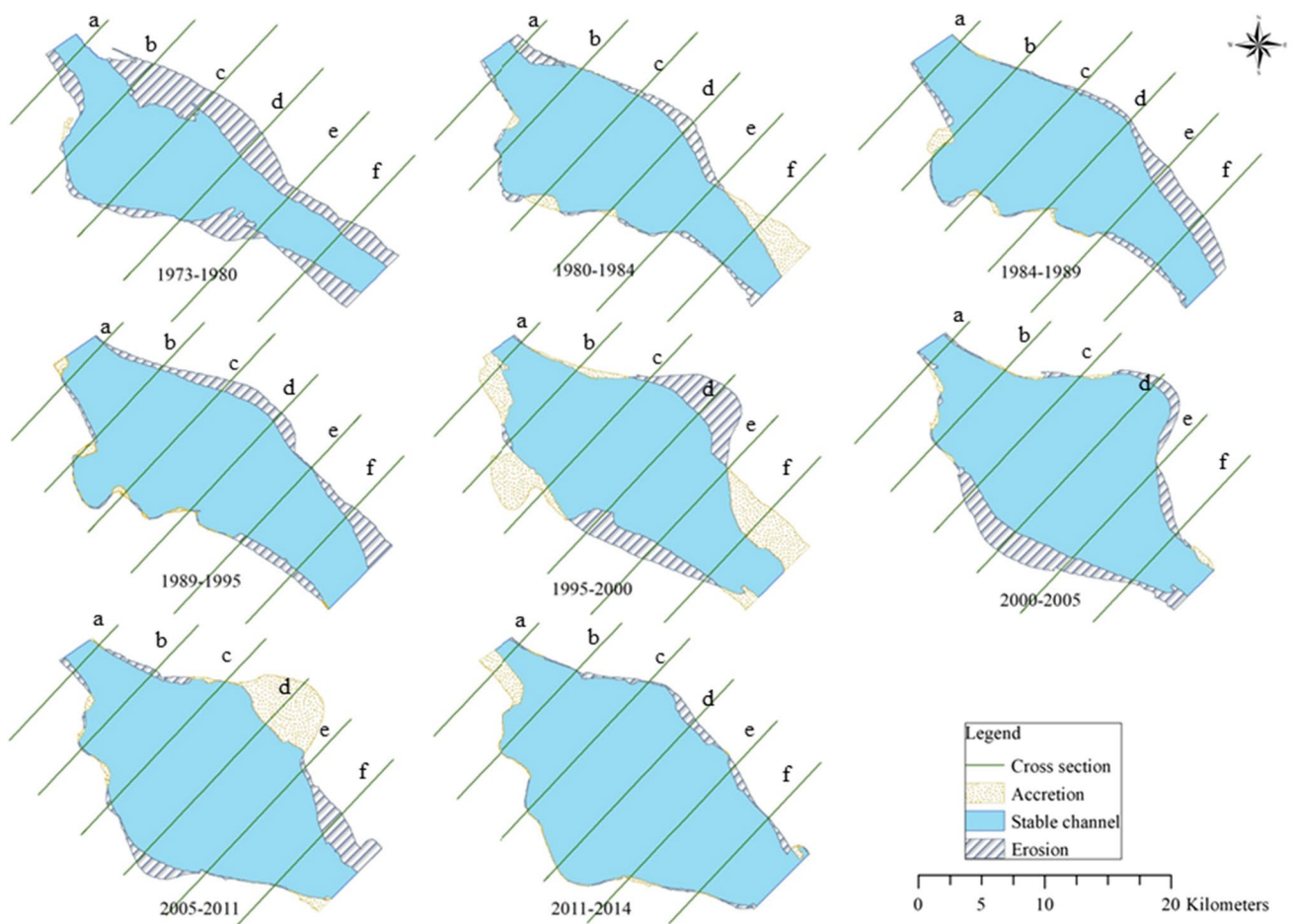
### Analysis of channel change

The analysis showed that, between 1973 and 2014, the width of the selected reach of the river has almost doubled, increasing from 5485 m in 1973 to 10,607 m in 2005. In detail, the channel width increment was gradual until 2005, but has been variable since then, including a decrease since 2011 (Fig. 5). The rate of increment was at a maximum between 1973 and 1980, while the second highest rate was observed between 2000 and 2005.

