

Application of remote sensing and GIS for evaluation of the recent morphological characteristics of the lower Brahmaputra–Jamuna River, Bangladesh

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Abstract This paper deals with the morphological changes of the lower Brahmaputra–Jamuna River (BJR) in Bangladesh. Within few decades, the planform of the river has been changed abruptly by the combined effect of natural process and human interventions. Morphological features observing in this study were river planform, channel width, bankline migration and channel bed elevation. Eighteen sets of remote sensing data series from 1973 to 2011 were analyzed using ERDAS/Imagine and GIS to document the variation of geomorphic elements of the lower BJR. GIS analysis of remote sensing data showed that the changes of channel planform were quite significant over the past 40 years, occurring two major phases of channel development. The changing patterns in the first phase (i.e., between 1973 and 1992) were quite irregular. However, the second phase ranging between 1992 and 2011 was unidirectional (mostly eastward). In general, the studied river reach was widened and the average rate of migration was 225 m y^{-1} that was three–folds the values of the first phase. The height and slope of sand bars were gradually increasing, showing the highest value around the Jamuna Multipurpose Bridge (JMB) section. The planform characteristics of BJR at the downstream of JMB showed that the river reach was gradually widening and shifting eastwards. However, the reach at the upstream of the JMB showed

westward migration. The recent trends of channel changes suggest that the river planform has lost its naturally condition and it may, therefore, be predicted that increasing nature of channel width likely to continue in the immediate future.

Keywords Remote sensing · GIS · Brahmaputra–Jamuna River · Channel planform

Introduction

In various catchments throughout the world human intervention has strongly altered natural river dynamics, especially in recent decades (Surian 1999). The response of flow processes and channel morphology to engineering and regulation of alluvial streams have been studied widely (e.g. Gregory and Park 1974; Petts 1977; Williams 1978; Castiglioni and Pellegrini 1981; Williams and Wolman 1984; Andrews 1986; Knighton 1989; Dutto and Maraga 1994; Petit et al. 1996; Billi and Rinaldi 1997; Kondolf 1997). The results of these studies not only demonstrate that process–response may generate remarkable channel changes, but also show that the modes of change and response times vary considerably from one stream to another.

Systematic, large-scale observations of channel morphology are essential to evaluating human impact on stream behavior (Marston et al. 1995; Graf 2000). Observations of physical dimensions (such as width and volume), combined with observations of vegetation and channel form, provide critical parameters with which to identify anthropogenic perturbations in natural drainages (Buckingham and Whitney 2007). Numerous studies have evaluated basic channel change by using geospatial techniques, such as overlaying a series of historical channel maps (Downward et al. 1994; Marston et al. 1995; Gurnell 1997) in different types of river systems. Besides, geospatial studies of channel morphology have

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largely been limited to examinations of alterations in channel form (e.g., width, shape, change of position).

The Brahmaputra–Jamuna is one of the largest braided fluvial systems in the world (Fig. 1). In Bangladesh part, the river was flowing naturally up to early 1990s with average width of 14 km in the lower BJR (Fig. 2). Recently, the natural flow system of this river reach has been modified by river training works during construction of Jamuna Multipurpose Bridge (JMB). The total length of JMB is 4.8 km. The east and west guide bunds of the bridge are 3.07 km and 3.26 km, respectively. The width of the east guide bank is 500 m whereas that of west bank is 532 m. In fact, the Bridge was constructed over 50 piers, each of circular shape with 8 m wide with pile length of 83 m. Thus, river corridor was reduced 400 m in addition to the bridge length and extreme erosion was observing at various parts of the study reach. Due to rapid sedimentation, bar growth was gradually increasing with the expansion of the channel corridor. These processes thus, accelerated the braided development at different parts of the river systems. Therefore, the nature and trend of channel

migration at different parts of the major tributary and distributary channels within the braided system attempts vitally to scientific interest.

Recently, few studies concentrated on the morphological development of the BJR, Bangladesh. For example, Takagi et al. (2007) evaluated channel braiding and stability of the BJR in Bangladesh part using remote sensing analyses from late 1960s to late 1990s. Mount et al. (2013) showed the continuous wavelet transforms are used to explore spatio-temporal patterns of multi-scale bank line retreat along a 204 km reach of the Jamuna River, Bangladesh. Furthermore, Sarker et al. (2014) studied the morpho–dynamics of the Brahmaputra–Jamuna River, Bangladesh which has attended the morphological evolution of the Jamuna River since the avulsion that created it about 200 years ago, and to establish temporal trends and spatial patterns in the changes that have characterized process–response mechanisms in this fluvial system since then. Nevertheless, the effects of recent morphological development and human-induced process on channel morphology (e.g., river training works and excess

Fig. 1 Location map of the study area



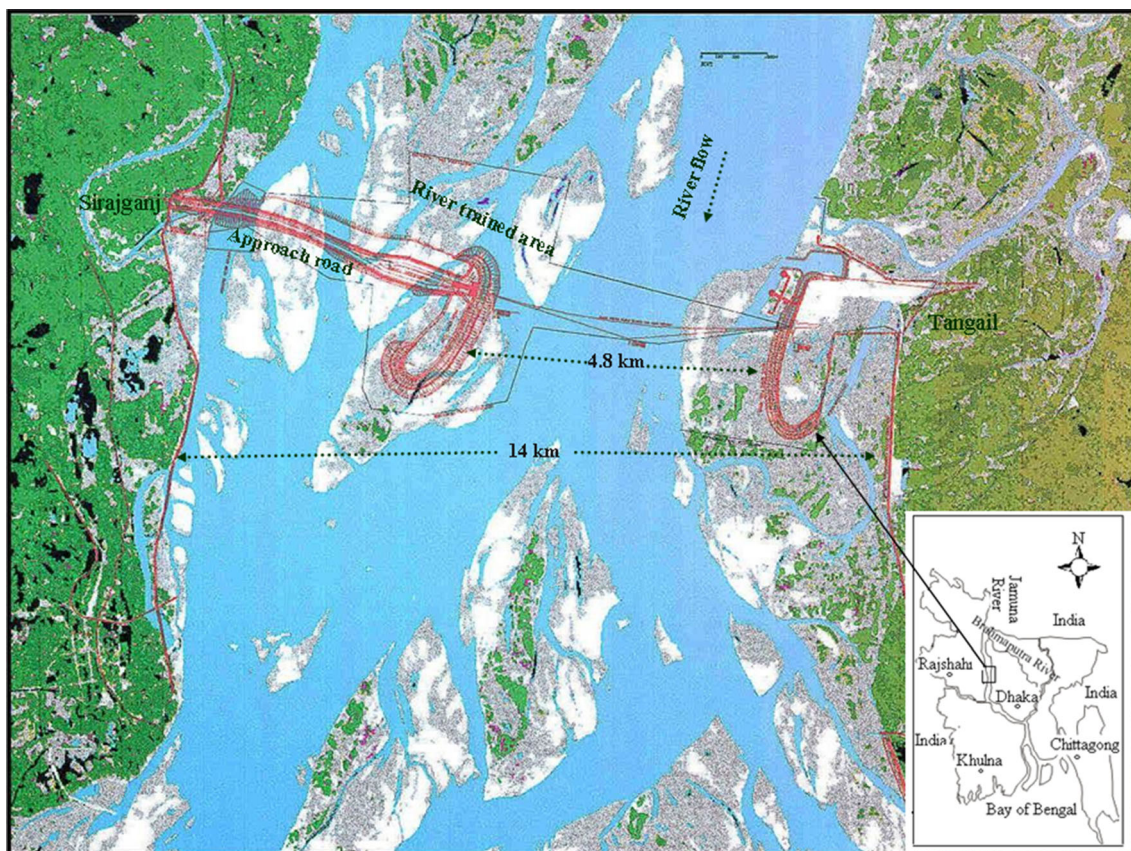


Fig. 2 Plan view of Jamuna Bridge section in the lower Brahmaputra–Jamuna River, Bangladesh

narrowing of river width) of the lower BJR were far from scientific evaluation. However, in addition to natural condition, the present study aims to evaluate the effects of large scale human-induced processes on the small scale river reach in the lower part of BJR. This research will also investigate the comparative morphological condition in natural condition and after modification by human-induced process across the lower BJR.

In view of all aspects mentioned above, this research examines the channel morphology of the lower BJR in Bangladesh, and, in particular, changes that have occurred in response to imposing human-induced alteration on the river reach (river training works) in a fine scale observation. However, documentation of these changes will be useful in several ways. First, it will support the evaluation of the effects of human intervention on the channel morphology. Second, it will provide data for future management of the fluvial system.

Geographical settings

The Brahmaputra River (BR) drains a catchment area of 580,000 km² with more than half of the area lying within China and Tibet; the remaining includes parts of Bhutan, India and Bangladesh. The total length of the BR is 2,906 km with its source being the Kanglelung Kang glacier in Tibet at an

altitude of 4877 m (Boruah et al. 2008). The Brahmaputra, flowing along the northern slope of the Himalayas enters into Bangladesh at Kurigram after crossing Asam (India). On the other hand, the lower BR (locally called Jamuna) is quite young and the history is not more than 250 years. The study area is around 20 km river reach located at the lower part of BJR, lies between Bahadurabad (the off-take of Old Brahmaputra and Jamuna Rivers) and Aricha (the confluence of Ganges and Jamuna River) (Fig. 1), maintains its gradient from 0.10 to 0.06 m/km (Takagi et al. 2007) and maintains the mean elevation around 10 m from the mean sea level. Jamuna can be visualized as the lowest reach of BR in Bangladesh. The world 11th largest (4.8 km) JMB construction was inaugurated in 1996 across the study area (Fig. 2). Therefore, this area is considered an economic buffer zone for the central and northern part of Bangladesh. The commercially important cities, Sirajganj and Tangail, are situated on the west and east banks of study reach, respectively. These two cities are densely populated (1,980 person per km²) and overall 1 million people live in these two cities.

