Assessing the long-term planform dynamics of Ganges–Jamuna confluence with the aid of remote sensing and GIS

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Abstract
The confluence of the Ganges, Jamuna, and Padma rivers is one of the most dynamic in the world, an internationally important research area because of the confluence of two of the world’s major rivers, the Ganges and the Brahmaputra. Morphological changes in this area have resulted in severe erosion along the banks. Riverbank erosion is one of Bangladesh’s most critical issues, requiring a substantial solution. Riverbank erosion affects millions of people in Bangladesh each year because of erosion in this confluence zone. Consequently, understanding the morphological shifting pattern of the confluence is crucial. The research aims to quantify actual bank shifting near the confluence of the Ganges, Jamuna, and Padma rivers in terms of shifting rate and area during a 25-year period (1990–2015). The acquired satellite images were geo-referenced, and bank lines were digitized to carry out this research. The bank line is the linear construction that separates the outside boundary of the river channel from the floodplains. To assess channel width fluctuation, the distance between the extreme borders of the left and right banks, including mid-channel sandbars, was measured. This period is split into five stages, each lasting 5 years, to measure the maturity of change. Furthermore, the long-term trend from 1972 to 2015 is qualitatively discernible. Landsat satellite pictures were used to investigate this morphological change. The study provides current and reliable information on the planform dynamics of the Ganga–Jamuna confluence. This study will help design and implement drainage development plans and erosion control techniques in this crucial confluence zone.

Keywords Channel planform · Remote sensing and GIS · Ganga–Jamuna · Erosion and deposition
1 Introduction

Being the essence of life, the river performs a vital role in the world (Islam 2016). Overall, it performs crucial ecological and social responsibilities (Postel and Richter 2012). Similarly, river confluences are important governing points of channel geomorphology (Mosley 1976; Best 1988). Planform shifting is a natural autogenic process that happens in rivers because of high flow quantity, huge sediment load, stream type (perennial or seasonal), topography, and the ethnography of the regime passing through the river (Roy and Mitra 2020). Channel planform dynamics is one of the world’s most serious challenges with alluvial rivers. However, river dynamics may pose significant dangers to nearby areas and communities (Hirabayashi et al. 2013). The river course in Bangladesh is a crucial concern because of its unstable nature and position in a tectonically active zone (Islam 2016). As a result, river course alterations cause the loss of human settlements, urban centers, and valuable lands (Pahlowan and Hossain 2015). This results in natural hazards such as lateral channel transition, floods, bank erosion, and disturbance to hydraulic infrastructure, transportation networks, agricultural land, and towns. To carry out river management operations, many water resources experts, engineers, and policymakers depend on a solid understanding of the historical planform change of rivers through time (Roy and Sinha 2018; Majumdar and Mandal 2020). Over the past three decades, enormous efforts have been made to examine channel planform behavior locally and globally (Bora and Goswami 2021; Hasanuzzaman et al. 2021). Many geospatial technology-based studies have been conducted across the world, including in the USA on the four rivers of Olympic National park (East et al. 2017), Taiwan on the Zhuoshui River and the Gaoping River (Kuo et al. 2017), Italy on the Scrivia river (Mandarino et al. 2020), Germany on the Old Rhine downstream (Arnaud et al. 2015), China on the lower yellow river (Kong et al. 2020; Guo et al. 2021) and the lower jingjiang reach (Yang et al. 2015), India on the Koshi river (Sinha et al. 2014), the Sharda river (Midha and Mathur 2014), the Dwarkeswar river (Ghosh and Mukhopadhyay 2021), the middle lower part of Ganga (Pal and Pani 2019), and the Ramganga river basin (Agnihotri et al. 2020), and Bangladesh on the lower Padma river (Rashid 2020; Nawfee et al. 2018; Halder and Chowdhury 2021), the rivers in southern estuarine Region (Islam et al. 2018), the Lower Meghna river (Mahmud et al. 2020), Madhumati river (Biswa et al. 2021), the lower Teesta river (Akther et al. 2019), and the Brahmaputra river (Rashid et al. 2021). Lower sections of rivers regularly change their course because of hydrological variability and sedimentological readjustments (Agnihothri et al. 2020; Talukdar and Pal 2017, 2018; Saha and Pal 2019; Nawfee et al. 2018; Dewan et al. 2017). At the same time, the junction of the Ganga and Jamuna rivers is no exception (Rashid 2020; Mahmud et al. 2020; Dewan et al. 2017). Any natural or anthropogenic alterations might cause a shift away from dynamic equilibrium (Sinha et al. 2014; Dewan et al. 2017; Rashid et al. 2021; Mahmud et al. 2020). As a result, channel instability may occur, which causes changes in channel shape and pattern (Dewan et al. 2017).