Figure 6 shows erosion and accretion statistics of both banks from 1973 to 2014. The results indicate that, almost 281 km<sup>2</sup> of land was eroded between 1973 and 2014, while the amount of accretion was 123 km<sup>2</sup>, suggesting a net loss of bank materials to the channel. The analysis further indicated that rates of erosion and accretion varied between



**Fig. 5** Variation in mean channel width along the study reach between 1973 and 2014



**Fig. 6** Spatial patterns of erosion and accretion in the study reach

**Table 2** Areas of erosion along the study reach, 1973–2014

Duration	Left bank		Right bank		Total	
	Total (km <sup>2</sup> )	Rate (km <sup>2</sup> /year)	Total (km <sup>2</sup> )	Rate (km <sup>2</sup> /year)	Total (km <sup>2</sup> )	Rate (km <sup>2</sup> /year)
1973–1980	50.42	7.20	23.96	3.42	74.37	10.62
1980–1984	14.19	3.55	6.512	1.63	20.70	5.17
1984–1989	21.90	4.38	6.94	1.39	28.84	5.77
1989–1995	25.60	4.27	8.25	1.37	33.85	5.64
1995–2000	23.34	4.67	19.30	3.86	42.64	8.53
2000–2005	11.81	2.36	31.12	6.22	42.93	8.59
2005–2011	19.34	3.22	8.81	1.47	28.15	4.69
2011–2014	8.91	2.97	1.12	0.37	10.03	3.34

banks for each time period examined. As shown in Table 2, the right bank experienced maximum erosion (31.12 km<sup>2</sup>) between 2000 and 2005, while erosion of the left bank was a maximum of 50 km<sup>2</sup> during the first assessment period (1973–1980). On the other hand, the rate of accretion was highest between 1995 and 2000 for both the right and left banks (Table 3).

An overall assessment of the erosion–accretion pattern is provided in Tables 2 and 3. The rate of bank erosion was highest between 1973 and 1980. For the next three epochs (e.g. 1980–1984; 1984–1989 and 1989–1995), the rate of erosion reduced, but was always higher than the rate of accretion. During 1995–2000, a sharp increase in erosion and accretion was observed. This was the first period in

**Table 3** Areas of accretion along the study reach, 1973–2014

Duration	Left bank		Right bank		Total	
	Total (km <sup>2</sup> )	Rate (km <sup>2</sup> /year)	Total (km <sup>2</sup> )	Rate (km <sup>2</sup> /year)	Total (km <sup>2</sup> )	Rate (km <sup>2</sup> /year)
1973–1980	0	0	0.76	0.11	0.76	0.11
1980–1984	14.10	3.53	3.52	0.88	17.63	4.41
1984–1989	0.21	0.04	4.20	0.84	4.41	0.88
1989–1995	0	0	3.14	0.52	3.14	0.52
1995–2000	25.00	5.00	26.86	5.37	51.87	10.37
2000–2005	2.11	0.42	1.47	0.29	3.58	0.72
2005–2011	29.15	4.86	3.34	0.56	32.49	5.41
2011–2014	0.64	0.21	8.04	2.68	8.68	2.89

**Table 4** Number and area of bars from 1973 to 2014

Year	Number	Area (km <sup>2</sup> )
1973	4	89.97
1980	13	139.84
1984	11	120.72
1989	13	137.92
1995	16	179.92
2000	7	160.02
2005	14	208.14
2011	17	209.82
2014	12	198.69

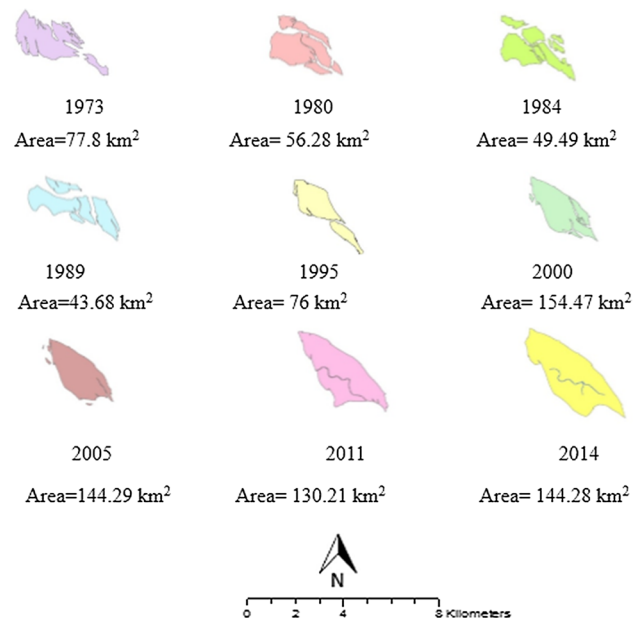
**Table 5** Erosion-accretion of the bars on the study reach

