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# Bank erosion and accretion dynamics of Middle-Lower Ganga River from Kosi Confluence to Padma Confluence: A Geo-Spatial Analysis

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**Abstract - This study aims to assess an area of about 327 km along Ganga River from the Kosi confluence in India to the Padma confluence in Bangladesh, which is highly vulnerable to erosion. The area eroded and deposited during 1924-2019 (more than 95 years) is analysed. Time series satellite data (Landsat) and topographical map are used and MNDWI (Modified Normalized Difference Water Index) model has been developed to extract the bank line precisely from the satellite images. The overall pattern of the bend development process and bank line shifting of the channel of study reach suggest that continuously widening of the river channel and the shifting north-eastward of upper segment of Farrakka Barrage and south-eastward of lower segment of Farakka Barrage. Channel widening is more evident in upper segment of barrage in comparison to lower segment. It has been observed that left bank (1662.36 km$^2$) of river is more eroded in comparison to the right bank (1490.58 km$^2$). Highest amount of erosion occurred during 1980-1990, which is 844.08 km$^2$, and the highest rate of erosion also occurred in 1980-1990, which is 84.41 km$^2$/year. On the other hand, the left bank (2042.85 km$^2$) having more sediment deposited in comparison to the right bank (1354.27 km$^2$). The highest amount of deposition (1234.86 km$^2$) occurred during 1924-1975, but the highest per year deposition occurred during 1975-1980, which is 96.04 km$^2$/year. Upstream of Farakka barrage has witnessed more bank erosion rather than downstream. It is concluded that Farakka barrage (1974) accelerate the rate of sediment deposited alongside of the river.**

**Keywords** *Accretion, Erosion, Farakka Barrage, Ganga River, Landsat image, MNDWI*

## I. INTRODUCTION

Rivers are highly sensitive to environmental conditions [14, 50] and alluvial channel can re-adjust in response to the variations caused by water and sediment inputs, active tectonics and human activities at a range of spatial and temporal scales [56, 21, 13]. Any changes, whether natural and anthropogenic, can initiate a departure from a state of dynamic equilibrium [62]. This may in turn, result in channel instability causing changes in channel form and pattern [64]. Riverbanks are transitional boundaries and the ecotone between the aquatic and terrestrial ecosystems [40]. In the geomorphological point of view, riverbank can be identified as "the landform distinguished by the topographic gradient from the bed of channel along the lateral land-water margin up to the highest stage of the flow or up to the topographic edge where water begins to spread laterally over the flood plain surface" [16]. The lateral shift of river channels within flood plain regions is a natural event [31, 63, 61], but increasing anthropogenic interference has made it semi-natural [11]. Riverbank frequently changes their position especially in monsoon season due to the fluctuation in sediment discharge and water supply.

The usual change in river channels due to down-cutting of banks, mechanism of erosion and accretion is the natural adjustment mechanism of alluvial channels of dynamic non-equilibrium [30, 58, 50, 32, 28, 47].These are the natural processes in regards to an alluvial river [66]. Bank erosion refers to the erosion of sediment from bank wall under turbulent flow conditions. The eroded bank materials move laterally towards the channel or in the downstream direction [41]. When flow velocity decreases, the suspended sediments deposit near or on the river banks which is known as riverbank accretion [29, 38]. Bank erosion and accretion processes largely affect flood plain dynamics, and the basin sediment yielding. Such mechanisms play an important role in the changing morphological characteristics of any river especially in alluvial reaches. If hydrological properties, sediment characters, active tectonics etc. adjust with channel then the channel can easily migrate. Migration of the river channel is determined by several aspects such as properties of the soil, river bank geometry (e.g. channel width,

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meander wavelength, meander length, amplitude, sinuosity, radius of channel bend etc), discharge frequency [7, 33, 17, 40], river bank resistivity, riverine vegetation cover [39] etc. Moreover, various human activities stimulate the rate of river channel migration. For example, the elimination of vegetation cover in flood plain can accelerate the rate of migration [46].

Presently, the availability of remote sensing and GIS application enable the detailed and spatio-temporal monitoring of the bank erosion and accretion phenomena. Thoma (2001) has assessed the river bank erosion by using lesser altimetry. Mani et al. (2005) has studied the river bank erosion of a part of the Majuli River-Island, India; by using Survey of India (SOI) toposheets and Indian Remote Sensing (IRS) satellite data. Bhakal et al. (2003) has estimated the bank erosion of the Brahmaputra through GIS. Sharma et al. (2007) has measured the sequential bank line migration due to the effect of bank erosion and accretion of Burhi Dihing River in India, applying SOI toposheets and IRS satellite data. Ahmed and Fawzi (2011) have investigated the evolution of meander bend and associated bank erosion of the Nile river between Sohag and El-Minia, Egypt. Thakur et.al. (2012) has studied the bank erosion of the Ganga river in the upstream of Farakka barrage up to Rajmahal by using Landsat and IRS satellite images. Pal et al. (2016) has predicted the vulnerability of bank erosion along the meander bend of the Bhagirathi-Hugli river of lower Ganga plain, India, by applying channel avulsion modelling.