Many geomorphologists have observed that channel planform dynamics are a significant issue in Himalayan rivers, which have always switched channels in their lower reaches (Dewan et al. 2017; Rudra 2010, 2014; Sinha et al. 2014; Gupta et al. 2013a, b). Because of the extensive area coverage, synoptic view, and frequent data acquisition capability, satellite remote sensing data and historical topographic maps provided an enormous opportunity for fluvial geomorphologists to understand channel planform dynamics, particularly for long and highly moveable rivers (Gupta et al. 2013a, b). Using remote sensing and geographic information systems (GIS) to analyze and monitor river erosion and central line movement is becoming...
more common (Pal and Pani 2019; Agnihotri et al. 2020; Gupta et al. 2013a, b; Rozo et al. 2014; Ashwini et al. 2021; Jung et al. 2021; Yang et al. 2015). Introducing Geographic Information Systems (GIS) has enhanced the researcher’s capacity to discover planform characteristics like variations in length, centerline migration, and sinuosity index, among others, by merging images of river planforms from diverse sources. It has been revealed that Landsat images can effectively categorize river lengths. Pal (2017) conducted research on assessing meandering and braiding characteristics in the Ganga with the help of GIS and remote sensing, especially in the middle lower stretch of the Ganga, and found significant changes in the Ganga river course serving as the reach for the investigation (Pal 2017). The Ganga–Padma river system in Bangladesh was analyzed for planform changes between 1973 and 2011 using Landsat imagery and streamflow data collected over a more extended period (Dewan et al. 2017). Following an investigation of the Ganga River’s erosion–deposition by Dewan et al. (2017), it was determined that about 57 km² of land was lost on the right bank during the assessment period, whereas 59 km² of land was deposited on the left bank. Farakka Barrage is a water control structure in India’s Murshidabad district. The barrage construction started in 1962 and was completed in 1970; operations began on April 21, 1975. According to previous research, the shape of the Ganga River altered considerably after the construction of the Farakka barrier (Ashwini et al. 2021; Pal and Pani 2019; Dewan et al. 2017; Rudra 2014; Agnihotri et al. 2020; Anand et al. 2018; Sinha and Ghosh 2012; Raj and Singh 2020). Several investigations have been carried out on the upstream and downstream parts of the Farakka Barrage on the Ganga River (Rudra 2014; Agnihotri et al. 2020; Anand et al. 2018; Sinha and Ghosh 2012; Raj and Singh 2020). Islam and Guchhait (2017) showed that the Farraka barrage causes in increasing the number of wide and open loops in the river course. Raj and Singh (2020) showed that the Ganga River had shown a considerable configurational readjustment and course change from 1973 to 2019.

Similarly, Sarif et al. (2021) found that the erosion rate was more on the east bank while deposition was more on the west bank from 1965 to 2017. Recent research has not investigated the morphological changes of the Ganga–Jamuna River, which includes both the Ganga river downstream of the Farakka barrier and the confluence of the Jamuna and the Ganga rivers. This research seeks to determine historical changes in the confluence’s planform of the Ganga and the Jamuna River using dynamic fluvial characteristics acquired from Landsat images taken at different temporal scales. By analyzing Landsat satellite images taken between 1990 and 2015, this research will analyze the planform dynamics of the Ganges–Jamuna confluence zone from 1990 to 2015. The objectives of this study are as follows:

- To assess the bank shifting near the confluence of the Ganges, Jamuna and Padma rivers in short and long-term basis.
- To find out the trends on bank line shifting.
- To quantify the short and long-term erosion and deposition.
- To determine the variation of river widths in different years.

2 Materials and methodology

2.1 Study area

The Brahmaputra and Ganges Rivers both originated from glaciers in the Himalayas. The Brahmaputra flows through China, India, and Bangladesh over a length of 2900 km (Islam
et al. 1999) and has a drainage area of about 573,500 km², of which only 8% is inside Bangladesh (Hassan et al. 1999). At the same time, the Ganges has a basin area of over 1.1 million km², with only 4% of the catchment lying in Bangladesh. The Ganges–Brahmaputra system brought sediments during the post-Pleistocene period that shaped the Bengal deep-sea fan (Biswa 1992). The lower Brahmaputra, prominently known as Jamuna, has a length of 240 km from the point of entry into Bangladesh to its confluence point with the Ganges. It is very dynamic in nature because of its multichannel split-offs around the bars, followed by rejoining, giving it a braided shape in the process. Jamuna has an average channel width of about 11 km (Sarker et al. 2003). In this study, we selected a reach of 60 km from the confluence point to upward (Fig. 1). The discharge of Jamuna ranges from 3000 cumecs to 100,000 cumecs, with a bank full discharge of approximately 48,000 cumecs (Hossain 1992). The annual monsoon governs the water and sediment discharge of the Jamuna. The flow of Jamuna reaches its peak in July or early August. The catchment has an annual average precipitation of 1900 mm, with more than 80% of it occurring during the five months of the monsoon (EGIS 2002). The sandbars of the Jamuna River, locally known as ‘Char,’ encompass about 1700 square kilometers and are used mainly for rice cultivation by the char dwellers (EGIS 1999). The movement of these bars, islands, and both the banks of Jamuna, is a widespread phenomenon, making it harder for the char dwellers to cope. Sometimes, the bank lines even shift between kilometers per year. The Ganges has an annual average discharge of about 30,000 cumecs and a bank full discharge of about 75,000 cumecs (FAP24 1996). The lower part of the Ganges is much straighter than its upper part because of the heavy discharges from two mighty rivers. So, both the riverbanks are prone to bank erosion and migration, which results in land loss and displacement of the population. Information is scarce regarding the number of displaced people because of erosion. However, a study on the resilience and vulnerability of 10 major deltas showed that the number of people displaced per year due to erosion along the river banks of the Ganges delta is higher than 60,000 (Bucx et al. 2010). This number is expected to rise because of climate change (Moors et al. 2011).