Time period	Erosion		Accretion	
	Total eroded area (km <sup>2</sup> )	Rate of erosion (km <sup>2</sup> /year)	Total accreted area (km <sup>2</sup> )	Rate of accretion (km <sup>2</sup> /year)
1973–1980	19.48	2.78	68.93	9.85
1980–1984	51.26	12.82	32.55	8.14
1984–1989	43.37	8.67	60.57	12.11
1989–1995	41.96	6.99	83.96	13.99
1995–2000	75.21	15.04	55.31	11.06
2000–2005	25.6	5.12	73.72	14.74
2005–2011	63.58	10.6	57.58	9.6
2011–2014	30.85	10.28	27.53	9.18

which overall accretion was higher than erosion (9.23 km<sup>2</sup>). From 2000 onwards, the rate of erosion progressively reduced, but was higher than the rate of accretion for study area.

**Bar evolution**

Overall, the number of bars increased from 1973 to 2014, and the area covered by all bars increased from almost 90 to 199 km<sup>2</sup> during the same period (Table 4). Between



**Fig. 7** Bar evolution between 1973 and 2014

1980 and 1989, the number of bars remained the same (13 bars). Bar numbers were highest (16 bars) in 1995, but then almost halved again by 2000. However, the area covered by the bars remained almost the same during this period. An increase in bar numbers was observed in 2014.

The annual rate of bar erosion was highest (at 15.04 km<sup>2</sup>/year) from 1995 to 2000, while the rate of accretion was highest (at 14.74 km<sup>2</sup>/year) between 2000 and 2005 (Table 5). After 2005, the rate of erosion increased from 5.12 km<sup>2</sup>/year in 2005 to 10.28 km<sup>2</sup>/year in 2014, while the rate of accretion reduced from 14.74 km<sup>2</sup>/year in 2005 to 9.18 km<sup>2</sup>/year in 2014.

The bar chosen for stratigraphic analysis also shows areal expansion from almost 78 km<sup>2</sup> in 1973 to 144 km<sup>2</sup> in 2014 (Fig. 7). This is the largest bar in the study reach and has undergone frequent changes in size and shape, as inferred from the multi-date satellite images.