Precipitation and discharge

The annual average precipitation in the study area ranged from 1,500 mm to 2,500 mm. The variation of precipitation

maintains a regular trend from 1950 to 1986. After that it slightly increased and the maximum value was observed 3,000 mm between 1986 and 1994. Behind that it decreased to 2,000 mm in 1998. Indeed, the climate in the study reach is a part of Aw (Climate Zone 10: Tropische Kontinental–Monsunklimate) of Köppen's (1936) climatic zones which maintains high temperatures and shows a clear contrast between the wet and dry seasons (Takagi et al. 2007). As a result, the seasonal variation of discharge is very high in this river system. The maximum discharge during the monsoon season is 50,000 m³ s⁻¹, while that of the winter season is less than 10,000 m³ s⁻¹ (Takagi et al. 2007). In general, the mean annual discharge measured at Bahadurabad point range from 35,000 to 45,000 m³ s⁻¹. The entire area is submerged with monsoon flood which sometimes overflows up to 3 to 4 m above the flood plain (e.g. 1988, 1998 floods etc.). Annually 1.5×10⁷ tons of sediments deposited at the JMB region, where the maximum values 2.3×10⁷ and 2.4×10⁷ tons were observed in 1988 and 1998 flood's seasons (data collected from Bangladesh Water Development Board data–sheets). The mean annual discharge of BJR is 60,000 m³ s⁻¹. The flood flow in 1998 remained above riverbank for nearly 3 months in the Jamuna. The average flood discharges in the BJR during July to September of 1998 were around 150 % of the long-term average discharge for that period (Islam and Chowdhury 1999). An analysis of inflow and outflow as a function of time indicates that the floodplains stored about 10 % of the flow during 1998 flood, and as a result the peak discharge diminished considerably as the flood wave moved downstream. The stage–discharge relationships for flood waves in the Jamuna and the Ganges displayed significant loop characteristics (Islam and Chowdhury 1999).

Sedimentological characteristics

This drainage basin contains very young, unweathered sediments, and little clay is available for transport. The bed load thus predominantly consists of medium to fine sand and silt. Being recently deposited, the sediments are characterized by high water content and are loosely compacted. The characteristics of sediments and the high amount of materials imposed on the channels by the flow system turns the rivers continuously to adjust their bed configurations to differ flow regimes. In this regard, the sediments of BR are not only deposited in millions of tons but are also highly susceptible to erosion when flow conditions alter (Coleman 1969).

Methods

The satellite-based remote sensing data is effective in investigating river channel morphology over a wide area. Although

this method has often been employed to investigate river channel migration (Thorne et al. 1993; Yang et al. 1999) and to identify paleo–braided channels on terrace surfaces (Leigh et al. 2004), its application to the braided channel dynamics over a wide area has been employed to many studies (e.g. Muller et al. 1993; Milton et al. 1995; Gilvear et al. 1995; Gupta 1995; Ashworth et al. 2000; Gupta et al. 2002; Gilvear and Bryant 2003; Ollero 2010). However, lack of appropriate resolution, the satellite imagery sometimes performs poorly to evaluate base-channel morphology of the deep water fluvial systems. Hence, by integrating cross–sectional data, satellite image may provide better results for understanding the morpho–dynamics of the channel parameters. The behavior of major channel and/ or some selected channel segments of the lower braided BJR have been analyzed for 38 years from 1973 to 2011. Satellite imagery of Landsat MSS (1973, 1976, 1980 and 1985) and TM (1992, 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002, 2005, 2006, 2009, 2010 and 2011) bands of 18 different year–sets (Table 1) were used for plan–form analysis (Fig. 3a–b). The data used in this study have been sourced from the Centre for Environmental and Geographical Information Services (CEGIS), Dhaka. CEGIS have been responsible for quantifying bank retreat rates along the entire length of the BJR in Bangladesh from satellite imagery for the period 1973–present (shown in Table 1). Their data has formed the baseline geomorphological dataset for the World Bank's Flood Action Plans (1991 and 1992) and where details were mentioned in (EGIS 1997).

Table 1 Information about satellite images used in the study

Year	Date of acquisition	Types of images	Resolution (in meter)
1973	21-Feb	Landsat MSS	80 X 80
1976	10-Jan	Landsat MSS	80 X 80
1980	12-Feb	Landsat MSS	80 X 80
1985	25-Feb	Landsat MSS	80 X 80
1992	8-Mar	Landsat TM	30 X 30
1995	28-Jan	Landsat TM	30 X 30
1996	31-Jan	Landsat TM	30 X 30
1997	18-Feb	Landsat TM	30 X 30
1998	5-Feb	Landsat TM	30 X 30
1999	23-Jan	Landsat TM	30 X 30
2000	19-Feb	Landsat TM	30 X 30
2001	28-Jan	Landsat TM	30 X 30
2002	20-Feb	Landsat TM	30 X 30
2003	15-Feb	Landsat TM	30 X 30
2005	10-Feb	Landsat TM	30 X 30
2006	21-Feb	Landsat TM	30 X 30
2009	12-Feb	Landsat TM	30 X 30
2010	7-Feb	Landsat TM	30 X 30
2011	10-Feb	Landsat TM	30 X 30

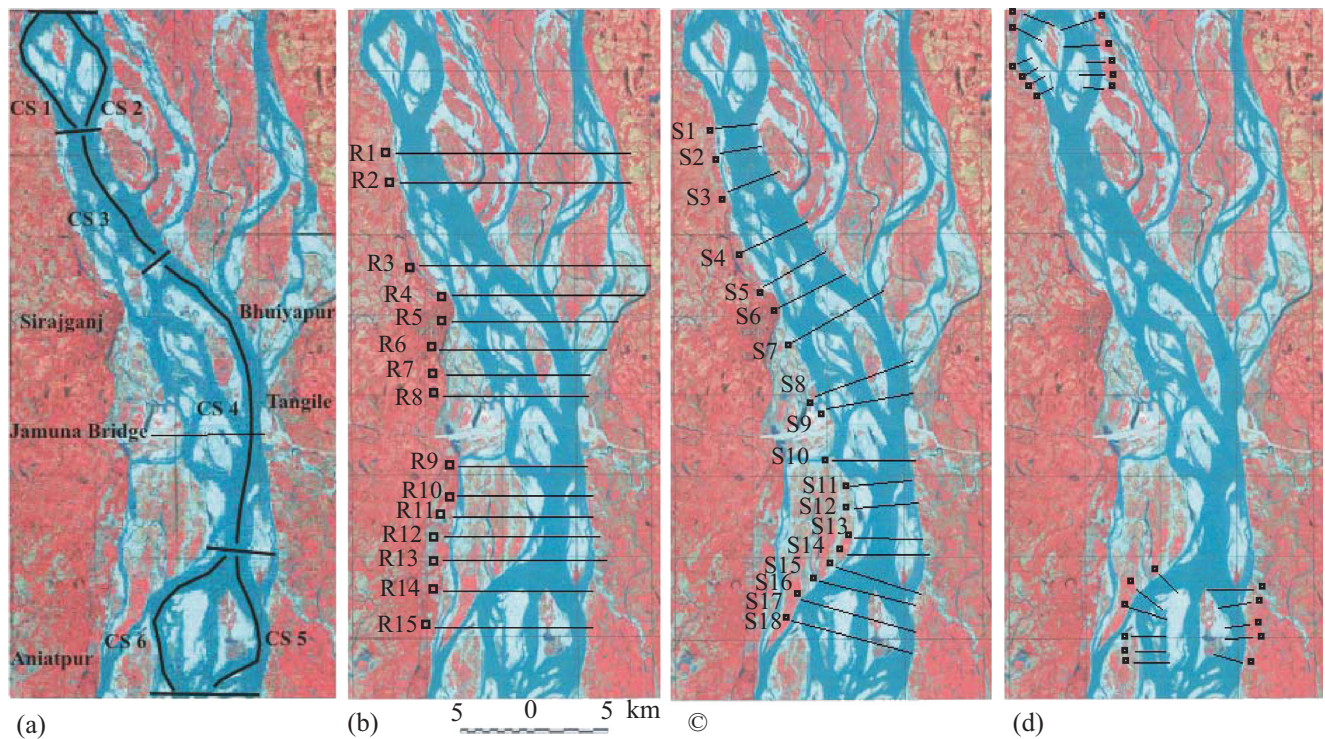


Fig. 3 (a–d) Scratch of the channel segments and width measuring points of different channel systems. (a) Location of the channel segments (CS) (Image February, 2000), (b) Width measuring points (R) for the

braided-belt, (c) Width measuring points (S) for the major channel, and (d) Width measuring points for the secondary channels

All images were mosaiced and georeferenced to a 1:50,000 scale colour base map and projected using the UTM-46 N projection (CEGIS, 2007). For each image in the mosaic, more than 25 ground control points (GCP) were employed to characterize a first order transformation to the base map. Where possible, GCPs were taken from recognizable and permanent features such as road intersections, airport runways and large buildings. The maximum root mean square (RMS) error of the transformation was 96 m for the Landsat MSS imagery (1987) and 45 m for the Landsat TM imagery (1989–1999). Due to availability of cross section data, the bottom–topography in the study reach was analyzed only for the year of 1999, 2000 and 2001. For meander bend evolution, entire river reach was divided into six channel segments (prefixed as CS) on the basis of their potential bend development affinity. These were denoted as numerical value from 1 to 6 (Fig. 3a). Where, CS 1, CS2, CS3 and CS5 are flowing along the Sirajganj district and CS 4 and CS6 dominantly flow along Tangail areas.