The confluence of Ganges, Brahmaputra, Meghna, and their tributaries has formed and shaped the deltaic plains of Bangladesh. Two of the major rivers of the GBM basin are Ganges and Jamuna (Lower Brahmaputra) meet at a point named Goualondo Ghat, situated in the Rajbari district of Bangladesh. Ganges and Brahmaputra are two of the world’s largest river systems with a combined catchment area of 16, 30,700 km², of which only 5.23% lies in Bangladesh (JRCB). Usually, confluence morphology is dictated by three factors: discharge and sediment loads at upstream control, junction angle of converging channels, and bar formation downstream of the confluence (Mosley 1976). However, the Jamuna River avulsed during the nineteenth century, causing the confluence to shift dramatically to the north (Rahman et al. 2020). Jamuna is a geomorphologically active braided river where higher sediment loads than its carrying capacity (Baki and Gan 2012). This channel migration (Best and Ashworth 1997) governs the dynamics of the Ganges–Jamuna confluence.

In contrast, the Ganges is a branching river (Kleinhans 2010) with sinuosity ranging from 1.2 to 1.35 (Dewan et al. 2017). Eighty percent of the channel’s annual discharge volume is drained to the Bay of Bengal during the monsoon months (July–October). This highly seasonal variability of discharge coupled with development activities the upstream of Ganges have made bank erosion and bed scouring worse in recent times (Sharma et al. 2010). Banks of both Ganges and Jamuna are mostly made up of fine-grained clay and silt carried by these rivers (Datta and Subramanian 1997). From 1973 to 2017, the banks of Ganges, Padma (Lower Ganges), and Jamuna have eroded around 1540 km², leaving about 1.6 million people homeless (Islam et al. 2017). A significant amount of agricultural land
was also lost, which has created growing concern about the country’s future food security. Several studies have been carried out to understand the morphological characteristics of the Ganges and Jamuna rivers. Dewan et al. (2017) used remotely sensed imagery and found that the Ganges lost 57 km² of land on its right bank while gaining 59 km² of land on the left bank from 1973 to 2011. Baki and Gan (2012) investigated Jamuna River’s short- and long-term erosion-accretion rate using Landsat imagery from 1973 to 2003. Monsoon Season has a dominant influence on the rivers in Bangladesh, and enormous bank erosion is being happened in this season. The changes in the water flows would affect the morphology of the Padma River of Bangladesh during the monsoon. A significant change has been observed in the bank, channel, and bars, along with their geometry and morphology (Islam et al. 2021).

### 2.2 Materials and methods

The Open Source Landsat time-series data have been used extensively to quantify morphological changes in rivers worldwide. Wang and Xu (2020) also used long-term satellite imagery to study bar dynamics of the Amite and Comite Rivers in the USA. However, moderate resolution Landsat images also provide great scope for quantifying riverbank migration. Several studies, including Raj and Singh (2020) and Agnihotri et al. (2018), investigated the change in morphological parameters over many years. For this study, Landsat imagery from 1972 to 2015 has been selected for analysis. We have presented the details of Landsat imageries used in the present study in Table 1.
We selected the December to February time frame to obtain cloud-free imagery. Also, it is the dry season when the river flows with inadequate discharge to fill the main channel and remains relatively constant on a year-to-year basis (Gupta et al. 2013a, b). Simple pre-processing of satellite datasets was performed for these datasets. Using the layer stack technique in ERDAS software, we layered the satellite images into one file (single layer). Because of this procedure, a False Color Composite (FCC) image was created. Geometric rectification and subsetting were two crucial processes in extracting the dataset of the study region. For the geometric correction of the single-layered image, the geo-referenced toposheet in the raster format was used as reference data. During geometric rectification, we used GCPs for the toposheet and satellite image (2015). The overall Root Mean Square (RMS) error was less than 0.5 pixels in the satellite image. ERDAS Imagine software was used to register multitemporal images (1990–2015). We used the Landsat 8 image (2015) as the reference image. Based on the reference image, the Landsat 4-5TM images were registered and projected to the UTM WGS 1984 datum.

The study area was divided into three segments: Ganges, Padma, and Jamuna. We then divided each segment into 13 equal sub-segments by 4 km distance. The total length of each river reaches extends up to 48 km. Thirty-nine sections were generated according to the determined 4 km distance. The combined portion of the three significant river segments falls under the downward Padma River. Figure 2 shows details of the segments, including the different locations, places, and bank line of three rivers for 5 years intervals from 1990 to 2015. Figure 2 shows that the bank line of the Padma River is prone to scatter shifting, which occurs because of the combined flow of the upper river.