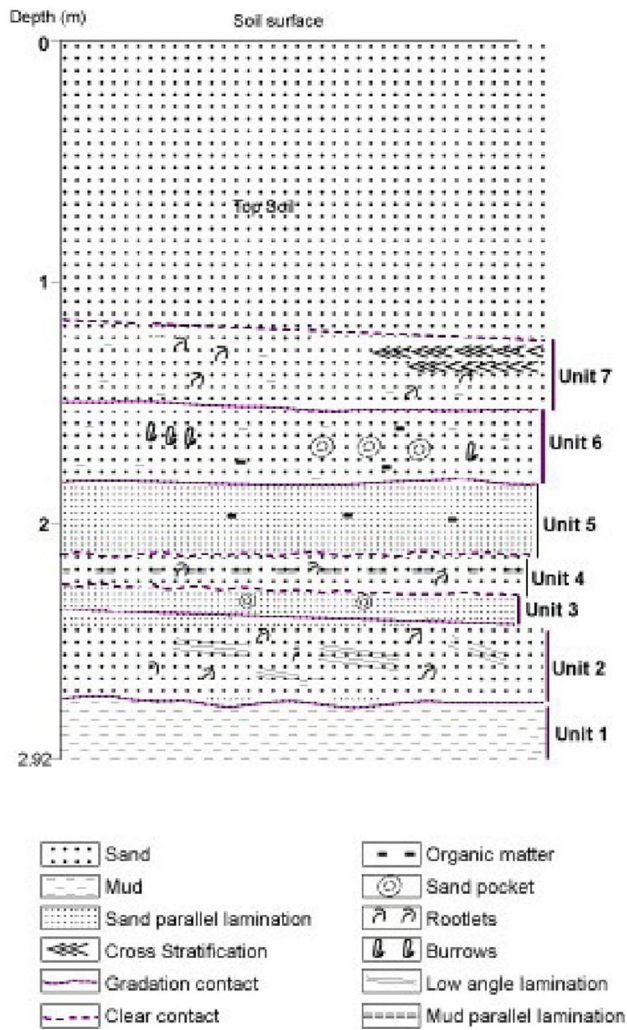


Fig. 8 Stratigraphy of the head section of the bar

**Stratigraphic records**

The head section was divided into eight lithostratigraphic units (Fig. 8). As is evident from Fig. 8, the lowermost layer (i.e. unit one) is comprised of mud and is overlain by the thick sandy second unit. Notable features in the subsequent layers are: the presence of sand pockets in unit three (Fig. 9a), roots in unit four, sand parallel lamination in unit five (Fig. 9b) and roots and burrows in unit six. The next unit (i.e. unit seven) shows herring bone lamination (Fig. 9c) in a sandy layer, as well as some rootlets. The uppermost layer, i.e. the eighth unit, is a massive sandy layer.

The tail section was divided into eight units (Fig. 10). This section was almost 1 m thicker than the head section. In this section, the lowermost unit (unit one) contains ripple marks; the second unit exhibits sand pockets, rootlets and burrows and the third unit contains sand parallel lamination. The fourth unit is a thick massive sand and silt layer

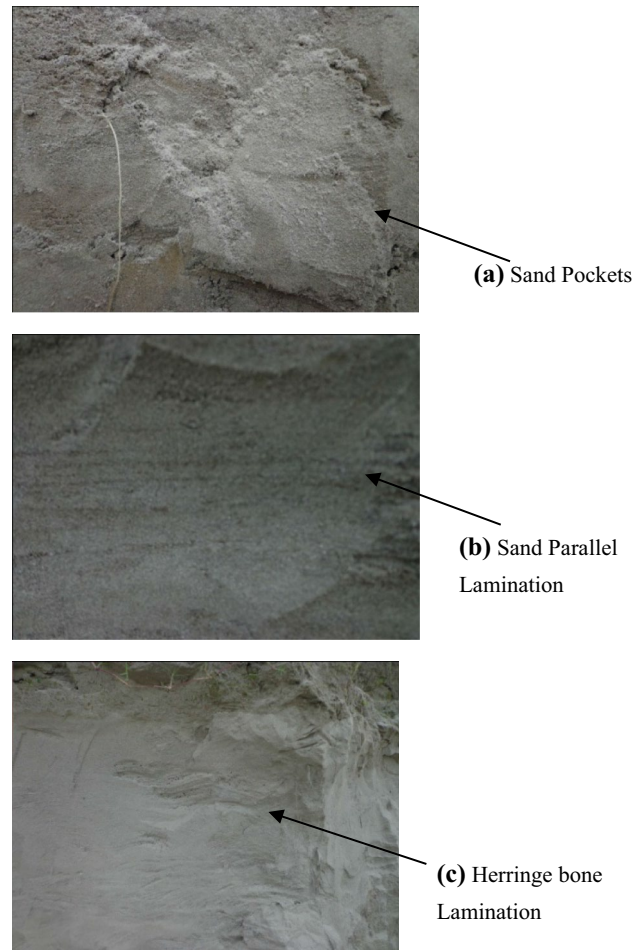


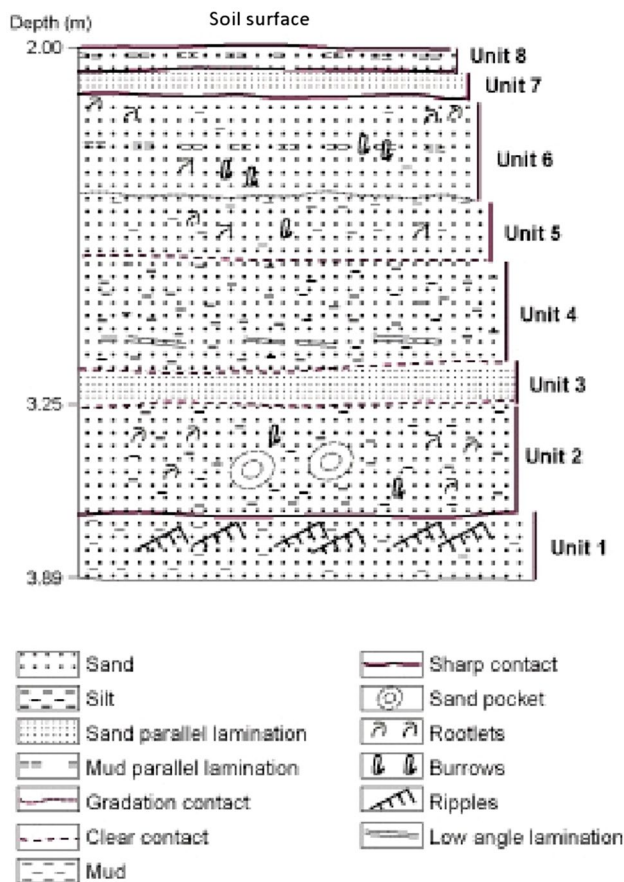
Fig. 9 a Sand pockets in unit 3; b sand parallel lamination in unit 5; and c herringbone lamination in unit 7