The present study has been concentrated to evaluate fluvial geomorphic features both in spatial and temporal scale based on the satellite image and bathymetric data. Remote sensing data in this study were used for predicting the morphological changes of the river reach. The multi–temporal image results were analyzed to determine the interaction between channel-changes and bar-growth. The ERDAS Imagine 10.0, ArcGIS Desktop 10.0 and AutoCAD Map 2000 software were used for image processing and vector raster GIS analysis. In image

processing stage, geometric corrections were conducted to rectify the images into UTM–46 N projection system. In this study, orthogonal transformation was not carried out because the study area was very flat and the effects of height differences were negligible. In order to co-register the datasets in georeferencing process, each image has to be warped onto a base map. This process requires the selection of ground control points (GCPs) which feature on a map and also can be identified on the satellite image. Ideally, GCPs should be well dispersed for accurate rectification. However, preferred GCPs used in this study are road intersections and bridge abutments. The digital satellite images were classified using image processing techniques (supervised classification) to classify the land cover into areas of similar spectral characteristics, which were classified into three broad groups by using an iterative classification procedure, i.e., water, new bar (sand bar) and old bar (including cultivated/vegetated land). Lastly, to facilitate the appropriate comparisons of datasets for different periods, the resolution of land cover data for all the periods was reduced to the least common multiple (240 m) of the Landsat MSS resolution (80 m) and TM resolution (30 m), using a data aggregation algorithm (Takagi et al. 2007). A spatial overlay of each pair of classified images between two consecutive years was carried out by using GIS modeling techniques. While both the classified images were in the same projection system, the overlay (Dale and Morris 1996) generates a map showing the migration of the channel parameters.

The width of braid–belt, major channel and secondary (tributary/distributary) channels (Fig. 3b–d) (after Thorne et al. 1993) for each year was measured at each of the 833 E–W lines aligned from north to south following the procedure of Takagi et al. (2007). Here Channel–width determinations were made simply by measuring the bank–to–bank width at the cross section of interest on the particular image. In computing channel width, the width of stabilized islands (those covered by perennial vegetation) was subtracted from the bank–to–bank width of the general channel. Thus the width data presented here approximately represent the width of flowing water at bankfull flow (Williams 1978). The method proposed by Mount et al. (2003) was applied to establish the validity of assessing the changing width of the BJR using the time–series of available satellite images. The detection of left and right bankfull positions along a predetermined section line, drawn onto the corrected imagery at 90° to the channel, formed the basis of bankfull width measurement calculations for all imagery. In this study, as the imageries were geo–corrected and ortho–corrected, channel bankfull width was determined by ERDAS Imagine’s measurement tool. This tool links images geographically, so that a section line drawn onto one image appears in the same location, on all other images according to their individual registrations (Mount et al. 2003). Section lines were established at 90° to the river channel on the 1992 image, at a downstream interval of approximately 300–800 m (roughly a single channel width). Where erosion/deposition between successive images had caused channel rotation, relative to earlier imagery, section line azimuths were adjusted to confirm they were always at 90° to the bank. Cartesian coordinates for left and right bankfull positions on the section lines were recorded. Bankfull width was calculated from the Cartesian coordinates using basic geometry (Mount et al. 2003). It is better to maintain the uniformity for the distance between two transects. In this study the distance between two transects were relatively irregular (around 300–800 m). In the study reach the banklines in several places were protected by some engineering structures (e.g., hardpoints, dykes, spars, groins etc.) where the width of the channel has no variation. Therefore, the engineering structures have been avoid before selecting the transect points and thus transects were not uniform.

Radius of curvature of each channel segment was measured along a channel centerline that consisted of successive line segments using standard methods of Goudie (1990). Maximum migration rates (meters per year) for each meander bend were determined by dividing the distance between successive low–water banklines and then dividing by the number of years, following the approach of Hooke (1987). In this study, the center line of the major channel was drawn by connecting channel mid–points from upstream to downstream

sections. The lateral shifts of channel center line were calculated from the respective satellite images. In this study, we employed the standard use of the term “major channel” to describe the channel which exhibited the dominant flow path, and also divert and rejoin the subsidiary/secondary channels to the main flow. Most braided reaches will include one or more larger channels which persist between flood and drought events. These larger channels usually have multiple side channels which exemplify the characteristics of a braided river (Gray and Harding 2007). Our general usage of the term “braid–belt” hereafter refers to the entire belt of braid channels (major and secondary) as a whole. Likewise, channel refers to the secondary/ tributary/ distributary channels in the braided systems.

Traditionally, bank erosion has been examined by intensive fieldwork involving the use of erosion pins or cross–profile surveying. These methods have several limitations: firstly, they involve interference with the bank face being measured; and secondly, the spatial resolution is limited to the points under investigation. Photogrammetry/remote sensing reduces spatial sampling problems and enables bank erosion to be monitored with minimal contact on the bank face itself (Barker et al. 1997). However, among the available methods erosion lengths within the reaches in this study have been identified based on the exhibited bank line shifts in the duration of study area (after Akhtar et al. 2011). In this study, following the established methods of Gurnell et al. (1994), Gurnell (1997), Mount et al. (2003) and Mount and Louis (2005) maximum bank erosion in the BJR could therefore be assumed to occur in a direction orthogonal to the main channel (i.e. in an easterly direction). Consequently, bank migration between consecutive images at each location was computed as the difference in the easting coordinate of the bank line position, converted to m y⁻¹ according to the capture dates of the imagery (Table 1).

The major channel width and the width of braid–belt/flood–plain ratio were calculated from the satellite image (Fig. 3). To demonstrate the fact of flow separation and bend development intensity, the ratio of radius of curvature (R_c) to channel width (B) was calculated from the available satellite imagery. Bagnold (1960) argued that total resistance to flow around a bend depends upon the ratio of R_c/B , with a local minimum ratio at approximately 2. Leeder and Bridges (1975) also demonstrated that flow separation occurs when, for a given Froude number, the radius of curvature to channel width ratio exceeds a critical value of 2. When this occurs, the zone of active flow constricts around the bend due to the development of a flow separation envelope, often with a reverse current, on the inside of the bend, producing a zone of higher flow velocity and thus maximum bank erosion downstream of the bend apex at the outside bank (Leeder and Bridges 1975). The expression for the lateral bed slope parameter, A_* can be written (after Rahman et al. 2002) as

$$A_* = \frac{H_B R_0}{2Bh}$$

Where, R_0 =radius of curvature of channel bend at apex, h =reach average water depth (m), B =channel width and H_B =bar height=difference between the highest and lowest bed level within a wavelength. For a given channel width and radius of curvature, A_* is directly proportional to the bar height (H_B), which obliges to deviate flow velocities towards the opposite bank of a sand bar.

Analysis and results

Bank erosion and bend development

On the basis of availability, eighteen year-sets of Landsat MSS and TM imagery (from 1973 to 2011) were used to illustrate the chronology of channel migration. While all available year-sets were evaluated in GIS for change analysis. But the only year-sets marking significant morphological transitions were depicted in accompanying figures (Fig. 4a–d) so that graphical clarity and interpretability could be maximized.

Lateral migration of channel is arguably the dominant erosion process in fluvial environment. In order to compare the changes of river bank position using GIS overlays depicted on the 1973–1980, 1980–1985, 1985–1992, 1992–1995, 1998 (Fig. 5a–f) and 2000, 2002, 2005, 2009 and 2011 (Fig. 4g–k) satellite images, the differential trend of erosion was observed in 18 time series data from 1973 to 2011. Finally, the overall shifting of the major channel in the study reach was projected in Fig. 4l. The migration pattern of bankline in the upstream (Sirajganj) and downstream part (Aniatpur) of JMB was slightly regular between 1973 and 1980 (Fig. 5a). A significant movement of bankline was observed at the downstream part which directed westward. While the major eastward shifting of bankline was observed in the central part of the channel segment 4 (near Sirajganj–Tangail) (Fig. 4b) which just reverses of 1980. After 1992, the bankline migration in the central part of channel segment 4 was relatively unidirectional (Fig. 4c–f) and directed eastward. In general, the channel at upper part of JMB (Sirajganj region) showed westward migration, whereas the central and downstream part (Tangail region) migrated eastward from 1992 to 2011.