### 2.3 Methods for analyzing bank line shifting and channel width changes

We have performed the entire work in ArcGIS 10.5 software, such as analyzing the bank line and channel width dynamics. The bank lines were digitized from all geo-referenced images. A bank line is defined as the feature that separates the outer edge of a river channel from the floodplain. We carefully analyzed all selected satellite images for creating bank lines and boundaries using the software at a scale of 1:50,000. Bank line digitization is consistently one of the crucial aspects when changes in the channel’s planform, pattern, or position are being monitored. We did digitization of bank lines from satellite images using ArcGIS software.

The bank line is taken as the linear feature that separates the outer margin of the river channel from the floodplains. Hence, all sand bodies (bed and bar features) visible in an image are considered part of the channel except for coarse sediment spread over the flood plains during floods that spill over the bank.

### Table 1 Details of the used satellite images for the present study

| Year   | Date       | Satellite data (TIF format and geo-referenced) | Resolution (m) |
|--------|------------|-----------------------------------------------|----------------|
| 1990   | 23-December| Landsat 4-5™                                  | 30             |
| 1995   | 16-January | Landsat 4-5™                                  | 30             |
| 2000   | 24-February| Landsat 4-5™                                  | 30             |
| 2005   | 09-December| Landsat 4-5™                                  | 30             |
| 2010   | 08-February| Landsat 4-5™                                  | 30             |
| 2015   | 07-January | Landsat 8 OLI                                  | 30             |
Variation of channel width was analyzed by measuring the distance between the extreme edges of the left and right bank, including mid-channel sandbars. Thirty-nine sections were created at equal distances to evaluate the bank’s migratory trend. To quantify the shifting of bank lines, digitized bank lines from two different years were superimposed on one another.

2.4 Method for measuring sinuosity

The degree of meandering in a river channel is determined by river sinuosity. The ratio between the length of the river bed (which is channel length) and the shortest distance of the river bed from beginning to finish is the sinuosity of a river (which is valley length). With more wandering, the sinuosity grows (Brice 1964).

\[
SI = \frac{AC}{AV}
\]  

(1)

where SI denotes the sinuosity index, while AC and AV are channel length and valley length.

The sinuosity of the river was computed using Eq. (1) after establishing the mid-channel line of river courses using the HWATH’s tool, which is also an ArcGIS extension (Garca 2014).
2.5 Method of erosion and deposition calculation

The river channel polygons for 1990, 1995, 2000, 2005, 2010, and 2015 have been overlaid. After superimposing these polygons representing river channel erosion and deposition of the research region owing to river course alteration, long- and short-term changes were estimated for both the left and right banks (Deb and Ferreira 2015). The river flows from north to south; instead of using the terms left and right banks in the analysis, the terms east and west bank could also be employed. Between 1990–1995, 1990–2000, 1990–2005, 1990–2010, and 1990–2015, the river’s erosion and deposition area were retrieved using the overlay tool in ArcGIS 10.6. The 1972 image was digitized for qualitative examination of very long-term change bank lines and char lands. After that, the most recent image accessible as a base map in ESRI’s ArcGIS software was compared.

3 Results

3.1 Dynamics of river width

River width is an important morphological feature that determines the extent of the river. Figure 4 depicts the variations in river width over time and space in all the branches that converge at the confluence.

Figure 3 depicts the morphological instability of the river, which demonstrates how the breadth of the river fluctuates over time. During this time, Padma’s range of variation between maximum and minimum breadth had widened substantially. Jamuna’s average width stayed constant from 1990 to 2010; however, from 2010 to 2015, it was expanded to 1 km. Ganges’ maximum and lowest width ranges throughout the research period are very consistent.

![Fig. 3 Changes in river width from 1990 to 2015 for a Ganges, b Jamuna and c Padma river](image)
The average, maximum, and minimum widths in the selected parts of the Ganges and Padma Rivers follow a similar trend, as seen in Fig. 3. With the Jamuna River, however, no such tendency was observed. Figure 4 depicts the spatial pattern of this shift, which shows that the variance in width change as a function of Padma’s distance follows a similar pattern in different years. The Ganges and the Jamuna River do not follow any pattern. In the downstream direction, the breadth of the Jamuna has increased. We found a highly decreasing trend in width along the selected sections of the confluence of the Ganga River at the chainage 0 km stretch at Kushtia Sadar, where the breadth decreased by about 3 km between 1995 and 2010.

Similarly, between the 1990s and 2000s, the most considerable width change on the Jamuna stretch was observed at a chainage of 12 km portion near Delduar. During this time, the breadth of this stretch narrowed by about 8 km. In the instance of the Padma stretch, the river’s breadth rose by roughly 10 km in parts near Faridpur, when the chainage was 24 km.

3.2 Bar movement and sinuosity

Secondary, across-channel circulation can enhance meander wavelength and migration of meanders across a floodplain, resulting in channel sinuosity. One of the most important indices of river morphology is river sinuosity (Mueller 1968). Variations in river sinuosity affect water flow characteristics. Extremely dynamic, the Ganges–Jamuna confluence shows the net effect of these morpho-dynamical processes as a southern movement of the confluence point from 1990 to the present. The changing tendency and position of the Jamuna River’s widest channel altered over this period. The broadest channel tends to dominate the right bank of the braid plain in the early stage before lateral migration in the later stage. Multichannel flow was prevalent around big islands that were forested and therefore established. The confluence’s meandering Ganges section likewise exhibits a gradual southerly movement, with bars moving into the confluence zone (Fig. 5).
During this period, the sinuosity of the Ganges section fluctuates from 1.03 to 1.1. Between 1972 and 2015, the sinuosity of the Ganges section reduced. The number of bar spaces has grown qualitatively throughout the years.