with low angle lamination in the lower part only. Unit five contains rootlets and burrows (Fig. 11a) and is overlain by a thick sandy layer (unit six) with clay laminations, along with depositional features like roots and burrows. Unit seven consists of sand and shows low angle mud parallel lamination. The eighth unit consists of clay and has a sharp contact with unit seven (Fig. 11b).

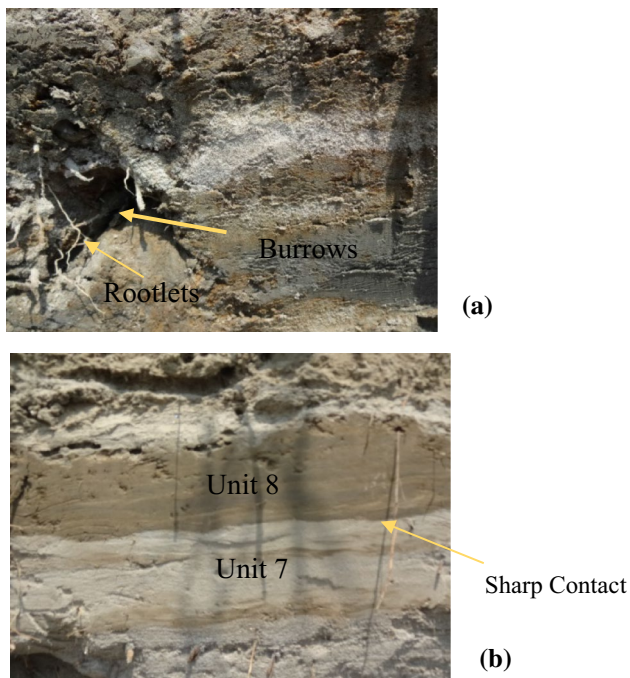
**Texture analysis**

The textural variations within the head, tail and middle sections are illustrated in Fig. 12. The middle section contained much less variation in sedimentary texture than the tail and head sections (Fig. 12b). However, a dominance of sand is common to all the three sections (Fig. 12a–c).

The middle section was divided into 17 textural units (Table 6). The analysis showed that the bottommost unit of the middle section is dominated by sand. Unit two is also dominated by a sandy texture, but unit three showed some variation, with half of it containing more silt than sand or



**Fig. 10** Stratigraphy of the tail section of the bar



**Fig. 11** **a** Unit 5 showing rootlets and burrows; and **b** sharp contact between units 7 and 8

clay fractions. The next two units (four and five) return to a high fraction of sand. Unit six and seven are similar, both exhibiting high percentages of clay. Unit eight to eleven have similar textural types with high amounts of sand once again. Units twelve to sixteen were dominated by sand but also contained significant amount of clay. The topmost unit, i.e. unit seventeen, however, comprises a high proportion of silt.

### Contribution of flow variation to bar area expansion

Spatial analysis of bar areas indicated that they increased from 90 to 199 km<sup>2</sup> between 1973 and 2014. At the same time, water discharge fluctuated significantly (27,931 m<sup>3</sup>/s<sup>-1</sup> in 1970 to 33,983 m<sup>3</sup>/s<sup>-1</sup> in 2013) as inferred from yearly water flow data from the BWDB (Bangladesh Water Development Board). From 1989 to 1995, the number of bars increased from 13 to 16, while the discharge was approximately 30,000 m<sup>3</sup>/s<sup>-1</sup> (Table 4) a somewhat stable discharge relative to flood discharge levels. The annual rate of bar erosion was highest (i.e. 15 km<sup>2</sup>/year) during the period of 1995–2000, despite the fact that when the river also experienced a high discharge of 56,623 m<sup>3</sup>/s<sup>-1</sup> in the 1998 flood. The rate of accretion was maximum (i.e. 15 km<sup>2</sup>/year) between 2000 and 2005, when the discharge rate was between 30,000 and 31,000 m<sup>3</sup>/s<sup>-1</sup> and there were no large flooding events.