Using satellite images, the maximum erosion and deposition rates were calculated 2376 m y^{-1} and 2340 m y^{-1} , respectively. Rates of bank erosion and deposition, however, were highly variable depending upon position of the channel bend, sediment and vegetation characteristics of the respective channel. The results of Takagi et al. (2007) were quite similar for channel braiding and morphological stability. In the present study, four distinct stages/phases of change were evident

from remote sensing image between 1973 and 2011 (Table 2). In stage 1 (1973–1980), the upper part of the study reach was characterized as erosional side and the maximum rate of erosion was 1093 m y^{-1} (Fig. 4a). This finding is also similar to that of Sarker et al. (2014) where the bank retreat was evaluated for the entire BJR. Whereas, the lower reach was identified as depositional/contraction and the maximum rate of contraction was 2187 m y^{-1} . In stage 2 (1980–1992), the upper part of the study reach was contracted (Fig. 4b and c). The maximum rate of contraction was 400 m y^{-1} . The lower part of the channel however, was characterized by gradual widening/erosion. The annual rate of widening was 223 m y^{-1} which ranging from $118 - 381 \text{ m y}^{-1}$. In stage 3 (1992–1999), most of the reach was characterized by widening process (Fig. 4d–f). The rate of contraction varied from $32 - 640 \text{ m y}^{-1}$ with the mean being 272 m y^{-1} . In stage 4 (2000–2011), the widening process was still continued in all sections (Fig. 4g–k). The rate of widening varied from $137 - 597 \text{ m y}^{-1}$ with the mean value of 350 m y^{-1} that almost same as the value evaluated by Sarker et al. (2014). The outer banks of the study reach were highly dynamic, with rapid migration of its channels along the east bank from 1973 to 2011 (Fig. 4l). A maximum erosion rate 736 m y^{-1} was observed at the immediate upstream of the bridge site. The east bank was mostly dominated by erosion after 1992 and continued up to 2011. Within the time span, the net migration of bankline toward the east bank and west bank was 5000 m and 900 m respectively.

Lateral shifting of the channel center line

The variation of the channel center line between 1973 and 1976 was small (Fig. 5). While the shifting between 1980 and 1985 was relatively high and recurrently oscillated in opposite directions. The oscillation between the time periods was prominent at the downstream section of the bridge site. Using the method of Nicoll and Hickin (2010), the average calculated movement for all bends in the study reaches for each time interval afterward divided by the number of years between the sets of time series to obtain an annual migration rate. The significant changes of the center lines 5000 m were observed between 1985 and 1992. This change was considered as the major evolutionary stage of the study reach. However, maximum shifting (5880 m) was located in the lower part of channel segment 4. In fact, this type of phenomena was also reported from the GIS overlying of major channel in Fig. 4a–l described in the previous section. The river center line showed significant changes at the upstream, whereas the downstream part showed reverse order of migration pattern (Fig. 5). After 1992, the river center line showed major changes at the upstream part of the bridge site. Compare to 1992, the center line of 1995 was shifted diagonally towards the east bank. However, the shifting trend along the lower section was not prominent. At this time significant

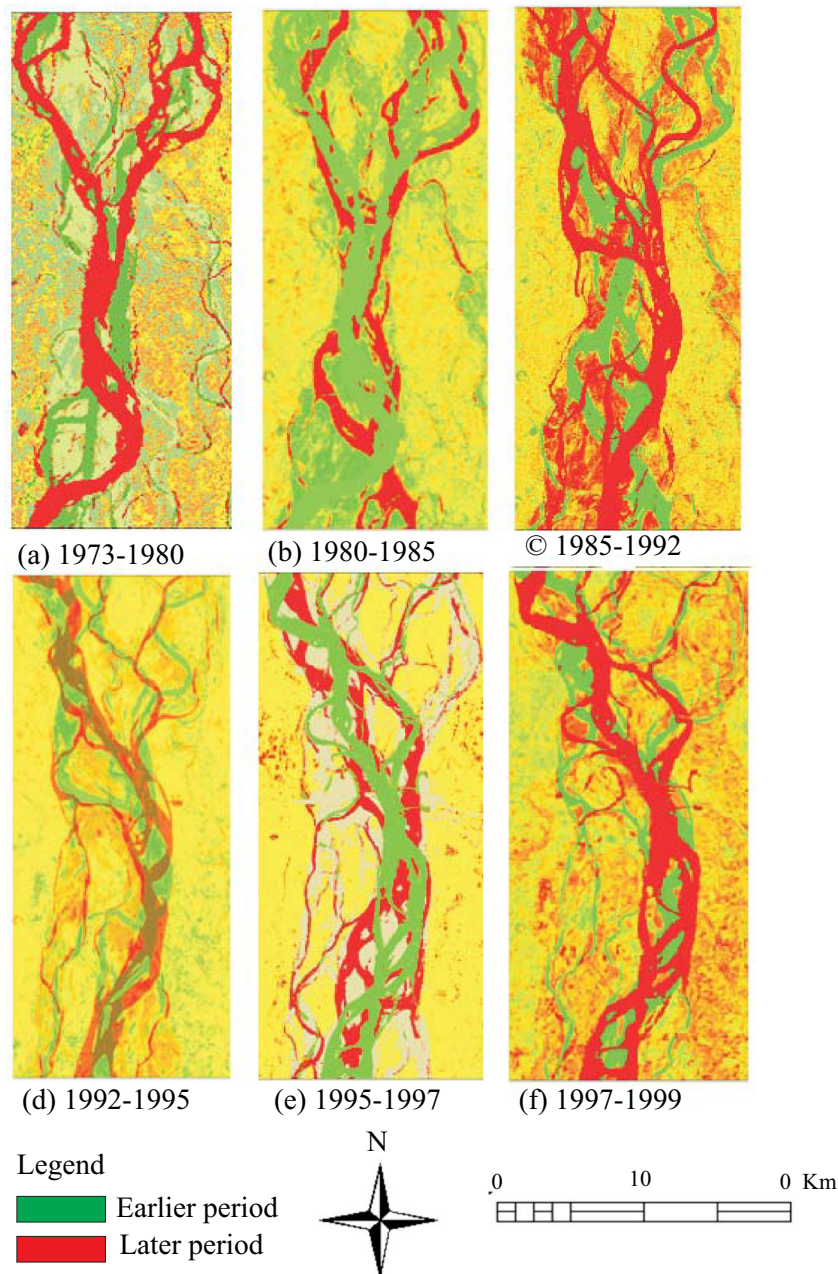


Fig. 4 (a-d) Pattern of bank line movement and channel bend development (from 1973 to 1999). Here, (a) indicates changes between 1973-1980, (b) indicates 1980-1985, (c) indicates 1985-1992, (d) indicates 1992-1995, (e) indicates 1995-1997 and (f) indicates 1997-1999. **g-l**

Pattern of bank line movement and bend development (from 2000 to 2011). Here, (g) indicates changes between 2000-2002, (h) indicates 2002-2005, (i) indicate 2005-2006, (j) indicates 2006-2009, (k) indicates 2009-2011 and (l) indicates 1973-2011

morphological change was occurred in 1995. The changes in 1996, 1997 and 1998 were small compared to the previous time span, though they showed some reverse trend in their swing. The changes of river center line in 1999 were very high and the pattern of migration was erratic at the upstream and downstream part. The maximum shifting was located at the upstream part of the bridge site. The movement of center line between 1999 and 2011 showed quite regular movement that was quite different in nature comparing to the previous migration slots. There were no significant changes at the

upstream section though the downstream part showed some changes in 1999 center line.

Change in braid-belt width

Following the method of Williams (1978) and Takagi et al. (2007), braid-belt width of river reach from 1973 to 2011 was determined by point to point measurement technique, a line at each of the 833 meters (Fig. 3b). The minimum, maximum, mean and standard deviation (SD) of the study reach were