### 3.3 Bank line shifting

Table 2 shows the average bank erosion and accretion rates for the left and right banks of the Ganges, Jamuna, and Padma confluence at 5-year intervals. Even though it would be ideal to have annual satellite images, this may not always be possible in practice because Landsat images are taken on a 16-day cycle. A clear Landsat image for the study site at a specific time of year may not always be available because the February images may suffer from partial or significant cloud cover in the study area in some years.

The left bank of the Ganges has a mean short-term erosion rate of 64.5 m/year, whereas the right bank has a rate of 105.2 m/year. The left bank of the Jamuna has a mean short-term erosion rate of 141.23 m/year, whereas the right bank has an erosion rate of 210 m/year. Padma’s mean short-term erosion rate is 240.4 m/year on the left and 281.1 m/year on the right. The mean accretion rates for the Ganges, Jamuna, and Padma rivers on the left bank are 115.4 m/year, 239.1 m/year, and 303.2 m/year, respectively, whereas the right banks are 133.6 m/year, 220.6 m/year, and 152.2 m/year. Between 2005 and 2010, the Ganges had maximum erosion of 297.2 m/year and maximum accretion of 473.9 m/year (1995–2000). The highest erosion and accretion rates on the right bank of the Ganges are 664.544 m/year (1995–2000) and 445.4 m/year (2005–2010), respectively. The highest erosion and accretion rates on the left bank of the Jamuna are 652.6807 m/year (1995–2000) and 969.2 m/year (1990–1995), respectively. The highest

![Fig. 5](image_url)  
Fig. 5 Evolution of Ganges–Jamuna confluence from 1972 to 2015
Table 2: Short-term analysis of mean erosion and accretion rate for Ganges, Jamuna, and Padma segment

| Year     | Ganges segment | Jamuna segment | Padma segment |
|----------|----------------|----------------|---------------|
|          | Left Bank Shifting (m/year) | Right Bank Shifting (m/year) | Left Bank Shifting (m/year) | Right Bank Shifting (m/year) | Left Bank Shifting (m/year) | Right Bank Shifting (m/year) |
|          | Erosion | Accretion | Erosion | Accretion | Erosion | Accretion | Erosion | Accretion |
| 1990–1995 | 48.58    | 100.6     | 105.4   | 152.16    | 164.66  | 244.30    | 372.46  | 411.16    |
| 1995–2000 | 30.56    | 65.28     | 190.4   | 189.4     | 230.40  | 115.63    | 150.61  | 133.11    |
| 2000–2005 | 64.85    | 99.65     | 82.40   | 56.56     | 122.91  | 263.04    | 263.14  | 154.77    |
| 2005–2010 | 72.36    | 121.03    | 60.92   | 107.30    | 120.97  | 63.44     | 85.27   | 290.79    |
| 2010–2015 | 106.6    | 124.28    | 89.46   | 64.96     | 69.62   | 114.78    | 180.99  | 115.47    |

Erosion: left bank shifting; Accretion: right bank shifting.
erosion and accretion rates on the right bank of the Jamuna are 815 m/year (2000–2005) and 782.9 m/year (1990–1995), respectively. The highest erosion and accretion rates on the left bank of the Padma are 781 m/year (1990–1995) and 1756 m/year (2000–2005), respectively. The highest erosion and accretion rates on the right bank of the Padma are 1118 m/year (1990–1995) and 727 m/year (2005–2010), respectively. Table 2 demonstrates that erosion has grown along the left bank of the Ganges portion throughout the research period. However, erosion has decreased along the left bank of the Padma section till 2010. Compared to the preceding 5 years, erosion rose by over 100% from 2010 to 2015. During the research period, erosion on the left bank of the Jamuna has decreased. The right banks of the Ganges, Jamuna, and Padma segments, on the other hand, have seen a very uneven erosional pattern.

The segments in the Padma River showed a relatively low mean accretion of 9.85 m/year during the previous 5 years of study. Between 2005 and 2010, accretion on the left bank of the Jamuna fell dramatically. Throughout the study period, the left bank of the Ganges exhibits an almost consistent rate of accretion. However, no regular accretion pattern was observed on the right bank of any segments.

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The right bank of the Ganges is very unstable. It shows continuous movement throughout the confluence zone, as illustrated in Fig. 6, from a short-term examination of the Ganges part of the confluence region. However, channel shifting has been observed on the left bank of the confluence zone’s upstream area of the Ganga River. The left bank of the Ganges remained relatively steady around the site of confluence.

Jamuna’s short-term alterations are depicted in Fig. 7. The upstream portion of the confluence zone is more mobile than the zone at the confluence site in the event of left bank movement, as seen in the diagram. The right bank of the Jamuna River follows a similar pattern.
During 5 years, the Padma section’s results reveal that the downstream portion of the right bank is unstable, with irregular movement, but the area near the confluence is less unstable. The left bank of the Padma, on the other hand, is relatively stable near the confluence, but the downstream part has a more significant changing propensity, as seen in Fig. 8.