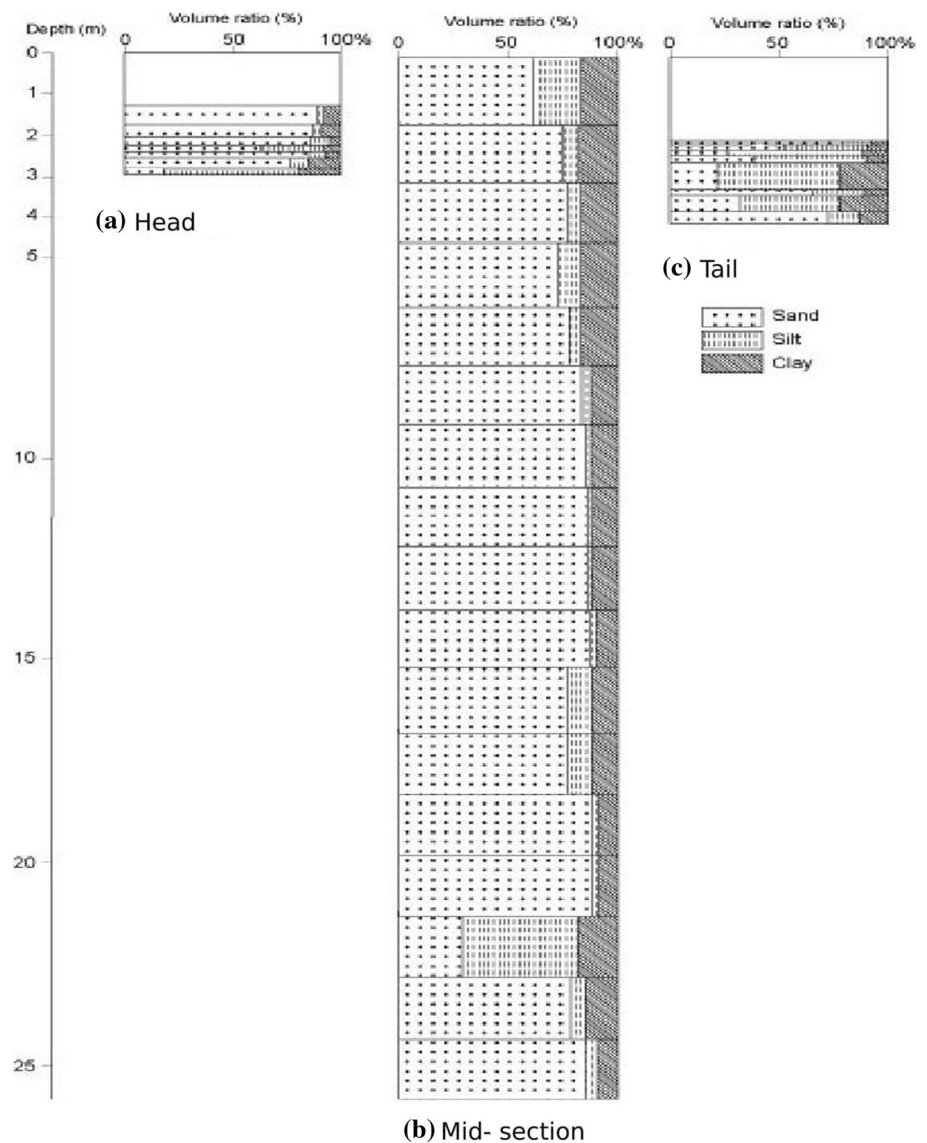
From 1980 to 1989, the discharge fluctuated between 29,605 and 42,824 m<sup>3</sup>/s<sup>-1</sup>. During the same period, the total bar area decreased from 56.28 to 43.68 km<sup>2</sup> (Fig. 7). After the flood discharges of 42,824 m<sup>3</sup>/s<sup>-1</sup> in 1988, the bar area again expanded up to 76 km<sup>2</sup>. After this, area of the studied bar continued to increase to 154.47 km<sup>2</sup> in 2000. The discharge also increased during this time, reaching 56,623 m<sup>3</sup>/s<sup>-1</sup> during the 1998 flood. The analysis further showed that discharge decreased to 33,983 m<sup>3</sup>/s<sup>-1</sup> by 2013, as did the reduction in bar area (144 km<sup>2</sup> in 2013).