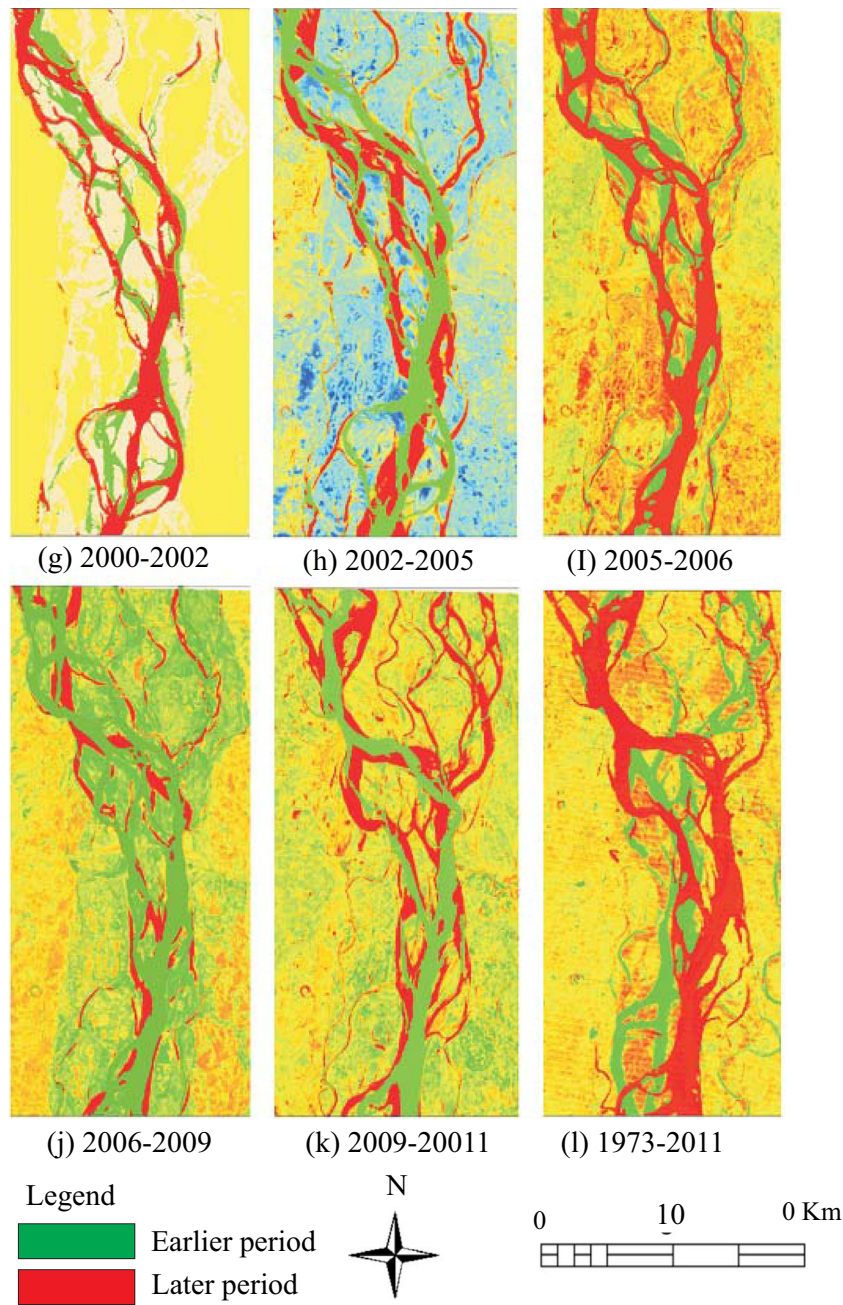


Fig. 4 (continued)

obtained for the respective years and projected in Fig. 6. The temporal changes of width over the time span showed that the maximum width ranged from 14 to 15 km, whereas the mean width increased from ca. 7 to 11 km. However, the changes in minimum width were the most significant within the time span. In 1973, it was only 3 km and remained constant to 1980. Later it sharply increased and the values were two folds in 1995. After that, the braid-belt was stabilized at ca. 6 to 7 km with minor changes (Fig. 6). On the other hand, the spatial changes of width showed distinct alteration at the middle reach that sharply divided the changes as before and

after 1985. The maximum changes were observed at the middle of the study reach. Between 1973 and 1985, the width differed from 3 to 4 km, whereas in 1992 it increased up to 2 to 3 folds. The changes between 1992 and 2011 were very small and they were regular with small increment with time (Fig. 6). Takagi et al. (2007) found that the spatial differences in braided-belt width were large at first but became smaller with time. This development continued until the mid 1990s, concurs with the findings of EGIS (1997) and Sarker et al. (2014) where performed a similar analysis using lower-resolution satellite data.

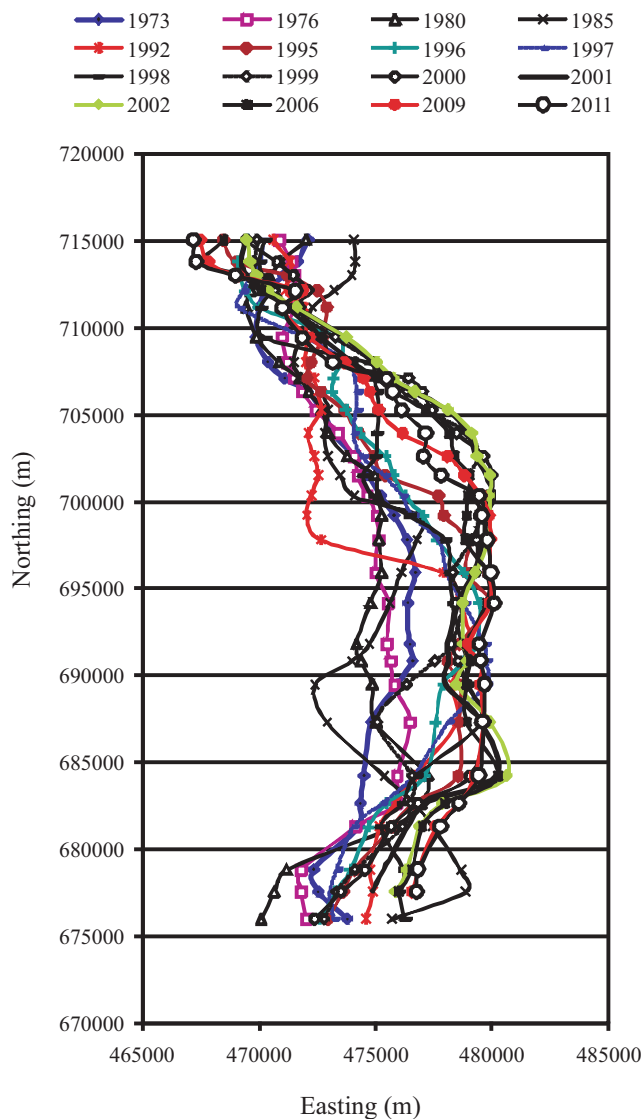


Fig. 5 Temporal changes of channel center line from 1973 to 2011

Changes in major channel width

The temporal and spatial changes of major channel width over the study period were shown in Figs. 7 and 8. It showed that the major channel width was highly variable along the river reach since 1973. The spatial distribution of width variation was somewhat heterogeneous and evident the significant difference between the upstream and downstream trend. For example, in 1976, the distribution of width changes over the distance travelled by the river was very significant. The width of downstream part, at the distance of 12 km from the bridge site increased up to 1000–2500 m compare to 1973. But in 1980, the width was decreased from 1000 m to 3000 m at various points that was reverse of 1976. In 1985, the river reach at downstream part again widened and the upstream part contracted which showed the similar phenomenon of 1973. In this stage, the increment of width was very high which range

from 200 m to 4700 m in some cases. The maximum widening (4000–4700 m) was located at 4 to 5 km downstream of the bridge site (Fig. 7). Whereas in 1992, the river reach was reduced in all measured points except small increment at few points which are located at 7, 9 and 17 km from the bridge site. In 1996, 1997 and 1998 the channel widths were increased along the downstream part which was relatively regular ($200\text{--}500\text{ m y}^{-1}$). However, in the most recent periods (1999–2000) these relationships have slightly reversed, with widening being more intense in the upstream part. In 1999, of the 18 measured points, 50 percent exhibit reduced width (400–2000 m) and other 50 percent exhibit widening. At this stage the maximum widening located at the downstream part (few hundred meters to 1800 m). In 2000, the channel width was reduced around the bridge section which is located 17 km to 23 km distance from the upstream points. On the other hand, width was increased at 6 upstream points located at 1 to 15 km distance from the measured points (about 300–600 m) and 3 downstream points (at 25, 35 and 37 km distance) also showed the increase in width which ranged from 200 to 600 m. Afterwards, the channel width continued to increase and in 2011, the river reach showed the widening characteristics almost along its distance and maximum changes (3000–5000 m) located at the immediate upstream of the bridge section.

However, the temporal changes of major channel width can be classified into two distinct phases: (i) 1973–1992 and (ii) 1992–2011 phases. The first temporal phase showed very chaotic changes in channel width (Fig. 7). In the upstream section, the variations were quite regular; the intensity of changes in 1980 was relatively small compare to the changes in other years of this phase. Width in the downstream part (at 21–29 km distance) increased from 1973 to 1985 (Fig. 7). Whereas from 1992 to 2000, it reduced noticeably both in the upstream and downstream part. In 2001, the width of the major channel sharply increased at the upstream that is reverse to earlier periods. The minimum and maximum width increment calculated in 2001 was 1000 to 4000 m which was higher values from the previous year (2000) (Fig. 8). There was some evidence for an overall reduction in major channel widths between 1973 and 2011 (Figs. 7 and 8) at the downstream part and that reverses at the upstream. The maximum, minimum, mean and standard deviation of secondary channel showed the similar characteristics to the major channel. The variation of width before 1992 was quite irregular and after that they maintained a regular pattern (Fig. 9).

Ratio of major channel width and total width of braid-belt

Similar to the channel planform result's describing in the previous section, the ratio in 1973, 1976, 1980 and 1985 show significant variations in downstream section Fig. 10. Later,

Table 2 Summary of planform changes of the entire Brahmaputra-Jamuna River and the study reach

Phases	Takagi et al (2007) and Sarker et al. (2014)	Description for entire river	Phases	Current research	Description for study reach
1	1960-1970	both braided-belt width and channel width were large		?	
2	1970-1980	Braided-belt width was still large, but channel width became smaller	1	1973-1980	Braided-belt width are large, channel width smaller
3	1980-1990	The narrow parts of the braided belt widened rapidly, the variation in the channel width also decreased	2	1980–1992	Braided-belt widen continuously, major channel also widen and unexpectedly bending towards the opposite direction
4	1990 -2002	the spatial variations in both braided-belt width and channel width became small	3	1992-1998	Variation of braided-belt width and channel width are small and the spatial migration maintain the same direction
	2003-2010	Entire channel of 250 km (from Kurigram to Aricha) migrating westward	4	1998–2011	Widening of braided-belt and major channel continuing and the migration dominated towards the east bank at the downstream of Jamuna Bridge

rest of the year-sets showed a similar pattern in the upstream part of JMB. After 2001, the ratio showed very higher values over all distance travelled by the river. However, two distinct phases were observed in the changing characteristics of these ratios, where the first phase occurred between 1973 and 1985 showed the elevated values. This pattern was consistent with the observation made by Takagi et al. (2007) for the entire river system. The second phase, starting from 1992 to 2011 showed relatively lower values of the ratio (MCW/BBW). Between 1992 and 2000, the temporal changes of planform were apparently regular, though the spatial variation was quite high at the downstream part (Fig. 10). Moreover, the changes were relatively high at the downstream part (between 19 and 29 km) compared to the upstream of the channel.