The river certainly alters its course, and in bank erosion a huge number of the population of that area gets affected in owing to the loss of property, life and land; and furthermore, they need to settle new colonies elsewhere. Rates of erosion, bank line migration and channel patterns of the Ganges have previously been studied through the use of just one or two indicator (sinuosity and/or width), both in Bangladesh [10, 35, 13, 24, 25, 48, 53] and India [46, 43, 20, 45, 42, 57]. Most of these scholar have studied small reach of the river. Hence, it is considerably difficult to understand the relation between bank form and pattern of erosion and accretion in large scale. In India, bank erosion and accretion study are mostly concentrated in the lower Ganga plain as well as Brahmaputra plain. But in the case of Middle-Lower Ganga plain, very little study has been conducted. Furthermore the villages located near the bank of the study reach are highly vulnerable to bank erosion and channel avulsion. In these contexts, this study is very much important.

## II. Study Area

The Ganga river system, with a catchment of 1.09 million km$^2$ is one of the largest river system in the world. Along its 2526 km course to the confluence with Meghna, flowing through Tibet, Nepal, India, and Bangladesh making it international character. India has the largest share (79.1 %) of its entire catchment whilst only 4. 3 % lies within Bangladesh (equivalent to 32% of the area of that country) [37]. The study area covers 327 km stretch of middle-lower Ganga river from kosi confluence in India to Padma confluence in Bangladesh, between longitudes 87$^0$15' E and 89$^0$ 46' E and latitudes 25$^0$24' N and 23$^0$ 47'N (Fig 1). The western most boundary started from Muradpur village in India, where river Kosi joins with the Ganga river and the eastern most boundary ends in Daulatdia village in Bangladesh, where the Brahmaputra river joins with the Ganga river.

The extent of study area encompasses 5 districts of India, i.e. Bhagalpur, Katihar, sahibganj, Malda and Mursidabad and 6 districts of Bangladesh, i.e. Rajshahi, Pabna, Nawabganj, Natore, Kustia and Rajbari. The study area fall under tropical climate zone, governed by the southwest monsoon. The average annual rainfall in the middle-lower Ganga river system is about 1600 mm, most of which falls during the monsoon [53]. This region known to be excessively flood and bank erosion prone area. Almost in every year most of the river stretch of study area is experienced flood hazard. Though it would be very difficult to estimate the number of people are displace and homeless every year because of flood and bank erosion, but the number would be huge in any measure and it would be progressive in upcoming year due to increase of discharge and runoff rate as a result of climate change. In the view point of recent river hydro-geomorphical evidence, the middle-lower Ganga river course are subdivided in to four zones, which are A (Kosi confluence to Rajmahal), B (Rajmahal to Farakka), C (Farakka to Akheriganj) and D (Akheriganj to Padma confluence) (Fig 1).

## III. Objectives

In the present study, assess the bank erosion and accretion between Kosi to Padma confluence of *Ganga* river. The primary objective is, to quantify the rate and amount of bank erosion and accretion processes of *Ganga* river in different time periods.

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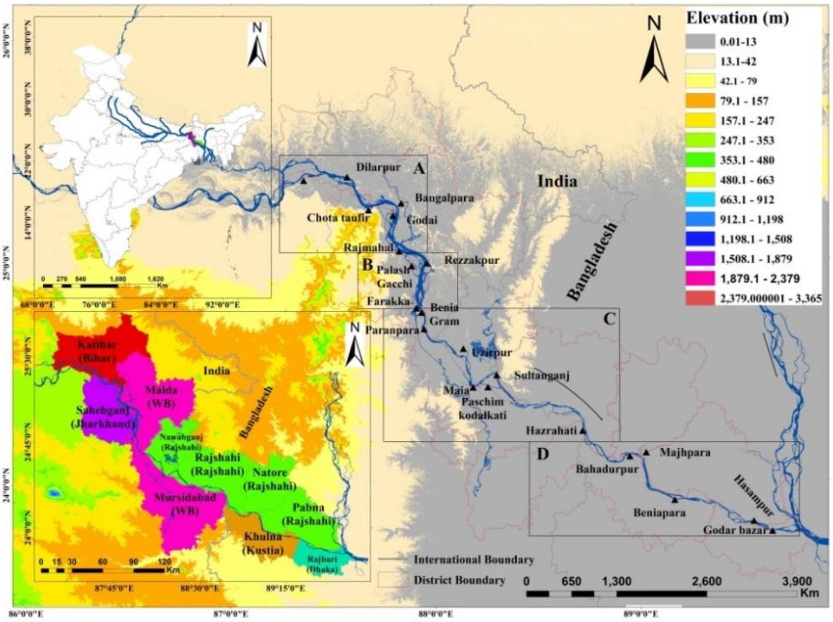


**Fig. 1 Location of the study area.**

## IV. DATABASE AND METHODOLOGY

### 4.1 Digital Image Processing

Main objective of the study is an assessment of bank erosion and bank accretion in a temporal context. Several series of multi-temporal data have been collected from different sources (Table1). Georeferenced and precisely orthorectified Landsat data have been downloaded from USGS (United States Geological Survey) website. The data has following parameters-

Projection Type: Universal Transverse Mercator (UTM).

