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ORIGINAL ARTICLE

Decoding spatio-temporal dynamics of river morphology: a comprehensive analysis of bank-line migration in lower Gangetic basin using DSAS

Rakhi Das[1]

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Abstract
Bank-line migration in lower basins is an ongoing phenomenon in river morphology that poses an existential threat to most dwellers, who depend on riverine ecosystems for their habitat and means of subsistence. This study strives to assess the changes in the bank line of the Ganga River upstream of the Farakka barrage over the past forty-nine years by utilizing satellite imagery and geospatial techniques. The results (1973–2022) reveal that approx. 309.97 sq km of land were lost due to erosion between 1973 and 2022, while 414.94 sq km of land were gained as a result of accretion. The bank line erosion and accretion rates were 61.39 and 35.93 m per year respectively based on linear regression rate (LRR). Erosion mainly has occurred along the banks of Kaliachak III and Manikchak block, while the highest rate of accretion was found along the Kaliachak II block. Furthermore, it was found that bank-lines in the whole upstream stretch of the Ganga River moved towards the land by 189.42 m based on net shoreline movement (NSM) between 1973 and 2022, with 70% of the bank-line experiencing landward shifting. These findings are highly useful for the government in managing the river bank area and in the development of bank protection measures.

Keywords Bank-line Migration · DSAS · EPR · NSM · LRR · Erosion · Accretion

Introduction

The scientific study of how sedimentation and erosion affect a river's cross section and planform is known as river morphology (Lovric and Tosic 2016). The morphology of a river is disrupted by the supply of silt and its deposition under varying discharge conditions (Bandyopadhyay et al. 2014). The most significant morphological processes of river, which have attracted a lot of interest from scholars and river scientist studying river over the past few decades, are erosion, accretion, and river channel migration (Ibitoye 2021). River channel migration across floodplains is a fluvial-geomorphological event where the main river starts flowing in a new river course due to aggradations, neo-tectonics, and human activities (Leopold 1994; Chakraborty and Mukhopadhyay 2015) which causes bank-line migration. Bank-line migration is regarded as the most notorious event worldwide which causes morphological changes of river through erosion and accretion (Bhattacharya et al. 2022). Alluvial rivers typically flow along meandering and braiding channels owing to shifting bars and eroding banks. Avulsions, or natural channel diversion, may temporarily halt this gradual movement and cause the channel to completely relocate across the floodplain (Slingerland and Smith 2004; Valenza et al. 2020). Water discharge, obstructions to natural water flow, deforestation, and unplanned flood interventions all affect the pace and pattern of channel bank-line migration (Micheli et al. 2004; Hazarika et al. 2015; Saur and Rathore 2022). In order to achieve a new equilibrium in channel geometry and morphology, erosion and deposition are ongoing processes in the river (Saikia et al. 2019; Raj and Singh 2022). The Ganga River is one of the most dynamic rivers in India, where channel migration is a common occurrence. Erosion and sedimentation processes have taken place to a significant level in the lower reaches of the Ganga. As the Farakka Barrage disrupts the general flow of the Ganga River (Rudra 2010; Mukherjee 2011; Mukherjee and Pal 2018), the process of erosion and sedimentation

✉ Rakhi Das
dasrakhikai@gmail.com

[1] Department of Geography, The University of Burdwan, Bardhaman, West Bengal 713104, India

(nearly 64 crore tonnes per year) has increased since it was built in 1975.

River erosion rates can display a seasonal pattern, since they often rise during flood occurrences (Knighton 1974). River erosion, which is the flow's capacity to remove individual particles or particle assemblages from the bank face, is the most important causative action (Lawler et al. 1997). Therefore, the cohesiveness or non-cohesiveness of the bank material, the roughness of the bank, the amount of vegetation present, and the presence or absence of massive trees in channels are all variables that affect the channel of a river (Thorne 1982; Davis and Gregory 1994; Debnath et al. 2007; Yu et al. 2015; Barman et al. 2019; Das et al. 2020). In addition, it is important to take into account the terrain, amount and intensity of rainfall, soil composition, and river morphology that have contributed to bank erosion (Mandal 2017; Hasan et al. 2018). Beside these, anthropogenic activities such as changes in land use, various construction projects along rivers, the installation of dams, barrages on rivers, etc. has accelerated the rate and intensity of bank erosion (Roy and Sahu 2016; Rhoads et al. 2016; Raj and Singh 2022; Wohl 2020). It increases the likelihood of sudden changes in the river's hydraulic geometry and depositional makeup. Large-scale sedimentation along the banks and riverbed has also taken place, resulting in a decrease in the depth of the riverbed and the formation of many new islands and bars in the river channel, which has caused channel migration (Mukherjee 2011; Ashmore 2015; Singha et al. 2020).

Studies on erosion–accretion and the resulting bank-line movement are now more important than ever since these destructive processes have a significant impact on people's livelihoods (Mukherjee and Pal 2018). The shift of the flood-induced channel causes additional environmental and socio-economic concerns, such as crop damage, loss of riparian arable land, and fatalities. Therefore, in order to ensure the sustainability of riparian residents, it is crucial to estimate the spatiotemporal variations of riverbank shifting and make future predictions. Riverbank shifting is still difficult to estimate despite the many methods and approaches. There are several conventional techniques to assess bank erosion. For instance, Thorne (1982) employed near-bank stress (NBS) method to estimate bank erosion, Lawler (1991) utilised photo electronic erosion pins to measure erosion, and Pyle et al. (1997) estimated erosion of rivers using digital photogrammetric monitoring. For the purpose of estimating bank erosion, scholars such as Rosgen (2001), Bandyapadhyay et al. (2014), Ghosh and Mukhopadhyay (2016), Simpson et al. (2015), Newton and Drenten (2015), Mandal (2017), Nosrati et al. (2020), Majumdar and Mandal (2021), etc., used the Bank Erosion Hazard Index (BEHI). However, while conventional techniques produce accurate results over a large area, they do not offer historical information like previous bank-line placements (Mahmud et al. 2020). The estimation of riverbank erosion and accretion is a challenging problem, even with the application of hybrid approaches and techniques. Remote sensing and GIS techniques are often employed nowadays to determine spatio-temporal changes in a range of dynamic rivers (Debnath et al. 2023). Different scholars have examined bank-line migration using RS-GIS techniques including Channel Migration Zoning and the Erosion-Accretion model (Kotoky et al. 2005; Yao et al. 2010; Sarma and Acharjee 2012; Chakrabarty and Datta 2013; Gogoi and Goswami 2014; Robinson 2013a, b; Chakraborty and Mukhopadhyay 2015; Mukherjee and Pal 2018; Dhali and Mukhopadhyay 2020; Momin and Chakraborty 2021; Hasanuzzaman and Mandal 2020; Chen et al. 2021; Ghosh et al. 2022; Khan et al. 2022).