Long-term changes in the confluence region are also examined for the Ganges, Padma, and Jamuna portions. This study gives a clear picture of these rivers’ changing tendencies. Figure 9 clearly shows that, except for the Yatra, the main pattern of the left bank of the Ganges is one of deposition from the year 1990 to 2005.

On the other hand, the rate of deposition has steadily reduced over time. The standard deviation of erosion has remained relatively consistent, implying homogeneous erosion in all portions of the confluence zone along the Ganges. However, between 1990 and 2000, the standard deviation for deposition instances was higher, which might show a lack of uniformity in the deposition of the sections. Deposition occurred on the right bank of the Ganges between 1990 and 2000; however, the bank quickly became prone to erosion and has continued to do so in recent years.

In the long term, the mean erosion and deposition tendency in the left bank of the Jamuna have stayed comparable. However, in recent years, there has been a depositional trend, as seen in Fig. 10. On the other hand, in the long-term, the right bank of the Jamuna is exhibiting erosional characteristics.

Figure 11 reveals that long-term bank shifting trend has showed mostly erosional tendency in both the banks of Padma.
Fig. 10  Long-term changes to erosion and accretion rates along the a left and b right banks of the Jamuna, (1990–2015)

It can be seen from Fig. 12 that a 5-year interval wise (1990–1995, 1995–2000, 2000–2005, 2005–2010, and 2010–2015) analysis based on satellite images has been done, and their short-term change has also been analyzed. First, the analysis of the confluence zone for the 5-year interval from 1990 to 1995 showed an erosional tendency in the lower portion of Jamuna and the lower portion of Padma. The erosional activity was prominent in the confluence zone at Dohar, Harirampur, and Faridpur. Besides, there was also a deposition scenario in the upper portion of the Jamuna River. From 1995 to 2000, erosional activity was prominent at Harirampur and Charbhadrasham. There was a significant change in the upper portion of Jamuna and Ganga River and frequent change in the whole portion Jamuna River. In addition, there was an insignificant deposition scenario in the uppercut point of Shariatpur. The erosional activity lost its dominance from 2000 to 2005 in Charbhadrasham, where minor erosional activity has been noticed. The net erosional activity at Dohar was negligible. But, significant deposition has been noticed in the lower part of Shariatpur. From 2005 to 2010, the deposition activity took prominence at Harirampur and Dohar, while erosional activity can be seen between these two places. The deposition portion in the year 2000–2005 was entirely eroded. For the period 2010 to 2015, there was no significant deposition in the confluence zone except in the upper portion of Jamuna. However, significant erosion occurred in this period for the lower part of Shariatpur and Dohar. So the overall scenario of the study area can represent a dynamic change status for the study area for the entire period.

Following long-term analysis from 1990 to 2015, a significant change has occurred in the confluence zone. Erosion most prominently happened during this period. Figure 13 represents a visual scenario of this change. From 1990 to 2000, there was an erosion portion on both sides of the Padma near Dohar, Charbhadrashan, and Doulatpur. From 1990 to 2005, there was changing stability similar to 1990–2000 in the Jamuna River.

Fig. 11  Long-term changes to erosion and accretion rates along the a left and b right banks of the Padma, (1990–2015)
Overall, the erosional tendency of the right banks of the Jamuna and Padma Rivers was less severe from 1990 to 2010. During this time, the right bank of the Padma River observed considerable accretion.

Fig. 12 Short-term erosion and deposition in the Ganges–Jamuna confluence zone
From 1990 to 2015, Charbhadrashan, Rajbari Sadar, and Pabna Sadar all experienced significant erosion. Except for the Dohar region, this erosional trend continued for the following over the 25 years. During this time, Dohar did not experience any severe erosion. However, the riverbanks of the Padma River in Dohar have been severely eroded in recent
years. We can ascribe the erosional tendency to create sand bars in rivers; as a result, flow is directed toward the rivers’ banks, producing erosion. Table 3 summarizes the findings of the study.

Table 3 shows that during the course of 25 years, the confluence zone lost 487.89 km² of the area while gaining just 173.28 km². It can also be noted that erosional tendency declined in the short term between 1990 and 2010. However, between 2010 and 2015, the degraded area nearly doubled compared to the previous 5 years. Meanwhile, there is no discernible pattern in the deposition tendency.

4 Discussion

For investigating the bank line movement of the Ganga–Jamuna River, the accuracy of the coarser-resolution Landsat MSS (80 m) data should be lower than the higher resolution Landsat TM and OLI (30 m) data. Several studies have reported using density slicing of Landsat OLI, TM, or MSS data to define water bodies without comparing the two types of Landsat data quantitatively (Asbury and Aly 2019; Bijeesh and Narasimhamurthy 2019; Mishra and Pant 2021). According to Mohajane et al. (2018), TM and OLI digital data are generally more helpful than MSS data for mapping homogenous, near-urban land covers. However, they may be less effective in mapping heterogeneous urban areas than MSS data. In other words, TM data may not necessarily be more valuable than MSS data, according to Mohajane et al. (2018). There have also been successful investigations of MSS data-based multispectral classifications of water borders (Bhaskaran et al. 2010).