The relationship between channel width and bar area showed a strong positive correlation ( $r^2 = 0.80$ ,  $p = 0.008$ ). On the other hand, a moderate correlation was found between bank erosion and bar area expansion with a correlation coefficient of  $p = 0.016$ , which was significant at the 95% confidence level.

### Discussion

The results show that the selected reach of the Padma River is highly dynamic. It has undergone erratic movement through erosion and accretion of banks and bars. A similar type of behaviour of the Padma was also observed by Dewan et al. (2017) and Rahman and Alam (1980). One of the important findings of this study is that the width of the study reach has almost doubled in the study period

**Fig. 12** Textural variation in different sections of the bar **a** head; **b** middle and **c** tail



(1973–2014) which corroborates the finding of Sarker et al. (2003). Amongst six cross sections, three of them, namely c, d and e (Fig. 1), experienced notable widening, and these sections are dominated by many mid-channel bars.

Erosion and deposition of the river bank varied both spatially and temporally throughout the study period (1973–2014). According to the physiographic division of the floodplains (Rashid 1991), the left bank of the river is an older floodplain than the right bank and the length-averaged erosion is higher along the left bank than the right bank (ISPAN 1995a, b). This study also showed that maximum bank erosion occurred along the left bank, compared to the right bank, reinforcing the theory that the composition of bank materials determines bank stability, particularly along the study reach. A similar observation was made by Li et al. (2007) in their study in China.

Significant changes in the bar area and number of bars were observed in the study. Satellite data, hydrological analysis and stratigraphic records showed that bar changes were related to the variation in water flow, and that discharge may be an important factor affecting bar growth and shrinkage. Other studies (Tiegs and Pohl 2005; Yao et al. 2011) support the link between water discharge and bar evolution.

Our analysis further indicated that erosion–accretion pattern of the river depends heavily on the occurrence of floods. For example, between 1989 and 1995, the number of bars increased, which may have been the result of the flood event of 1988, which supplied significant amounts of sediments to the river. However, the rate of bar erosion was highest in the period of 1995–2000, probably a response to high discharge of the 1998 big flood. On the other hand, the flood of 1998 may also have inundated the bars which possibly initially reduced in size, but with time, both the number of bars and

**Table 6** Textural description of the units of the midsection of the bar

Unit no.	Thickness (m)	Texture			Environment
		Sand (%)	Silt (%)	Clay (%)	
Unit 1	1.524	82	3	15	Sand bar
Unit 2	1.524	69	11	20	Sand bar
Unit 3	1.524	21.5	52.5	26	River-dominated deposit
Unit 4	1.524	86.63	0.875	12.5	Sand bar
Unit 5	1.524	86.63	0.875	12.5	Sand bar
Unit 6	1.524	74.5	11.75	13.75	Sand bar
Unit 7	1.524	74.5	11.75	13.75	Sand bar
Unit 8	1.524	83.25	6.25	10.5	Sand bar
Unit 9	1.524	80.75	6.25	13	Sand bar
Unit 10	1.524	80.75	6.25	13	Sand bar
Unit 11	1.524	82.25	3.75	14	Sand bar
Unit 12	1.524	79.75	6.25	14	Sand bar
Unit 13	1.524	76	7.5	16.5	Sand bar
Unit 14	1.524	73.5	11.25	15.25	Sand bar
Unit 15	1.524	76	8.75	15.25	Sand bar
Unit 16	1.524	73.5	10.5	16	Sand bar
Unit 17	1.524	58.5	27.5	14	River-dominated deposit

their corresponding area increased with further deposits. The rate of accretion was highest between 2000 and 2005, when the discharge remained relatively stable (i.e. year-to-year variation was relatively low). As the river experienced no large floods after 2004, the areal extent of the bar remained somewhat stable.

Bar stratigraphic records support the findings of satellite image analysis, especially by showing that bar evolution generally followed discharge fluctuation of the Padma River. For instance, the stratigraphic description of the bar head shows that the lowermost layer is a uniform mud layer overlain by sandy thick layer, which might have been created by sediment brought by high discharge during the 1988 flood though we have no sediment data to verify this. This supports the observation of Sinha et al. (2005), who noticed that mud-dominated units are recognized as flood deposits of major rivers. Sand pockets were observed in the next unit, which may have been created during fluctuations of inter-annual water flow between 1988 and 1990. In unit four, the presence of roots is likely to have resulted from stable flow conditions, which may correlate to the relatively stable discharge conditions between 1991 and 1995 (Fig. 4). The sand parallel lamination of unit five suggests that the flow regime was low energy during this period, while the presence of burrows and roots in unit six also supports stable depositional conditions during this time. Unit six was probably formed by sediment from the flood event of 1988. The rootlets in the seventh unit imply that it was exposed and vegetated for a few years. Between 2001 and 2004, water discharge fluctuated, which may be represented by the herring bone lamination of this unit.