For analysing historical channel changes, numerical modelling proved to be very helpful in quantifying bedload transport and in supporting the analysis of earlier modifications as well as probable future channel evolution (Ziliani and Surian 2012). In order to quantify channel migration rates, automated hybrid techniques such as Digital Shoreline Analysis System (DSAS), developed by the USGS, are being employed more frequently now. Worldwide, several scholars (Chaudhary et al. 2013, Salauddin et al. 2018; Nassar et al. 2019; Mahmud et al. 2020; Song et al. 2021; Natarajan et al. 2021; Bennett 2021; Dewidar and Bayoumi 2021; Quang et al. 2021; Obiene et al. 2022; Saad et al. 2022; Yuliana and Razi 2022; Beyene et al. 2023; Acharyya et al. 2023) have used this technique to analyse and predict shoreline and bank-line changes in coastal areas, deltas as well as rivers. Scholars such as Hasanuzzaman et al. (2023) estimate bank-line migration of the lower Ganga River, Debnath et al. (2023) investigate Jia Baharali River bank-line shifting, Singh et al. (2023) quantify Chambal River bank changes, Bhuyan et al. (2022) project the Brahmaputra River bank-line migration, Baig et al. (2020) analyse the Visakhapatnam Coast shoreline changes, and Bera and Maiti (2019) quantify erosion and accretion rates of the Indian Sundarban. The coastal changes of Jambudwip Island are examined by Das et al. (2021), Jana (2021) estimate river bank shifting and prediction of Subarnarekha river while the shoreline changes of Sagar Island are studied by Nandi et al. (2016). All of them have admitted that the DSAS tool is very effective to analyse and predict shoreline and bank-line changes. In coastal research, DSAS is generally employed to evaluate shoreline movement. In the area of fluvial research, however, it has not been applied frequently (Mahmud et al. 2020) especially in the lower Gangetic basin. Therefore, the present article tries to bridge this gap by estimating riverbank erosion rates using Net Shoreline Movement (NSM), Endpoint Rate (EPR), and Linear Regression Rate (LRR) utilising transects and a reference baseline.

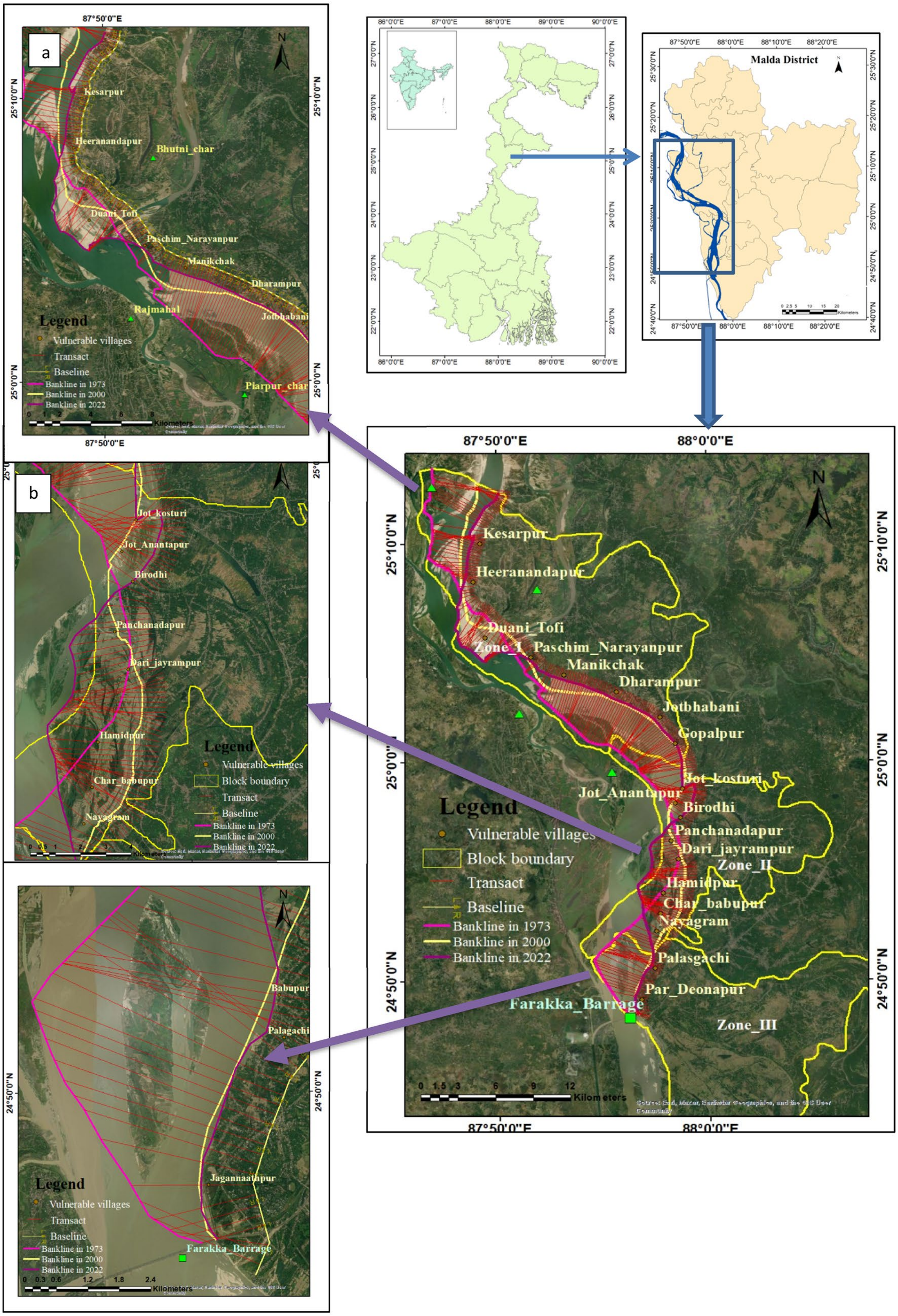

Fig. 1 Study area (**a** Zone I, **b** Zone II and **c** Zone III)

Table 1 Satellites dataset used for this study

Satellite data	Acquisition date	Path/Row	Resolution
Landsat MSS	1973/01/17	149/043	60 m
Landsat ETM+	2000/02/26	139/042	30 m
Landsat OLI	2023/01/24	139/043	30 m

Table 2 Bank-line length of each zone of the study area

Zone	Year	Bank line length (km)	Baseline length (km)
I	1973	32.20	57.02
	2000	34.52	
	2022	37.17	
II	1973	22.04	
	2000	18.47	
	2022	19.51	
III	1973	9.00	
	2000	5.56	
	2022	5.65	

The objectives of this study are to examine the spatio-temporal bank-line changes and quantify erosion and accretion rates of the Ganga River upstream of the Farakka Barrage with the help of remote sensing, GIS for the period 1973–2022 (49 years) through erosion accretion measurements and digital shoreline analysis model. The results will assist the government to develop rehabilitation programmes for each zone on a priority basis and also help to identify the vulnerable locations for developing protective measures to check erosion.

Study area

The Ganga River transports huge quantities of water and sediment across an area of 1.09 million sq km, making it the second largest river in the world (Dewan et al. 2017). After reaching West Bengal, the basin of the river is known as the lower Gangetic basin. The lower Gangetic basin is very prone to natural hazards like floods and riverbank erosion. The basin lays in the two districts of Malda and Murshidabad in West Bengal. In this reach, the river has the 'diara' region on the left bank (Malda side) and the Rajmahal hills on the right bank. Between the uplands and the swampy Tal track, there is an area of alluvial deposition known as the diara region (Hasanuzzaman et al. 2023) where erosion and accretion happens frequently. The current area of study is a segment of the lower Gangetic basin from Rajmahal to Farakka (Fig. 1), as this segment has witnessed dynamic changes to the Ganga River course after the construction of the Farakka Barrage (Rudra 2010; Thakur et al. 2011) where bank-line change and resultant erosion is a very common phenomenon. The segment covers an area of 172.84 sq km and falls under Malda district.

This segment's geographical location extends between 87° 49′32″ E and 25° 12′27″ N to 87° 56′39″ E and 24° 48′14″ N. The segment is divided into three zones based on the block boundary for calculating bank-line changes. Zone I is part of the Manikchak block, Zone II is part of the Kaliachak II block, and Zone III is part of the Kaliachak III block of Malda district. Each year, the riverbank erosion in these blocks affects a larger area of land due to the dynamicity of the Ganga River. According to Banerjee (1999), the river erosion damaged 66 villages in Kaliachak III, 17 villages in Kaliachak II, and 47 villages in Manikchak till 1990.