Ratio of radius of curvature and channel width

The results from the ratio of radius of curvature (R_o) to channel width (B) were analyzed to show the occurrence of flow separation intensity which was essential for bend development. The present results demonstrated that the ratio of R_o/B was quite high in all channel segments and the maximum value was shown in segment 4 (Fig. 11). It revealed that the highest bending occurred on the downstream limb of channel segment 4 and the ranking of erosion rates for different planforms was downstream limb of bends > bend apex > upstream limb of bends and straight reaches. This study showed that the growth of bar was increasing with time and the maximum height was

Fig. 6 Temporal and spatial changes of braided-belt width

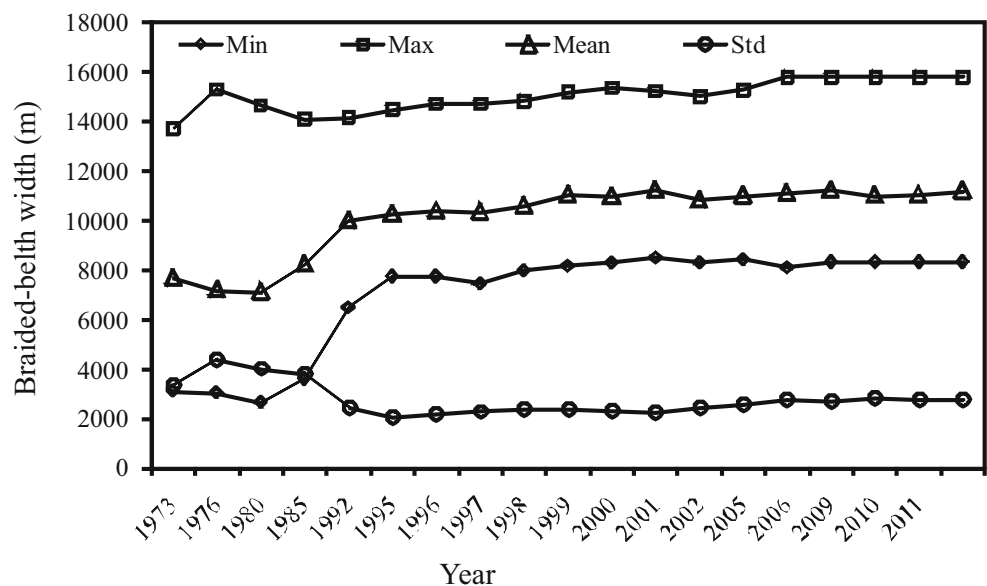
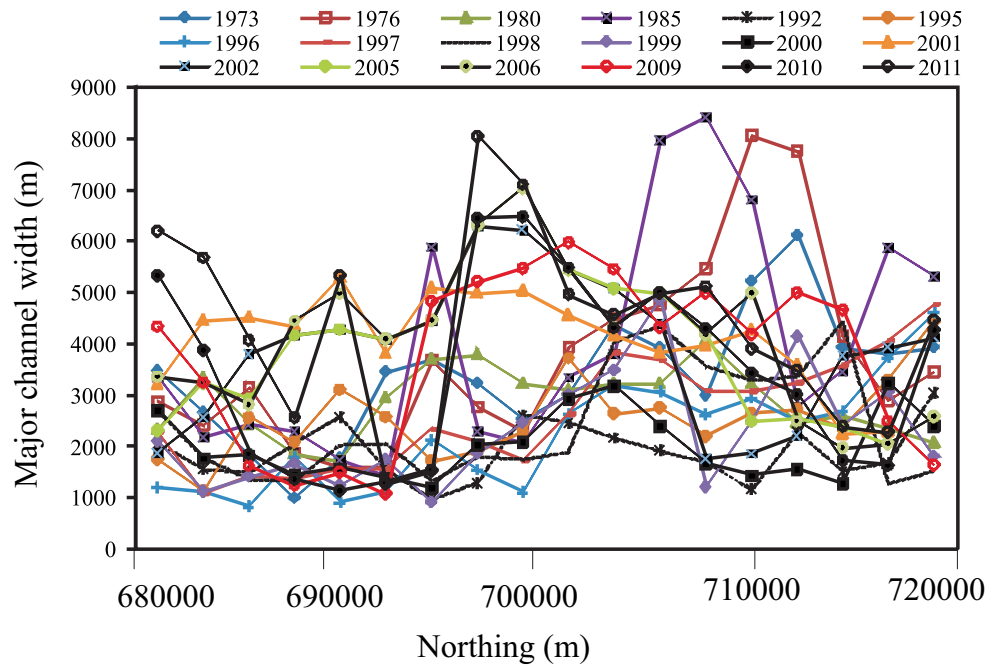


Fig. 7 Temporal variation of major channel width



observed at channel segment 4 (Fig. 12). The bar height ranged from 9.50 to 25 m with the mean being 16 m within the time span. The average rate of bar growth was 75 cm y^{-1} . Lateral bed slope parameter (A^*) calculated after Rahman et al. (2002) which is a function of channel width (B), bar height (H_B), meander radius (R_o) and water depth (h). Here, H_B was measured between bar top and minimum bed level of the channel. Fig. 12 was drawn using A^* with respect to different CSs. It showed that the maximum value of A^* ($A^*=6.8$) was observed in channel segment 4. This phenomenon in this study suggests the maximum channel-bend migration tendency towards the outer bank which is located around the immediate upstream and downstream of the bridge section.

Discussions

The analysis of remote sensing data suggested that three sub-reaches were identified within the six channel segments and each responded differently over time. The middle sub-reach showed lateral shift in 1985–1992, the upper sub-reach changed in 1973–1985 and the lowest sub-reach mostly changed in 1996–2011 (Figs. 4a–l and 5). These phenomena indicated that the sensitivities of the three sub-reaches to perturbations were different. The major channel movement between 1973 and 1980 indicated that the oscillation was confined around the valley axis. The changes in 1976–1980 also showed a high rate of average lateral shift, particularly in the upper CS (i.e., CS1 and 2). In fact, the average rate of

Fig. 8 Temporal and spatial variation of major channel width

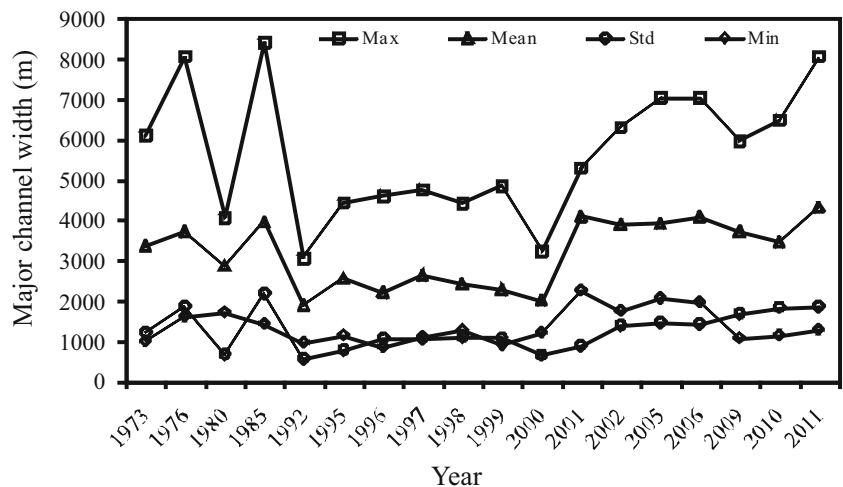
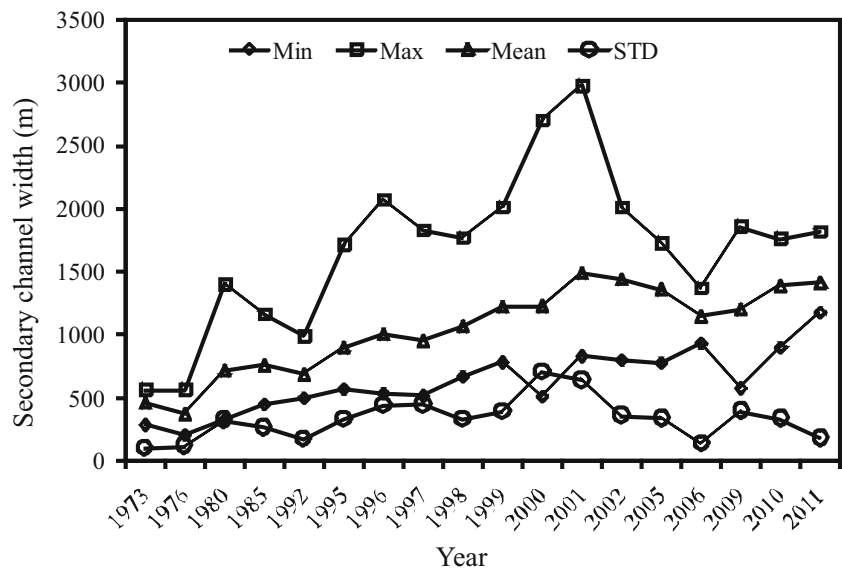