Lastly, the uppermost massive sandy layer is most likely the result of the large flood of 2004.

The stratigraphy of the tail section may be interpreted as a meandering river facies. Low angle lamination in a mid-unit in the stratigraphic record supports the occurrence of erosional processes in this section, suggesting that flooding has had an important role in determining bar evolution. In the tail section, the lowermost unit has ripple marks; indicating unidirectional flow and a low energy regime. The sand pockets of the second unit were probably formed during the sharp fall in discharge, while the sand parallel lamination of unit three and rootlets and burrows of unit two indicate stable flow. However, there is a lack of discharge data to determine the exact time of deposition of these units. The large amount of silt in the fourth unit was probably supplied by the meandering river created in 1984. Unit five represents stable conditions, given the presence of rootlets and burrows, and this might have been formed during the stable discharge conditions between 1991 and 1995. The thick sandy layer with clay laminations along with depositional features such as roots and burrows in unit six may have been brought by flooding in 1998. Unit seven consists of sand and shows low angle parallel lamination, which may correlate to a point bar facies of a meandering channel. Unit eight appears to be a floodplain facies, consisting predominantly of clay, and with a sharp contact with unit seven. This unit might have been flooded for some time and might be reflecting the fluctuation of discharge between 2001 and 2004. The top soil was formed probably after the high discharge flood event of 2004.

According to Sinha et al. (2005), in the lower Ganges plains, and in deltaic plains in general, sandy deposits dominate due to combined effect of lower tectonic activity and higher fluvial influence. Our findings on sediment textures reflect this observation.

However, unlike the bar head and tail, the middle section of the bar showed a high consistency in sedimentary texture. It is therefore the most stable part of the bar, corroborating the analysis from satellite data. Gao et al. (2013) suggested that the middle and lower portion of a bar grow due to erosion of the head section. Since the area of the examined bar is very large, and our sampling locations widely separated, the result of our work is inconclusive with regard to this suggestion. Further study is therefore required to determine whether the middle and tail sections were created through the eroded materials of the head section.

The analysis further indicated a positive association ( $r^2 = 0.64$ ) between river bank erosion and bar area expansion, which supports the hypothesis that eroded bank materials contribute to the growth of both the number and area of bars. This may be especially true of bank erosion in the immediate upstream zone, which initiates mid-channel bar formation downward (Ashworth et al. 2000). Moreover, the increases in channel width during the study period showed a strong correlation ( $r^2 = 0.80$ ) with the expansion of the bar area. This implies that the increase in bank erosion has resulted in channel widening, and the growth of bar numbers and area are largely associated with bank-to-channel sediment transfer (Ta et al. 2013). This type of relationship between channel change and bar evolution is also documented by Yao et al. (2011) in their study on the Yellow River. Sarker et al. (2003) study also supported this form of bar growth in alluvial systems of Bangladesh.

## Conclusion

In this study, morphological changes in a selected reach of the Padma River were studied with the use of both satellite images and stratigraphic records. Landsat data from 1973 to 2014 were used to quantify channel and bar characteristics. A spatial database containing river boundaries and bars was developed by analysing multi-temporal Landsat images. Channel characteristics such as river width, bank movement, and patterns of bar erosion and deposition were determined. A stratigraphic analysis was performed at two selected locations of the bar to assess its evolution. The midsection of the bar was subject to textural analysis. In addition, daily discharge data for the selected reach were analysed to determine the effect of discharge variations on channel properties.

Image analysis revealed that, over the study period, the width of the river almost doubled. Overall, erosion was higher than accretion. The bars in the river underwent

substantial changes. Many bars were formed in this reach since 1973. In particular, the rate of channel widening and bank erosion was seen to be positively correlated to increments in the bar area.

Study of the lithostratigraphy showed that the river bar formation has been affected by the variations in water discharge. The presence of rootlets and burrows in certain units is indicative of a stable depositional environment, and these layers were probably formed from sediment put into suspension following major floods (e.g. 1988, 1998 and 2004). The fluctuation and diminishing of water discharge was also noticeable through the presence of features like sand pockets.

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