Materials and method

Satellite data

In this study, satellite data of Landsat TM, ETM+, OLI have been used to analyse bank-line changes of the Ganga River upstream of the Farakka Barrage from 1973 to 2022, with an interval of 10 years (Approximately). Satellite images have been downloaded from USGS Glovis and earth explorer. Details about the satellite data have been shown in Table 1 and overall methodological flow has been compiled in Fig. 1. Moreover, all the satellite images were taken in the dry season (between the months of January to March) to minimize the seasonal effect.

Image processing

Any change detection investigations utilising satellite imagery from satellites must start with geo-corrected images (Salauddin et al. 2018). All of the imagery for this study was downloaded in Geo TIFF format with a spatial resolution of 30 m as level 1 pre-processed data from the USGS website. The level 1 product has a predetermined projection in the Universal Transverse Mercator system in the 45N zone and was geodetic corrected according to the World Geodetic System (WGS84) datum. Band composition and merging were used to determine the particular study area. Images taken without clouds have been used. Consequently, no additional atmospheric or radiometric correction was made.

Delineation and measurement of bank-line and baseline

To get precise rate of the bank-line migration, the usage of an extension called DSAS for ArcGIS 10.3 (Thieler et al. 2008) was applied. By establishing a baseline and coastline

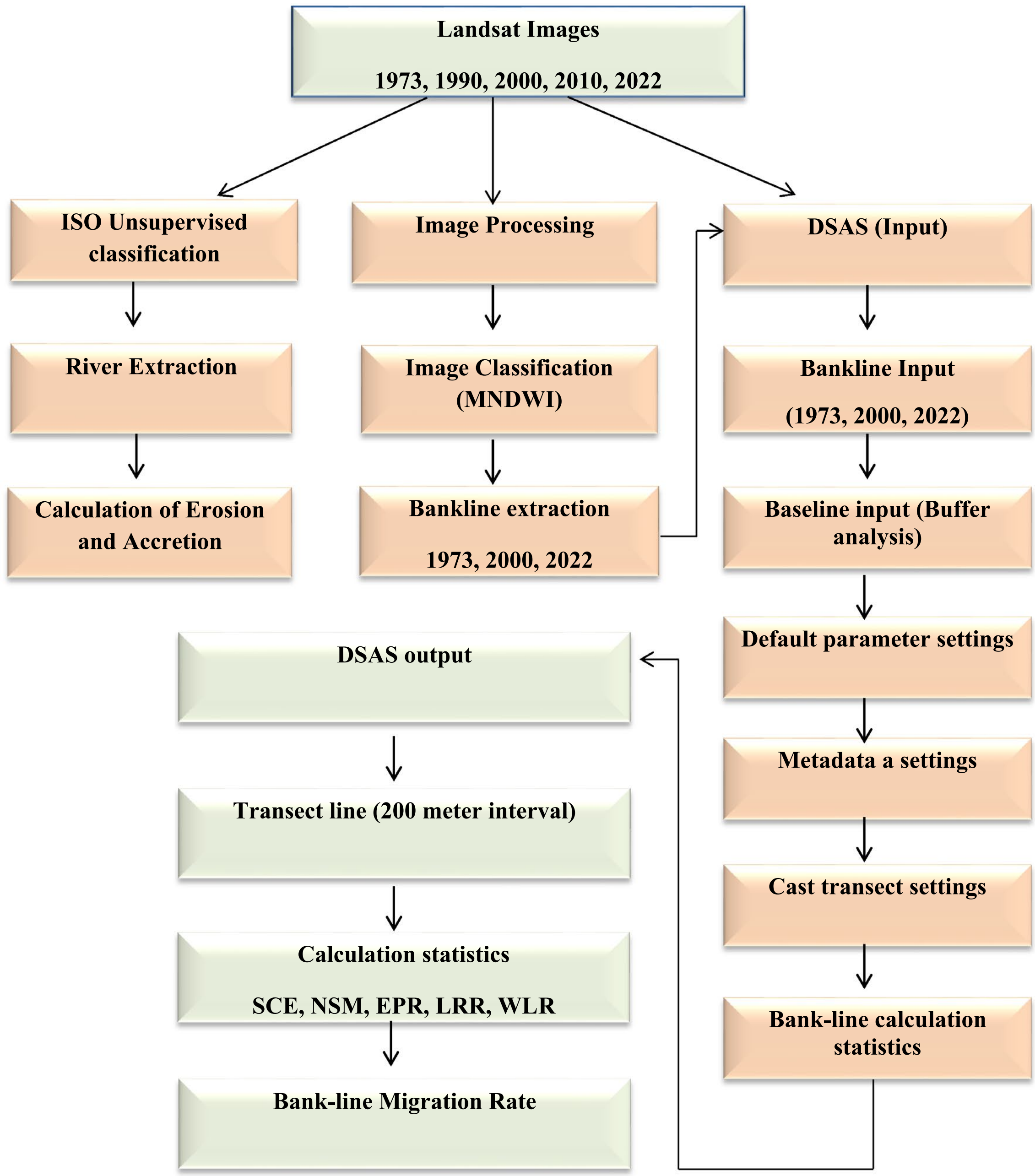

Fig. 2 Methodological flow chart

with the aid of transect, shoreline position movement and the rate of change will be measured using DSAS (Chand and Acharya 2010). The extension has used the following methods for calculating the bank-line.

The entire bank-line of the Ganga River upstream of the Farakka Barrage was divided into three zones (I,II,III) based on the block boundary of Malda district. In this study, MNDWI (Xu 2006) technique was applied for the bank-line identification. MNDWI values ranges between – 1 to 1 (positive value greater than 0.5 represent water bodies).The equation for MNDWI for Landsat 7 is as follows:

$$\text{MNDWI} = (p\text{Green} - p\text{MIR})/(p\text{Green} - p\text{MIR}) \quad (1)$$

where, p MIR refers to the reflection in the mid-infrared band.

Whereas, equation of MNDWI (Xu 2006) for the Landsat 5 and 8 is

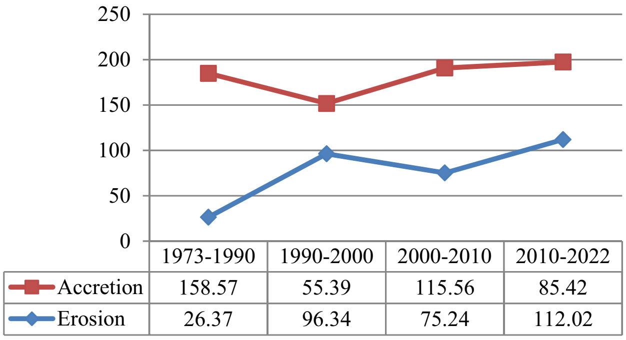

Fig. 3 Spatio-temporal change of the study area

$$\mathrm{MNDWI} = (p\mathrm{Green} - p\mathrm{SWIR}) / (p\mathrm{Green} + p\mathrm{SWIR}) \quad (2)$$

After that, the bank-lines were extracted from the multi-temporal satellite images through digitisation in Arc GIS10.3. With the help of the GIS merge tool, bank-lines that were extracted at various times were combined into a single feature, creating a single shape file out of several bank-lines. DSAS was then used to calculate the bank-line change over the subsequent forty-nine years, from 1973 to 2022. Five attribute elements, including Object ID (a transect-specific number), shape length, date (the year of the initial survey), and uncertainty values, were used to create the bank-lines field in the DSAS tool for the calculation of bank-line changes. A reference baseline was developed for the estimation of bank-line movement using the buffer approach in the GIS 10.3. After creating a buffer, the polygon feature was converted into the polyline. After that the baseline field was added in DSAS. Baseline placement can be in any direction off shore, onshore or middle shore (Himmelstoss et al. 2018). Here, the baseline was placed in onshore direction or towards the land side, from where transects were drawn. Five attribute elements, including Object ID (a transect-specific number), shape length, date (the year of the initial survey), and group are required to create a baseline field for the calculation of bank-line changes. Transects were drawn at varied lengths, with a transect spacing interval of 200 m, to measure from the baseline to intersect the whole bank-line. Transects were drawn separately for each zone (Table 2).