Fig. 9 Temporal changes of secondary channel width

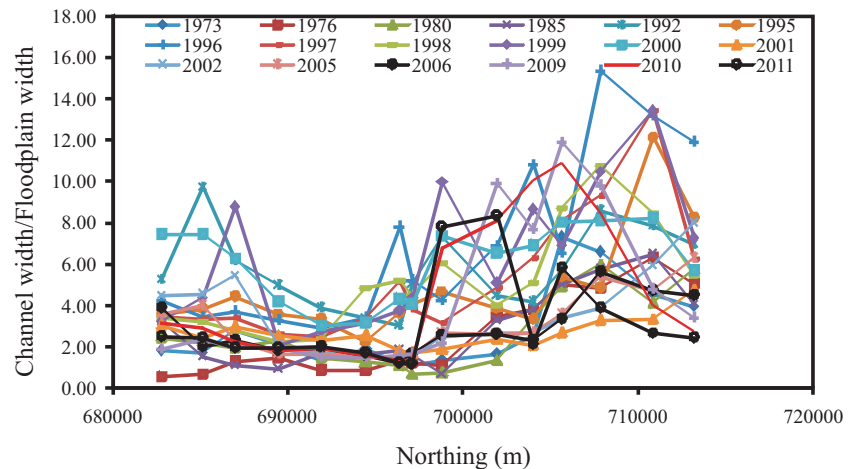


swing between 1976–1980 was greater than any event observed previously over the period 1973–2001. The average rate of lateral shift for the study reach was greatest in the period 1998–1999, which was associated with the flood of 1998.

The river width around the bridge section was confined by river training works (e.g., abandonment of secondary channel for construction of bridge abutments and some bank protection structures). Unusual narrowing of braided-belt width interrupt flood conveyance resulting in backwater effects which are increasing rates of sedimentation in the bridge site. Huge sedimentation occurring at the immediate upstream of the bridge increasing the bar development. Thus, the significance of channel contraction (narrowing) stemming from growth of mid-channel bars was likely understated. A larger number of mid-channel bar (Fig. 4a,1) indicated a greater degree of obstruction to the flow path which was then diverted sideways leading to an increase in bank erosion, resulting in overall channel widening. On the other hand, the upstream

flow resisted by JMB hard point resulting helical flow towards both banks (water turbulence) helps to develop scour at the bottom-channel and accelerates the bankline migration. In addition, the lower Ganges (locally called Padma) contributes a huge water discharge with suspended sediment loads to the confluence of lower Ganges and BJR. The flow of lower Ganges partially resists the flow of BJR (i.e., 50 km north of BJR and Ganges confluence). Therefore, back water effect generated by the lower Ganges in the downstream part of the lower JMB partially dilute the flow of lower BJR and deposit huge sediments. As a result, sediment deposition at the downstream part of the JMB helps to increase bar growth and consequently widened the river corridor. Previously, Takagi et al. (2007) summarized the recent historical dynamics of the Brahmaputra into four phases: 1) the late 1960s to early 1970s, 2) the mid-1970s to early 1980s, 3) the mid-1980s to early 1990s, and 4) the mid-1990s to early 2000s (Table 2). Among all phases, Takagi et al. (2007) described phases 1 and 3 as transitional phases and the dynamics of

Fig. 10 Temporal and spatial changes of the ratio of channel width to floodplain width



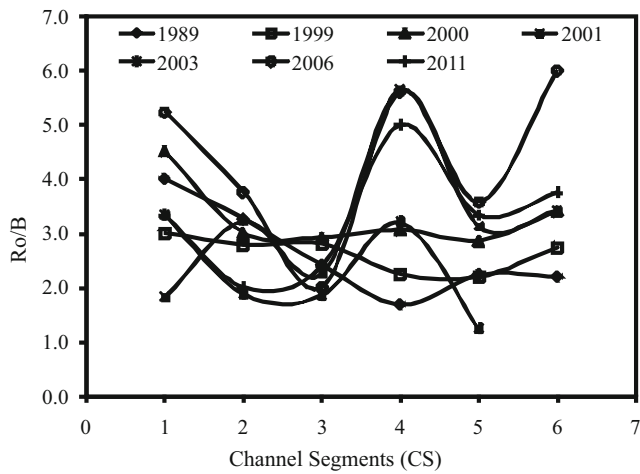


Fig. 11 Temporal changes of the ratio of the radius of curvature and width of the major channel

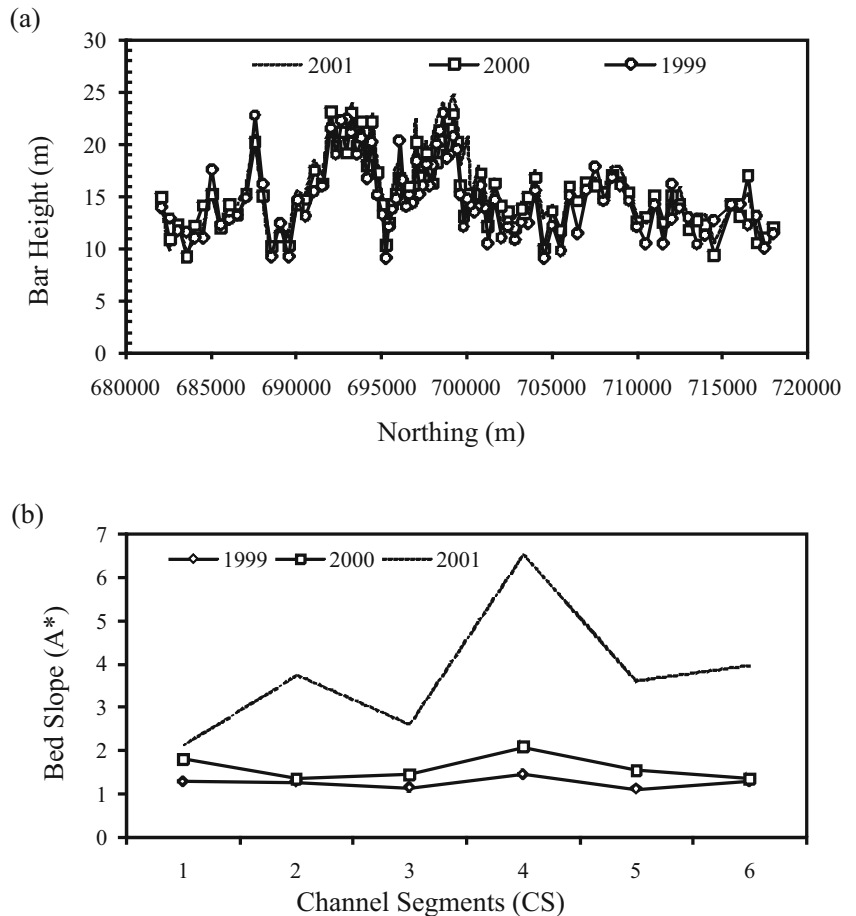
phase 2 was less irregular. Whereas, the spatial distributions of channels in phase 4 were quite regular suggesting a state of channel stability. In addition, the characteristics of the secondary channels of BJR also showed the similar results that of major and braided-belt width (Fig. 9).

Sarker et al. (2014) stated that the recent trend for migration of the centerline of the entire Jamuna, it is important to

recognize that since the 1970s this has been the net outcome of retreat of both banks, rather than that of retreat of the west bank and advance of the left (east) bank. Widening has forced both riverbanks to migrate outward, but during the last 14 years, the rate of retreat of the west (right) bank for the 250 km river has exceeded that of the east (left) bank, moving the centerline 150 m westwards. If this migration continues, the westward migration would be rejuvenated with a break of few decades. However, in this study the lower BJR reach showed a clear eastward migration which is quite different from the entire movement of the study area of Sarker et al. (2014).

Frequent large floods might have triggered huge water and sediments which occurred significant changes in the river system during Phases 1 and 3. Nevertheless, the morphological evolution of BJR in this study area is quite similar with the findings of other studies (e.g., Takagi et al. 2007 and Sarker et al. 2014) before construction of Jamuna Bridge in 1992. Overall, the river planform development in this study area between 1973 and 2011 has been classified into four phases: phase 1 (1973–1976), phase 2 (1980–1992), phase 3 (1992–1998), phase 4 (1998–2011) (Table 2). Among the four phases in the recent evolutionary stages of BJR, the first two phases ranging from 1973 to 1992 (Fig. 4a–c) were more

Fig. 12 Hydraulic characteristics of the study area showing (a) development of bar height, (b) changes of bed slope parameter