Ganga–Jamuna’s mean channel width is around 11 km, significantly larger than the resolution of Landsat satellite data, particularly Landsat TM and OLI. The radiometric values of pixels depicting river banks and water regions ought to be sufficiently homogenous, and the investigation must be suitable for detecting Ganga–Jamuna backline movement. This is because of the fact that the Ganga–Jamuna is a very active river, and the shift in the bank line between specific processed Landsat images should be apparent. The accuracy of identifying differences between two pictures might be somewhere between the resolution of the satellite data, such as between 30 and 80 m or better.

The erosion and accretion rates vary considerably throughout the river. They appear to be affected by the river’s meandering feature and flow direction, according to early analyses of overlay maps of bank movement and bank movement as a function of distance from 1990 to 2015. The magnitude of accretion on the left bank has typically been greater than the magnitude of erosion on the right bank, and their rates have only slightly changed

| Year       | Erosion (km²) | Deposition (km²) | Year       | Erosion (km²) | Deposition (km²) |
|------------|---------------|-----------------|------------|---------------|-----------------|
| 1990–1995  | 269.19        | 174.16          | 1990–1995  | 269.19        | 174.16          |
| 1995–2000  | 194.09        | 126.72          | 1990–2000  | 376.33        | 214.43          |
| 2000–2005  | 172.03        | 110.92          | 1990–2005  | 409.85        | 212.17          |
| 2005–2010  | 109.67        | 173.61          | 1990–2010  | 370.53        | 239.66          |
| 2010–2015  | 201.23        | 38.05           | 1990–2015  | 487.89        | 173.28          |
from 1990 to 2015, as predicted. Between 1990 and 2015, the left bank had more accretion than erosion, resulting in lower net movement rates than the right bank, in line with earlier research by Sarif et al. (2021).

The mean erosion and accretion rates estimated from the short-term analysis, where the migration rate is determined based on short-term changes between six accessible consecutive pictures, are 227 and 271 m/year on the left bank and 187 and 148 m/year on the right bank. In contrast, for the long-term analysis, the average erosion and accretion rates are 90 and 104 m/year on the left bank and 75 and 50 m/year on the right bank, respectively, which are identical to the work of Pal and Pani (2019) and Sarif et al. (2021). The right bank experienced more severe erosion, resulting in a quicker migration rate than the left bank, which experienced erosion and accretion, resulting in relatively modest net movement rates (Sarif et al. 2021). The Ganga–Jamuna River’s average short- and long-term migration findings show a particularly dynamic form of erosion and accretion processes that contribute to channel shifting, as seen by its short-term range of erosion and accretion rates. Also, Klaassen and Masselink (1992) found that bank erosion in curved channels occurred at rates ranging from 0 to 500 m/year, with a maximum of around 1000 m/year. It mainly occurred at 90° to the major flow direction (east–west). However, between 1990 and 2015, the right bank’s declining erosion and accretion patterns were more constant than the left bank.

It continually transports water and sediment burdens from one part of the river to another. The Ganga, like other tropical rivers, has specific particular fluvial-geomorphological characteristics that distinguish it from the others. For this reason, since over 80% of the Ganga’s annual flow travels through it during the monsoon season, its measured and displayed hydrograph seems to be highly distorted. In September 1998, the greatest peak discharge in Farakka was around 76,456 m³/s, according to the latest available data (Rudra 2010). The flow during the lean season lowers to less than 1557 m³/s, resulting in conflicts between India and Bangladesh over the sharing of water resources (Rudra 2010). Many experts have determined the quantity of suspended silt conveyed by the river annually. Rudra (2010) asserts it is 736 million tons in total. Wasson (2003) estimated that Himalayan tributaries provide over 90% of the sediment load in the Ganga, while peninsular tributaries contribute less than 10% of the sediment burden in the Ganga. Human contact in the fluvial regime disturbs dynamic equilibrium, causing course-altering processes to be delayed or expedited, depending on the situation. As a result, because of human interventions such as establishing bank protection measures, the long-term migration rate for both banks is lower than the short-term equivalent (Rudra 2014). Over the past 50 years, human interventions on the Ganga–Jamuna River have included: A massive barrage at Farakka was officially inaugurated on April 21, 1975. It is located where the river’s main flow enters Bangladesh, while the tributary Hooghly (also known as the Bhagirathi) runs through West Bengal and into Kolkata, respectively. (2) The Lav Khush Barrage spans the Ganges River in Kanpur, and (3) the Tehri Dam, which was constructed on the Bhagirathi River, a tributary of the Ganges, are examples of such infrastructure. It is located 1.5 km downstream of Ganesh Prayag, at the confluence of the Bhilangana and Bhagirathi rivers. (5) The construction of many bank protection structures since the early 1960s, such as the Sirajganj town protection work, which began during the British period and was strengthened in 1964 with brick mattress, which was washed away in 1969; and (6) the Jamuna Bridge Guide Bund (3.2 km on both banks) constructed in 1994–1998. Seventh, as part of the River Bank Protection Project from 1996 to 1998, the Sirajganj Hard Point (which featured the groin with the revetment) was constructed in Sirajganj (RBPP). The revetment test structures at Bahadurabad and Ghutail and a groin test structure at Kamarjani were
built in 1996–1997 as part of the FAP 21/22 program. The Kalitola and Sailabari Groynes, sponsored by the BWDB and constructed in 1980 and 1978, were built in 1980 and 1978. The variation in river width between 1990 and 2015 is analogous to that reported by Gupta et al. (2013a, b) and Gupta (2012), who found that the river widened from 1990 to 2015 but then stayed constant. The river’s breadth will often expand under the impact of erosion and shrink under the effect of accretion if the discharge rate does not change significantly (Asadi Sharif et al. 2021). However, assuming that both the sediment load and the discharge rate stay constant, a typical morphological feature of rivers is that as river width grows, erosion rates should decrease since river flow velocity decreases and vice versa. In the same way, like a river narrows, the rate of accretion should accelerate.