The study used statistical methods including Net Shoreline Movement (NSM), Shoreline Change Envelop (SCE), Linear Regression Rate (LRR), Weighted Linear Regression (WLR) and Endpoint Rate (EPR) in DSAS (an extension of GIS) to compare bank-line locations across time and assess bank-line changes. Among the entire bank lines that cross certain transect, the SCE value shows the distance that is the largest. Rather than reporting a rate, the SCE gives a distance (in meters). The number for SCE is always positive since the entire distance between the two shorelines has no sign. Equation of SCE is as follows:

$$\mathrm{SCE} = \mathrm{B_d} - \mathrm{B_f} \quad (3)$$

where, B_d = Distance between baseline and farthest shoreline (meter), B_f = Distance between baseline and closest shoreline (meter).

The distance (in meters) between the oldest and the youngest shorelines for each transect is known as NSM (Himmelstoss et al. 2018). By fitting a least squares regression line to each coastline point along a transect, one may estimate the LRR. Based on an assumed linear trend of change between the earliest and latest shoreline dates, the linear regression approach was used to calculate shoreline-change rates (Baig et al. 2020). The distance of shoreline movement is divided by the amount of time between the oldest and most recent coastline to determine the EPR. Equation of EPR is as follows:

$$\mathrm{EPR} = \frac{\text{Distance in Meter}}{\text{Time between oldest and most recent shoreline}} \quad (4)$$

While the LRR technique is more intuitive and based on well-established statistical ideas, it tends to produce results with acceptable output accuracy. Both methods often produce minimal differences for calculated outcomes (Baig et al. 2020) (see Fig. 2).

Result

Decadal rate of erosion–accretion of the Ganga River upstream of Farakka Barrage

Riverine areas frequently experience erosion and accretion due to their dynamic character. According to Das et al. (2017), the Ganga and Brahmaputra river basins in India are examples of areas that are worst affected by flooding and riverbank erosion. West Bengal's Malda and Murshidabad districts have been disproportionately affected by floods and riverbank erosion as a result of the Farakka Barrage project (Banerjee 1999; Rudra 2006; Thakur et al. 2011). Every year, a significant portion of land upstream of the Farakka Barrage erodes, while at the same time, accretion takes place.

Between 1973 and 1990, there was a substantial amount of accretion (158.57 sq km) and comparatively little erosion (26.37 sq km), leaving 46.82 sq km of land unchanged. Then, from 1990 to 2000, the erosion rate (96.34 sq km) was significantly higher than the accretion rate (55.39 sq km), and around 103.72 sq km of land was found to be unchanged (Fig. 3). This is because the area is dynamic, where the rates of accretion and erosion have been fluctuating greatly after

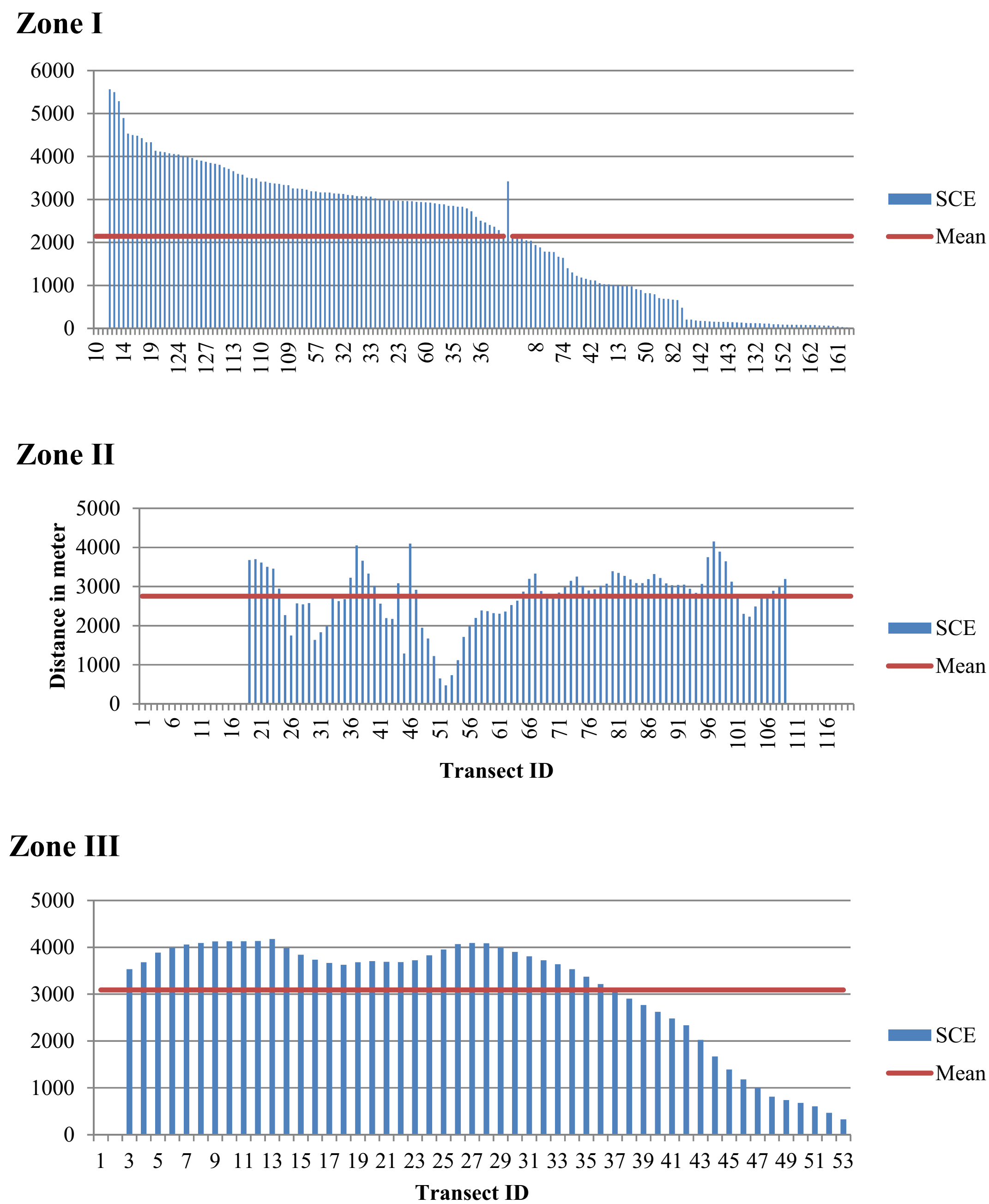

Fig. 4 Result of SCE of each zone of the study area

the construction of the Farakka Barrage. The accretion rate was once more quite high (115.56 sq km) over the next ten years (2000–2010) and the stable/unchanged land area was around 83.87 sq km, but erosion was not negligible (75.24 sq km). During the recent period (2010–2022), erosion rate (112.02 sq km) was very high and accretion rate was reduced (85.42 sq km) (Fig. 3). The blocks located along the Ganga River in upstream Farakka barrage like Manikchak and Kaliachak III had faced tremendous erosion during this period.