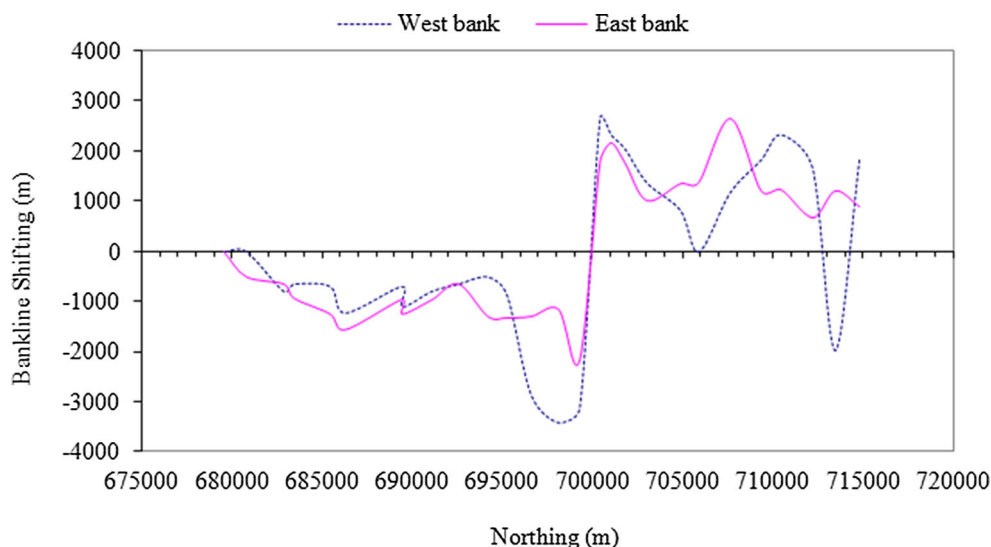
differentiable to the subsequent phases (1992–2011) (Fig. 4d–l). However, the changing pattern of morphology in recent phases between 1992 and 2011 is somewhere similar to the phase 3 and 4 of Takagi et al. (2007) and Sarker et al. (2014) which were reported a unidirectional dynamic equilibrium condition. However, in this study, it is demonstrated that the unidirectional changing behavior of BJR was characterized as the influence of human-induced processes (e.g., river training works prior to the construction of Jamuna Bridge and other bank stability treatments) rather than natural equilibrium. Thus, the natural flow of the river systems is restricted by the confined bridge section. The flow dynamics afterwards created a backwater effects and tried to find its way towards the outer banks. Therefore, huge sediments deposit at the upstream of the bridge section which helped to increase the mid-channel bar growth and as well as widened the braided systems. The increasing tendency of bar height indicated that further erosion might occur along the left bank around the bridge section which was reported from the satellite image from 2002 to 2011 described in Fig. 4g–k. The excessive widening of river planform from 2001 to 2011 provided more significant information on the recent channel dynamics. It indicated that the river was in dynamic form and tried to adjust its dynamic equilibrium. However, neither the erosion sites nor the erosion rate was constant in time. Likewise, accretion rates differed from spatially and temporary which was showed in higher rates along the west bank. Short-term comparison of planform profiles indicated a general pattern of aggradations (deposition) along the west bank and degradation (erosion) along the east bank, indicating a net eastward migration.

River flow and sediment regimes were recognized to be the primary controls on channel dynamics and pattern changes (e.g. Alabyan and Chalov 1998; Church and Rice 2009). Here, the channel is unable to accommodate the entire flow regime through the modified (narrower and funnel shaped) river segment (Fig. 2) and consequently increase the rate of sediment deposition in the upstream area. Moreover, backwater effects developed from river constriction has significant influence on sediment deposition in the bridge section. Carson (2006) assumed that rapid narrowing of valley width along a river reach can interrupt flood conveyance resulting in backwater effects, hence increased rates of sedimentation above the constriction. In this study, the morphologic changes observed from 1973 to 2011 demonstrated that the lower BJR underwent quite significant spatial and temporal changes. Ascertaining the natural dynamics of channel planform (from 1973 to 1992); human-induced channel changes (from 1992 to 2011) were estimated whether the changes were influenced by river training works prior to the Jamuna Bridge construction. In addition, the floods of 1998 and 2000 impacted severely on the river planform by deposition of huge sediments and accelerated the widening

processes of the river by the enlargement of the mid-channels bars. Along with morphologic changes, the bar height and bed slope parameter obtained from different cross-sections and bottom topography of the river reach showed that the growth of bar height and lateral slope of bars were increasing with time (from 1999 to 2001) (Fig. 12). Maximum value of bar height (25 m) was found at the channel segment 4 in 2001 (Fig. 12). The vertical growth of sand bars was enormous due to significant sedimentation in the upstream area of Jamuna Bridge after the large flood in 1998. Consequently, the outward migration of bank lines was also accelerated. In addition to the temporal variation of channel flow, it was noteworthy that changes in supply and transport of sediment were also play a critical control on braided river complexity and dynamics (e.g., Graf 2000; Piégay et al. 2006). As river discharges pass through the narrow constriction reach and approach the confluence, average channel and floodplain velocities increase and become erosive (Croke et al. 2008). In this case, the bridge abutments are under threat of bank erosion because they lie in a zone of potential bank migration. Therefore, the major channels at Tangail–Bhuiyapur and Sirajganj town may bypass the bridge abutments at some distance in future.

In this study, channel expansion and/or bank erosion is defined as a change in channel width that occurs when both banks are retreating laterally into the floodplain or adjacent material. Channel contraction is when the channel width reduces over the period of measurement; this can occur when one bank remains stable and the opposite bank undergoes accretion or deposition such as bar formation or when both banks contract inwards due to deposition on the channel boundary. The intensity of lateral erosion processes depend largely on the gradient and type of the bank materials (Teisseyre 1980; Thorne 1992). Moreover, the vulnerability of the bank erosion is significant as one can see from Fig. 13. Almost 20 km of bank line in both sides of the river has potential erosion tendency. The plot of potential erodible bank length versus reach length (northing) (Fig. 13) also shows that downstream of Jamuna Bridge and extreme upper part of the study reach, erosion tendency is considerably high in west bank lines. Whereas in the upstream of Jamuna bridge, deposition/contraction is dominant in east bank and erosion tendency is considerably high in downstream, indicating that geological control point at Tangail (Madhupur Tract) along east bank in respect to other control points (vegetations and engineering structures) has significant causative impact on the morphological behaviour of the BJR. The bank erosion as well as eroded bank length of west bank at the upstream part of Jamuna Bridge is relatively high. The maximum erosion of west bank at the downstream and upstream of Jamuna Bridge over the

Fig. 13 Lateral movement of the bank lines of the Jamuna River 1973–2011



time span is 3500 m and 2000 m, respectively. The erosion phenomenon is evident on the BJR for a stretch of 20 km around Jamuna bridge site covering Tangail and Siragganj Districts with the help of Satellite imagery from 1973 to 2011. Within the erosion–deposition sections, lateral erosion was a principal process to shape the channel configuration. The volume of the material supplied to the stream channel from bank slides each high flow stage widened the stream channel making its cross section larger, which resulted immediate deposition and consequences decrease in stream power and transport capacity. Therefore, the materials from bank slides were transported at increasingly proximal distances, and its substantial part was deposited within the section area (Bak et al 2013). However, in this study, the rate of bank retreat was calculated as maximum 1.08 km/y-1 that is more or less similar values of other findings. For the entire Jamuna River, Sarker et al (2014) demonstrated that the comparison of banklines derived from the 1973 and 2010 satellite images revealed that during that period of the 245 km of the 265 km length of the west (right) bank retreated, while 20 km showed no net change. However, the spatial distribution differed along the left (east) bank, where 190 km of the 245 km length of the bank retreated, while 2 km were unchanged and 53 km accreted. For the study period, erosion of the left (east) bank floodplain first increased during the late-1970s, peaking in the late 1980s. The rate of land loss during this period at the right (west) bank hardly changed. Post-1990, erosion of the left (east) bank floodplain changed at regular intervals, with oscillations of decreasing amplitude overlaid in general, decreasing trend. Erosion at right bank rates too began declining in 1990, also featuring a repeated swinging, though of smaller amplitude than that evidenced for the left (east) bank.

Conclusions

The recent trend of the lower Brahmaputra–Jamuna River provides a clear paradigm of how river training works can induce dramatic alterations in river morphology. Analysis of the obtained results can be applied to anticipate how the channels within the river reach may respond to future flow regime. The results showed that the magnitude of morphological response is very high in the study reach because of modification of the natural flow systems. Analysis of satellite image has documented the increases in width, bar growth and potential meander bend development along the bank, coupled to a planform change.

The overall pattern of bankline shifting and bend development process of channels in the study reach suggested that the river channel was progressively widening and moving eastwards at the lower reach. Channel widening is likely being more evident on the lower reach than the upper reach of Jamuna Bridge section. Likewise, the bar height was progressively increased and the maximum height (25 m) was observed in the immediate upstream of Jamuna Bridge. In general, four distinct phases of channel shifting can be grouped in to two stages. In the first stage, the first and second phases ranged from 1973 to 1992 were dominated by natural processes and generally showed the disordered changes. In the second stage, the third and fourth phases ranged from 1992 to 2011 were controlled by human induced processes and revealed the progressive (unidirectional) migration of banklines. Given a similar discharge and sediment regime, and channel and flood plain resistance, results suggest that recent planform adjustment might occur principally through channel modification by human induced process.

Rates of bank erosion, however, were highly variable, depending primarily upon the position and composition of the bank materials. The mean erosion rate calculated in this

study was 374 m y⁻¹. This is obvious because while river responded almost immediately to increase in human interventions in the early 1990s, it is still adjusting to the imposed flow and sediment regimes and has not yet attained a new equilibrium state. If the banklines migration pattern follows this trend, the bridge abutments may be under threat of potential bank erosion in near future and the channel may bypass the abutments eastward at Bhuiyapur or westward at Sirajganj town. Hence, effective river management and water resource strategies must take account of the ways and magnitudes of channel change determined in this study and consider steps to mitigate the adverse aspects of morphological response to future human activities.

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