For the short-term study, changes in the right (left) bank’s erosion (accretion) rate follow the general morphological pattern of river bank migration, but not so for the right (left) bank’s accretion (erosion) rate. When the left (right) bank undergoes accretion (erosion), the fundamental morphological characteristic of river movement appears to apply, but not when the left (right) bank undergoes erosion (accretion). Only the right bank erosion rate and the left bank accretion rate obey this concept owing to complexities created by the intricate interactions of both erosion and accretion processes and the Jamuna River’s meandering characteristic (Bomer et al. 2020).

For the long-term analysis, the observed erosion rate for the right bank and accretion rate for the left partly follow the general morphological principle of river migration, such as a river widens. The erosion rates generally decrease because the velocity of river flow decreases, and vice versa, assuming that both the sediment load and the discharge rate remain roughly unchanged. The Jamuna River observes several issues because of its braided, meandering, or anastomosing characteristics, such as unanticipated shifts in bank erosion or accretion (Sarker et al. 2014; Best et al. 2007; Richardson and Thorne 2001).

Instead of island migration, because of the shifting of sediment loads produced by each flood, some islands may vanish, or new islands may develop after a flood. According to Sarker et al. (2014), about 68% of the islands are under 6 years old or have lasted between 1 and 6 years. According to frequency analysis of changes of islands based on their size (in ha) in the Jamuna River, islands larger than 150 ha are more stable (fewer temporal changes in size, shape, and location) than small islands having areas less than 50 ha, which tend to be very unstable and subject to reasonably significant changes as observed in this 1990–2015 study period.

5 Conclusion

From the analysis, it can be seen that the Ganges–Jamuna confluence has undergone significant changes over the past few decades. In this paper, these changes are quantified in terms of river width change, bank line shifting and area of erosion or deposition. It is noted that the maximum width of the Ganges section is 4078.10 m, observed during the year 1995. Similarly, the maximum width of the Jamuna and Padma section was 13,925 m and 22,479.88 m consecutively observed during 2015. The maximum bank line shifting in the left bank of the Ganges segment is 473.92 m/year observed near Pabna Sadar at chainage 16 km during 1995–2000. Likewise, the maximum bank line shifting in the right bank of the Ganges segment is 394.83 m/year observed near Kumarkhali at chainage 4 km during 2005–2010. With the Jamuna segment, the maximum left bank line shifting is 959.30 m/year observed near Tangail at chainage 8 km during 1990–1995.
Similarly, maximum right bank line shifting is 975.12 m/year observed at chainage 36 km during 1990–1995. The Padma segment also shows significant migration, with a maximum left bank shifting of 1756 m/year observed at chainage 48 km near Dohar during 2000–2005. The maximum right bank shifting of the Padma segment is 1502.99 m/year, being noted at chainage 44 km near Sadarpur during 1990–1995. In terms of area, the confluence zone is losing land rapidly. The confluence zone has lost 201.23 km² of land between 2010 and 2015; in the same period, the zone has gained only 38.05 km² area. This means a net decrease of 163.18 km² occurred during the last 5 years. This may occur because of the various anthropogenic activities in this region.

As per the present work, massive sediment deposition boosts the attached bar and island bar, where agricultural farmland, plant cover, and population agglomeration grew. Because of repeated morphological changes, the socioeconomic condition has deteriorated. Several built barrages and dams are a crucial source of morphological changes in the river downstream. This structural structure alters river morphology by introducing island bars, connected bars, multichannel, increased sedimentation, and reduced water discharge flow velocity. The agriculture system and aquatic river ecology are greatly influenced by various morphological characteristics generated by morphological changes. In addition to the study areas, there are some policy implications and management strategies. Any unplanned artificial constructions, like dams and bridges, can negatively influence flow velocity and direction, causing massive sedimentation, bank line shifting, and bank narrowing, among other things. To reduce climatic effects, the government and other nonprofit organizations should propose plans to minimize the vulnerability of multiple fluvial hazards by stabilizing their banks through numerous restoration mechanisms such as riparian buffer zones, embankment flood protection systems, waste dumping processes, and toxic materials.

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Declarations

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