Analysing SCE and NSM matrices for bank-line movement

SCE and NSM matrices are produced by DSAS by measuring the distance between the baseline and every intersection of a bank-line along the transects, and combining date data with positional uncertainty for each shoreline (Himmelstoss et al. 2018). The following metrics were calculated for each zone, where SCE are taken as the most distant bank-line from the baseline, and NSM is taken from the youngest and

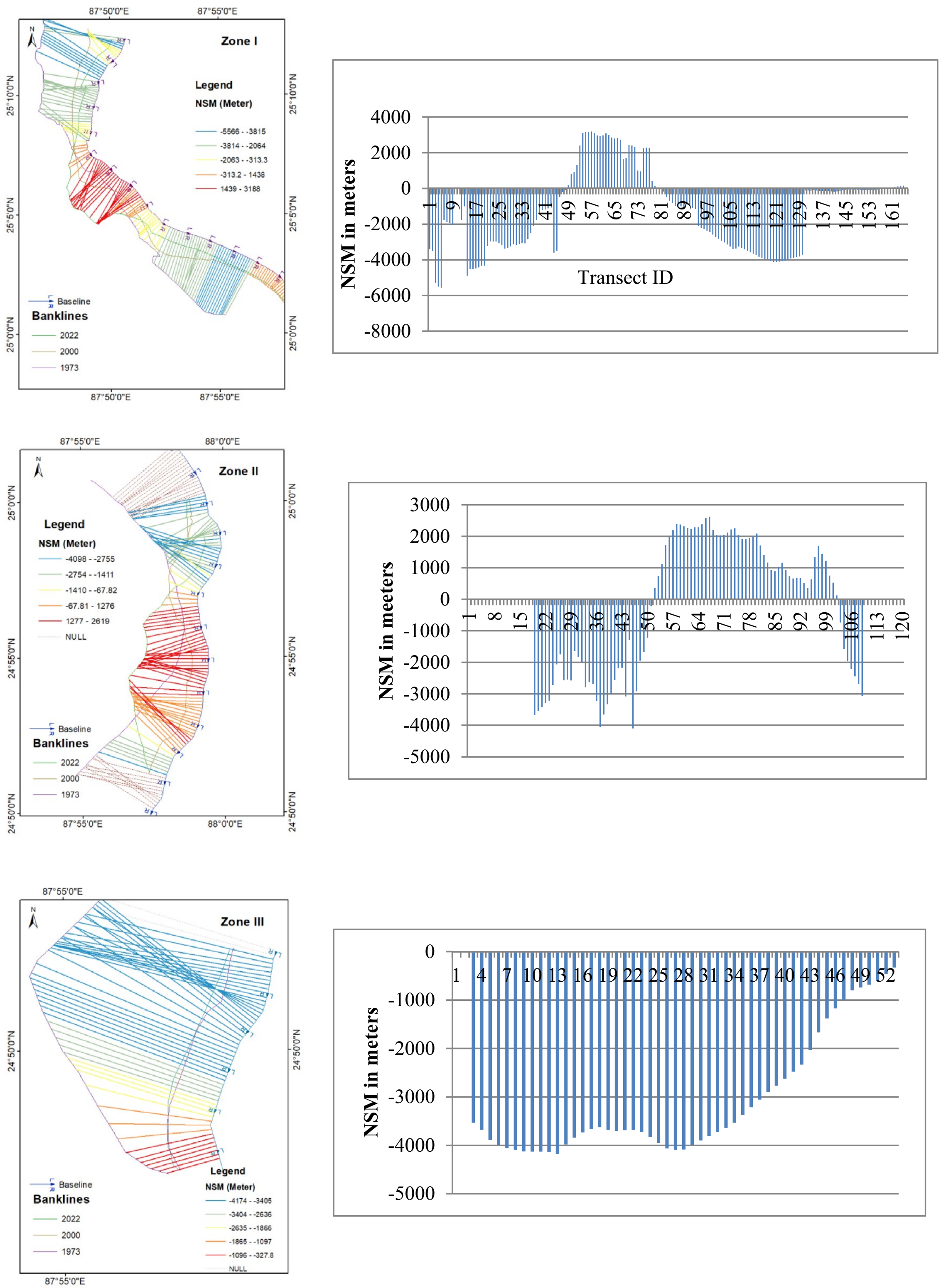

Fig. 5 Results of NSM of each zone of the study area

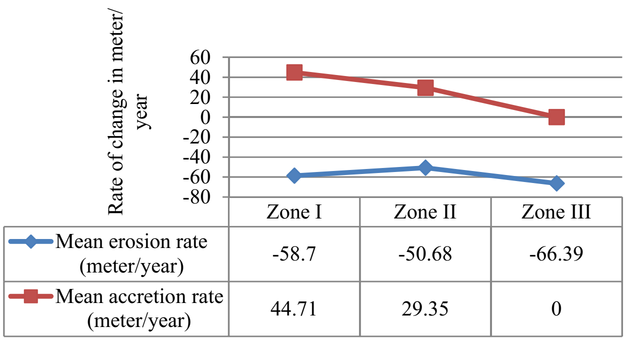

Fig. 6 Zone-wise average rate of erosion and accretion

oldest bank-line. Mean distances measured (SCE) among the bank-lines for each zone are 3089.43 m (Zone I), 2752.67 m (Zone II) and 2143.24 m (Zone III). Results show that Zone I has the maximum mean distance, indicating that the Manikchak block (Zone I) has experienced maximum bank-line change (Fig. 4). There are 88 transects in this zone whose length is more than the mean distance. When the NSM value was positive, the bank-line exhibited riverward shifting and an advancing bank-line. If the result was negative, the bank-line moved away from the land and began to fall apart. (Song et al.2021; Bhattacharya et al. 2022; Bhuyan et al. 2023). Through the study, it was found that bank-lines in the upstream stretch of the Ganga River moved away from the land by 189.42 m between 1973 and 2022, with 70% of the bank-line experiencing landward shifting. The largest NSM in Zone I was 5565.89 m, and the majority of the bank-line movement was in the direction of the land near Bhutni Char and Gopalpur village. The largest riverward NSM, which was 30,188.4 m, mostly occurred close to the settlement of Dakhsin Chandipur of Manikchak block. The greatest NSM for Zone II was 4098.41 m, and the majority of the bank-line movement was in the direction of the area near Jot Ananta, Birodhi, and Panchannadapur Village of Kaliachak II block (Fig. 5). The highest riverward NSM was 2390.72 m and was located close to Hamidpur and Char Babupur villages. The highest NSM in Zone III was 4174.21 m, and there was no riverward shifting (Fig. 5). The bank-line moved most towards the land around the villages of Nayagram, Palagachi, and Birnagar villages of Kaliachak III block. This area is hence extremely susceptible to erosion. According to the general pattern of change, the Kaliachak III and Manikchak blocks in Malda district contained the majority of the bank segments that had significant NSM alterations between 1973 and 2022.

LRR and EPR based Bank-line migration

Long-term migration for 49 years between 1973 and 2022 was analyzed using EPR and LRR statistical tools. To analyse changes along the bank-line of the Ganga River upstream of the Farakka Barrage, DSAS calculated a total of 339 transects which is divided into three zones. Analysis of EPR and LRR calculation results reveal that throughout the forty-nine years, the bank-line of the Ganga River upstream of the Farakka Barrage exhibited both accretion and erosion tendencies (Fig. 6). With an overall mean bank-line change rate of – 31.12 m per year, it is clear that erosion is the predominant process along the whole section. However, the rate of bank-line changes for the three zones is different. The bank-line length in Zone I increased to 37.17 km in 2021, compared to 32.20 km

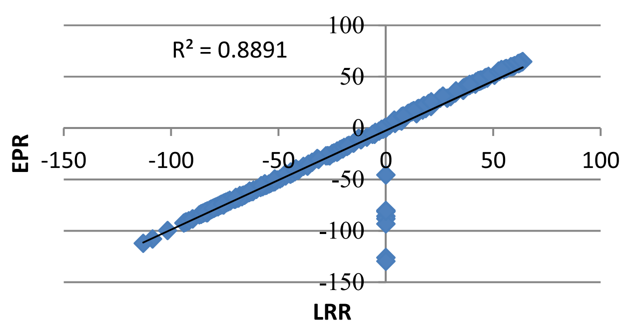

Fig. 7 Correlation between EPR and LRR for 1973 and 2022

Table 3 Zone-wise bank-line change rate using Linear Regression Rate (LRR)

S. No	Zones	I	II	III
1	Total number of transects	166	120	53
2	Bank-line length (km)	36.02	27.9	8.94
3	Mean bank-line change rate (meter/year)	– 23.28	3.88	60.39
4	Mean erosion rate (meter/year)	58.7	47.34	66.39
5	Mean accretion rate (meter/year)	44.71	29.35	0
6	Bank-line change rate (maximum)	– 114.46	– 84.33	– 87.49
7	Bank-line change rate (minimum)	– 0.27	– 0.6	– 6.83
8	Total transects that record erosion	89	39	50
9	Total transects that record accretion	31	50	0
10	Zone wise overall trend	Erosion	Accretion	Erosion

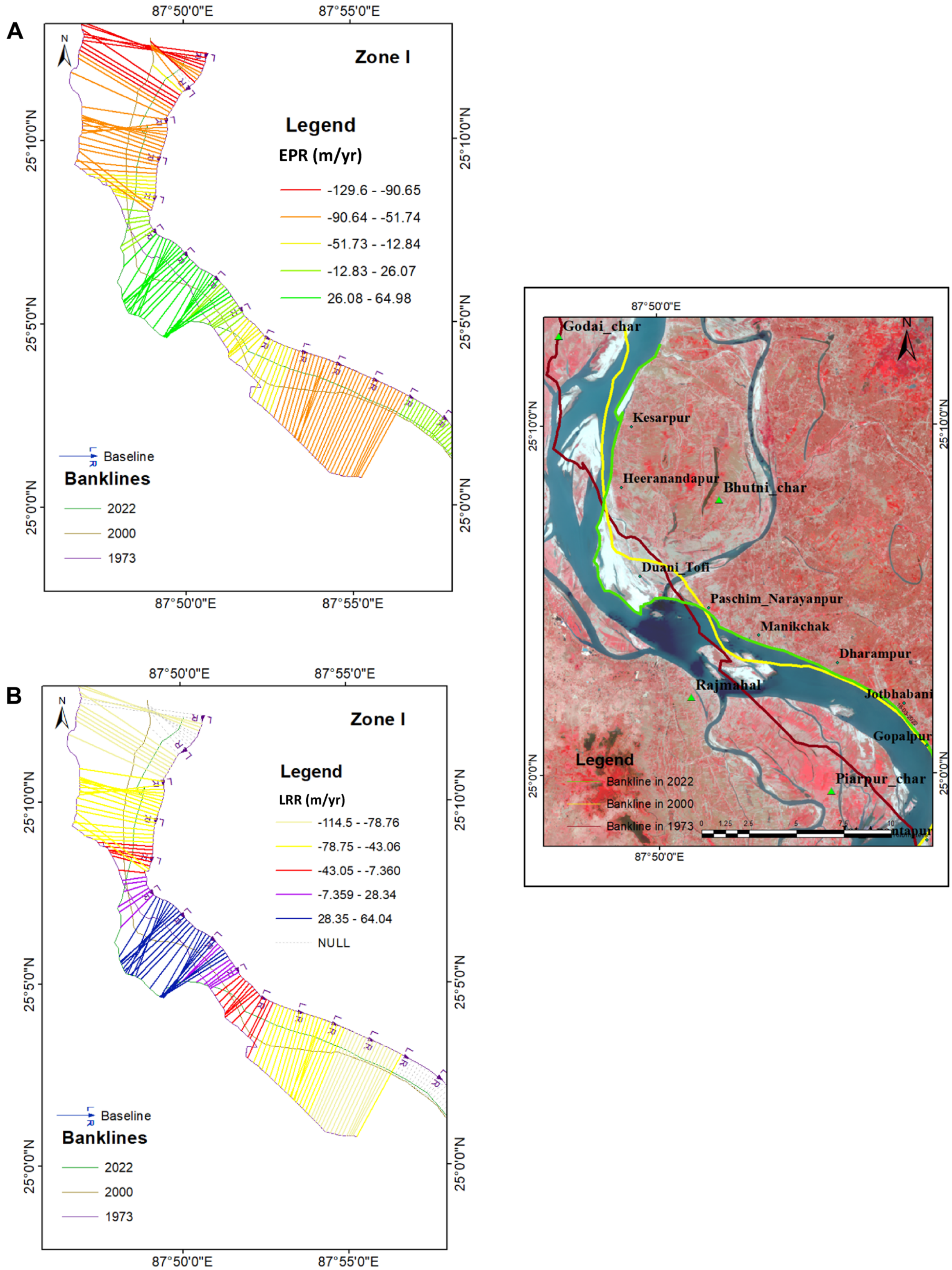

Fig. 8 **a**, **b** Result of EPR, LRR and of zone I. Where, – Value = Erosion, + Value = Accretion

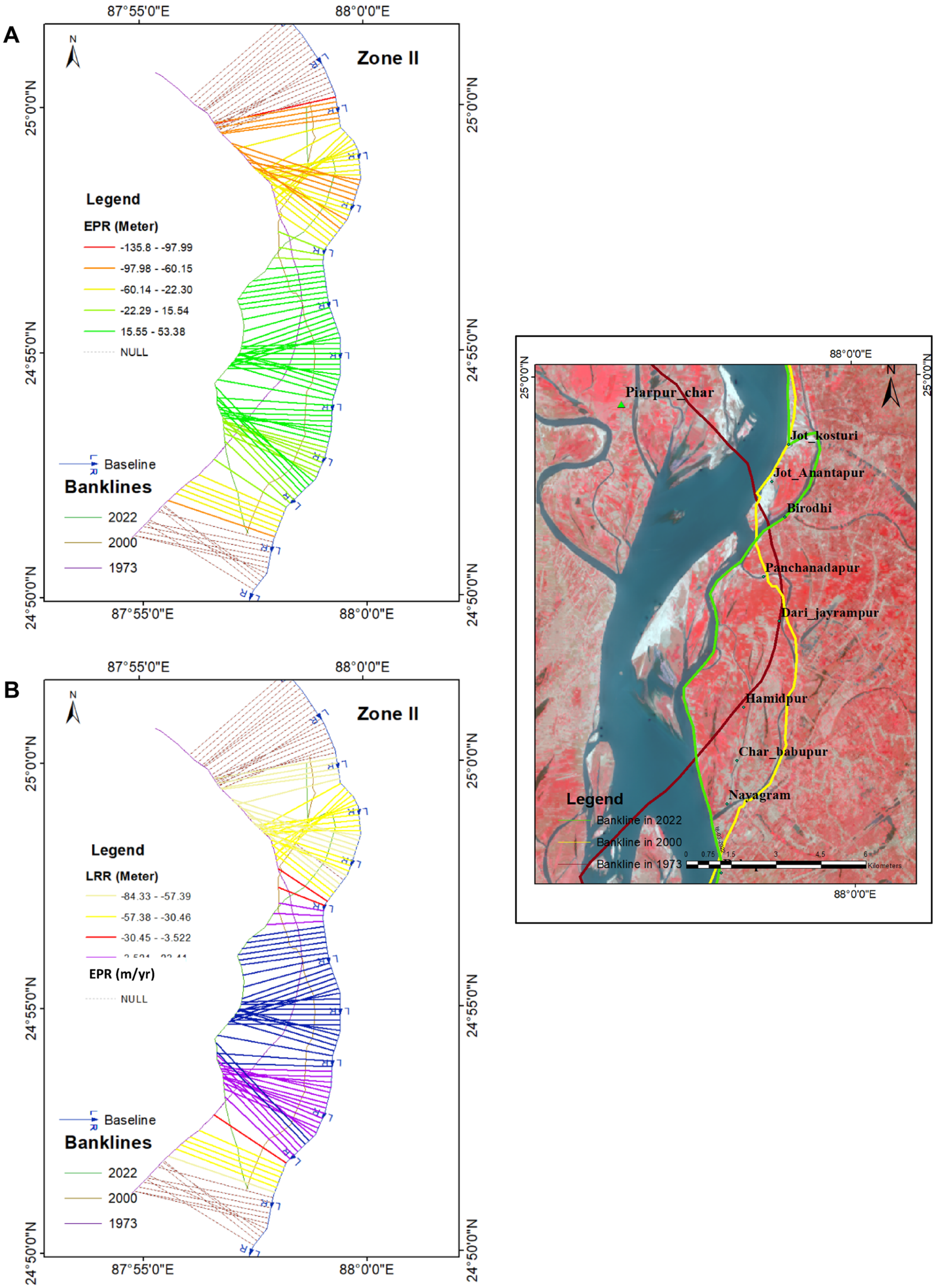

Fig. 9 **a**, **b** Result of EPR, LRR of Zone II. Where, – Value = Erosion, + Value = Accretion

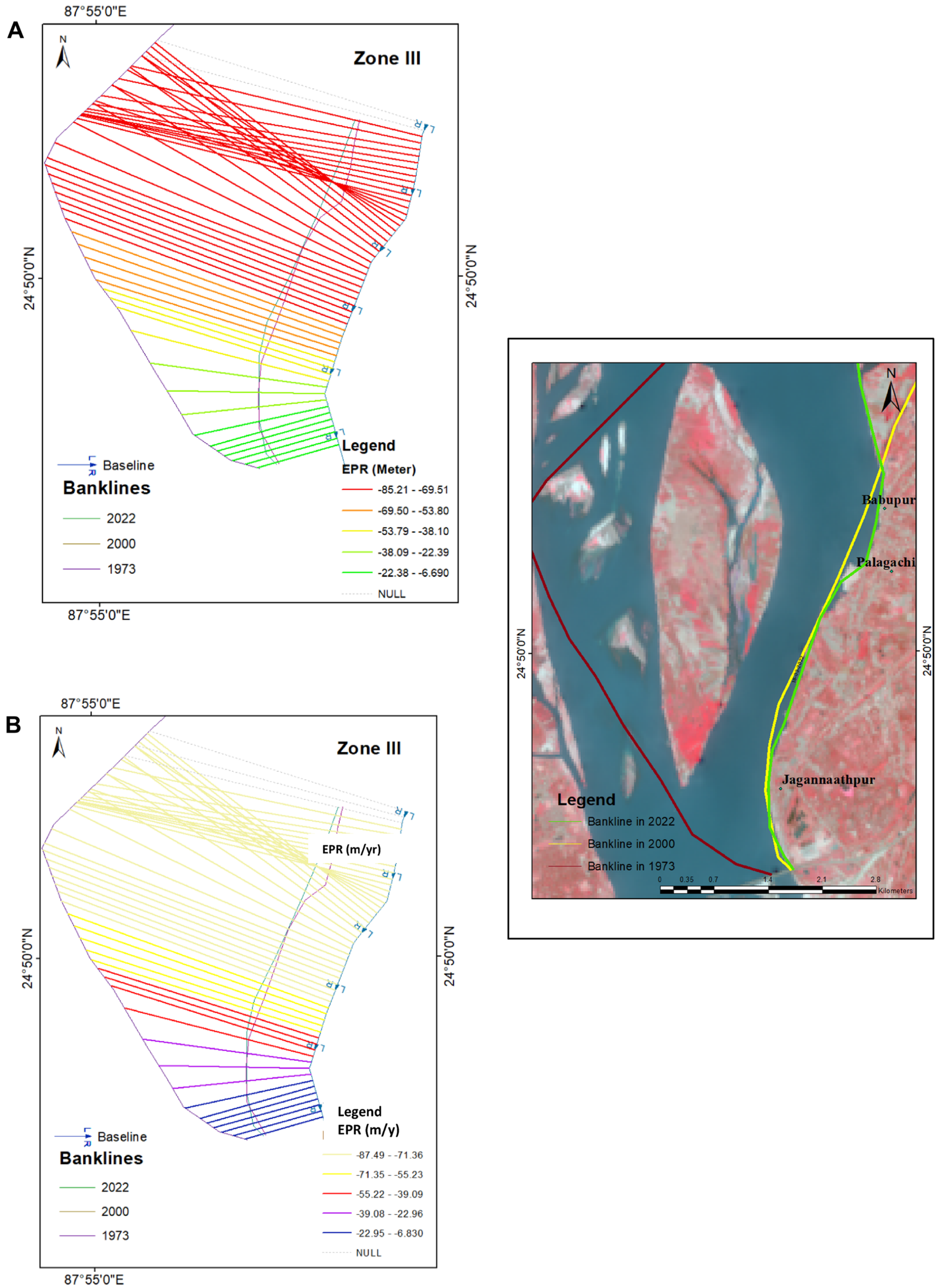

Fig. 10 **a**, **b** Result of EPR, LRR of Zone III. Where, – Value = Erosion, + Value = Accretion

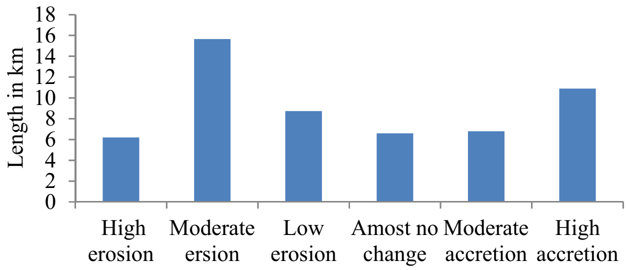

Fig. 11 Zonation of erosion and accretion rate based on LRR

in 1973, and 34.52 km in 2000 (Table 2), and had 166 transects total, of which 89 transects show erosion and 39 transects show accretion that indicate negative trend across the zone, suggesting erosion has been recorded most of the bank-line with an average erosion rate of 58.7 m per year. On the other hand, the overall rate of bank-line change in Zone II shows a positive trend, indicating that accretion has mostly occurred across the zone with average accretion rate approx. 29.35 m per year. The bank-line change study for Zone III demonstrates a tendency of erosion, with an average bank-line change of 66.39 m per year (Fig. 6); however this zone did not experience accretion during this period. According to EPR (Table 4), the average bank-line migration for each zone was as follows: Zone I: – 28.21 m per year; Zone II: – 5.75 m per year; and Zone III: – 63.05 m per year. Around 74.17% transects contain erosion values and 25.83% transects contain accretion values in case of Zone I, whereas in Zone II, around 43.82% transects contain erosion values and 56.18% transects contain accretion values (Table 3) (see Figs. 7, 8).

However, in Zone III all transects fall under erosion values, which means in Zone III only erosion has occurred. The findings demonstrate that out of the three zones, based on EPR, Zone III saw the highest amount of bank-line migration (Table 3). In case of Zone III, all transects contain erosion values, which shows that maximum erosion has occurred in Zone III and maximum accretion has occurred in Zone II (Table 3 and Figs. 9, 10). Zone I mainly has a high to moderate erosion rate (– 114.5 to – 43.06). In case of Zone II, rate of accretion is high (23.42–50.35), whereas Zone III has faced mostly high erosion rate (– 87.49 to – 71.36). The findings of the LRR and EPR calculations were also correlated in the study. It demonstrates that there was a consistent tendency in the positioning shift. While LRR uses numerous blank lines between the start and finish dates, EPR only uses two. These two approaches are distinct. Result (Fig. 7) shows a positive relation according to the correlation analysis ($r^2 = 0.89$) which indicates that the river was more dynamic in terms of positioning shift.

Discussion

River bank-line migration happens across the world as a result of erosion, a natural and destructive process (Bhuyan et al. 2022). The Bank line shifting and erosion-accretion stages on both bank sides of alluvial rivers are mostly determined by channel migration (Raj and Singh 2022; Ghosh and Mukhopadhyay 2016; Bhattacharya et al. 2022). The extent of river activities (erosion, transportation, and deposition), the volume of river water during peak season, soil, geological structure, and mass human interference with the river are some of the factors that directly contribute to bank-line migration (Nandi et al. 2016). The Ganga River, the longest river in India which carries a high quantity of sediment in its lower reaches causing a progressive decrease in river depth and water carrying capacity. Therefore, a little amount of extra rain during the monsoon causes destruction due to frequent flooding, and generally causes bank erosion. The river shifts very dynamically due to the erosion and accretion that occurs in the deltaic region (Bera et al. 2020). Channel instability is significantly impacted by this massive sedimentation (Xia et al. 2014; Bhattacharya et al. 2022; Hasanuzzaman et al. 2023). The dynamic character of the river depends on natural factors such as water discharge, seasonal flow variation, topography, soil character, geological structure, and anthropogenic factors such as deforestation, construction of bridges and dams in the river basin (Rudra 2004; Mondal et al. 2017; Hasan et al. 2018). Moreover, Farakka Barrage plays a significant role in reducing the depth and water holding capacity of the channel which increases the occurrence of floods and riverbank erosion (Rudra 2006, 2010; Thakur et al. 2011; Mukherjee 2011; Das et al. 2017; Sarif et al. 2021; Khatun et al. 2018; Singha et al. 2020).

Based on DSAS model it is found that bank-line of the Ganga River in upstream of Farakka Barrage shows maximum erosion than accretion. Average rate of bank line erosion and accretion was approximately 61.39 m/year and 35.93 m/year respectively. The findings are supported by different studies conducted on the Ganga River. Hasanuzzaman et al. (2023) worked on the bank-line changes of the Ganga River and found that upper part of Farakka barrage construction is the most dynamic channel which is evidenced by rapid rate of erosion. On the Stretching from the area immediately upstream of the Farakka Barrage to the Rajmahal hills, the Ganga erodes more at its east bank (Thakur et al. 2011; Sarif et al. 2021). Comparing erosion and deposition results in the three study zones based on DSAS, it is found that erosion predominates in the Manikchak and Kaliachak III blocks of the Malda district whereas accretion is more active in the Kaliachak II block because the river's concave bank erodes first due to the river's extreme seasonal flow variance. Similar results were derived by several scholars (Rudra 2004; Mukherjee 2011; Mukherjee and Pal 2017; Majumdar and Mandal 2020; Sarif et al. 2021; Talukdar et al. 2021) and they attributed this to the very high rate of erosion that leads to bank cutting and population displacement in these blocks every year (see Fig. 11).

Villages such as Birnagar, Panchanandapur, Manikchak, Hiranandapur, and Gopalpur which have a fragile alluvial loose soil structure, have been most affected by erosion. The main cause of bank erosion is under-cutting or loss of underlying support. Hydraulic activity causes the soil particles in the underlying layer to separate and be transported far away by the river's flow, creating an overhanging layer at the top. With time, this overhanging layer will collapse and cause quick bank erosion. Rotational failure is a major cause of bank failure in the Manikchak block and is regularly observed in places like Gopalpur and Dharampur (Mandal 2017; Mondal and Mandal 2018). As a result of the Ganga River's channel migration, these locations have faced huge land loss (Majumdar and Mandal 2020; Khatun et al. 2018) and have put the livelihood of the inhabitants at risk. At the same time, some new land have also come up along Nayagram, Panchanandapur, Duani char, etc., due to accumulation of sediments (Mukherjee and Pal 2017; Mandal 2017) where many displaced people have found a new area to reside. According to Hasanuzzaman et al. (2023) the overall area of charland accretion during the previous 47 years is 362.06 sq km. in the study area.

Although the DSAS derived results have some inherent uncertainties, several studies have demonstrated the effectiveness and superiority of DSAS in capturing the dynamics of bank lines (Ashraf and Shakir 2018; Jana 2021; Mahmud et al. 2020; Natarajan et al. 2021; Jana 2021; Bhattacharya et al. 2022; Bhuyan et al. 2022; Hasanuzzaman et al. 2023; Ritu et al. 2023). The present study delivers accurate measurement of erosion, accretion and bank-line migration using DSAS. For the purpose of future planning, it is imperative to calculate any erosion or accretion along the banks of all rivers. Planning bank protection work requires a thorough understanding of the process of erosion, deposition, and bank-line change, because these affect the stability of the riverbank which causes large-scale devastation. The erosion is at a hazardous level in the study area because of the low level of management and planning. Therefore, the government needs to take measures to reduce the impact of floods and riverbank erosion. While the government has taken several initiatives as protective measures to tackle riverbank erosion, all of these are not implemented sufficiently well. This study helps to get a detailed understanding about the bank-line shift through erosion and accretion, and it will make it easier for the government to take appropriate protective measures in these vulnerable places to check further erosion.

Conclusion

The multi-temporal data analyses indicate that over the last five decades, erosion and deposition have consistently changed the river's bank-line. The river-bank areas have become exceedingly susceptible due to ongoing erosion and deposition along the river and the resulting bank line migration. The study shows that average rate of bank line erosion and accretion was approximately 61.39 m/year and 35.93 m/year respectively. Overall mean bank-line change rate is – 31.12 m per year. Out of total 62 km long bank-line, high erosion took up 6.2 km while moderate erosion took up 15.66 km. The length of about 6.6 km exhibited essentially little or no change. While there is a strong accretion tendency detected along a 10.9 km bank, moderate accretion is observed along 6.8 km of bank sections. It is found that particularly in the Kaliachak III block; the majority of the area experienced serious bank erosion. The Kaliachak II block, which is in Zone II, is where accretion is most noticeable in the form of sand bars and chars. The current study highlights particular areas of erosion and accretion that can help with planning to reduce socio-economic and environmental concerns as well as undertaking zone-by-zone bank preservation strategies.

Appendix

See Table 4.

Table 4 Statistical techniques outputs from DSAS (Zone I, II, and III)

	Trans Order	Azimuth	Shr Count	TCD	SCE	NSM	EPR	LRR	WLR	Length (meter)
Zone I										
Maxi	166	142.88	3	33,000	5565.85	– 5565.85	– 129.56	– 114.46	– 114.46	5189.52
Mini	1	15.96	1	0	1.74	– 1.74	– 2.7	– 0.27	– 0.27	1714.21
Mean	83.5	58.72	2.70	11,900	2143.24	2042	– 28.21	– 5.72	– 5.72	5197.226
Zone II										
Maxi	120	136.24	3	23,800	4153.26	– 4098.41	– 83.53	84.33	84.33	5197.226
Mini	1	49.29	1	0	472.83	– 223.14	– 4.55	– 3.77	– 3.77	1714.214
Mean	60.5	93.02	2.5	11,900	– 231.927	– 231.927	– 5.75	– 5.71	– 5.72	4022.26
Zone III										
Maxi	53	128.23	3	5200	4174.21	– 4174.21	– 83.54	– 87.49	87.49	5136.91
Mini	1	74.3	1	0	327.79	– 327.79	– 6.69	– 6.83	– 6.83	1281.07
Mean	27	104.87	2.9	2600	3089.43	– 3089.62	– 63.05	– 64.64	– 64.64	4105.49

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Declarations

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