Spheroid Name: World Geodetic System (WGS) 1984.

Datum Name: World Geodetic System (WGS) 1984.

The study area falls under the UTM Zone 45. The whole study reach is covered in four scene of Landsat data, with the path-row of 138/43,138/44,139/42,139/43 (2000, 2010, and 2019) and 148/43,148/44,149/42,149/43,150/42 (1972, 1980 and 1990). The spatial resolution of different sensor is different, like: Multi Spectral Scanner (MSS) is 79 m and Landsat Thematic Mapper (TM), Landsat Enhanced Thematic Mapper (ETM) and Operational Land Imager (OLI) are 30 m, it has been necessary to bring all the images on the same scale to minimize the error. So, all the multi-temporal satellite images are resampled into 50 meter resolution by using resample operation in ERDAS-IMAGINE.

Four consecutive topographical sheets (NF 45-04, NG 45-11, NG 45-10, NG 45-15) (1922–1924) published by US Army Map Service are georeferenced by following the same parameters as used for Landsat Satellite Images. After georeferencing process, the toposheets were mosaicked in ERDAS-IMAGINE to extract the bank line by onscreen digitization process.

**Table 1 General information of data sets used in the present study**

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| Data type | Satellite sensor/map no | Date (mm/dd/year) | Spatial resolution (m) or scale | Sources |
|---|---|---|---|---|
| **Remote sensing images** | Landsat-MSS | 3/19/1972 | 79 | USGS |
| | Landsat-MSS | 3/15/1980 | 79 | USGS |
| | Landsat-TM | 2/22/1990 | 30 | USGS |
| | Landsat-ETM | 3/29/2000<br>2/21/2010 | 30 | USGS |
| | Landsat-OLI-TIRS | 03-09-19 | 30 | USGS |
| **Topographical maps** | NF 45-04 | 1922–1924 (surveyed) 1955 (published) | 1:2,50,000 | Series U502, US army map service |
| | NG 45-11 | | | |
| | NG 45-10 | | | |
| | NG 45-15 | | | |

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### 4.2 Preparation of MNDWI images

The Normalized Difference Water Index (NDWI) is a band ratio method which is calculated from near infrared and visible green spectrum to enhance the features of water and eliminating soil and other vegetation features from surface [52]. McFeeters (1996) has established NDWI (Normalized Difference Water Index) technique to create the signature differences between water and land surface features through analyzing the spectral signatures of each spatial object into different band combinations and then to differentiate the land from water surface. NDWIs are calculated by using following formulas:

$$NDWI = \frac{\text{Green} - \text{SWIR}}{Green + SWIR}$$

The NDWI proposed by McFeeters (1996) can detect very few water pixel, hence Xu's Modified Normalized Difference Water Index (MNDWI) is used to provide better result for demarcation between land area and channel area.

$$MNDWI = \frac{\text{Green} - \text{SWIR}}{\text{Green} + \text{SWIR}}$$

A model has been developed in ArcGIS that uses the Green and Short Wave Infra-Red (SWIR) bands of Landsat data and extracts MNDWI image. In present study, it was noticed that McFeeters's (1996) NDWI method detect very few water pixel. Only Xu's Modified Normalized Difference Water Index (MNDWI) provided accurate demarcation between channel area and land area. Therefore, Modified NDWI (MNDWI) have been applied for onscreen bankline digitization for the further bank shifting analysis.

### 4.3 River bank delineation

The delineation of bank lines of Middle-lower Ganga River is a hard task, because the study reach shift their position and leave their old courses frequently. So, the active channels are not well defined. The places where the bank accretion predominates and the bank heights are not prominent, the active channels can create ambiguities in bank demarcation [3]. So, to solve the problems, at first, MNDWI are applied on the multi-temporal Landsat images by which it has become possible to mark out the bankline quite easily [40]. For further verification, field visits have been done, and errors of bank line demarcation are rectified. Shape files have been created for delineation bank line for each concerned year in ArcGIS. Topographical map is also used for demarcation of bank line; it is comparatively easier than satellite image, because all the banks are clearly marked on the toposheets. Fig. 2 described the flowchart of the methodology which is used in this study.

Spatial analyst and geo-processing tools are used in detecting the composite changes of the bank line (i.e. gradual erosion and accretion). Bank line of each and every year are drawn manually in ArcGIS and compared with other layers. Each layer has been subtracted with preceding year to identify the erosion and accretion with previous year. This estimation empowers precise calculations of the distance to river, eroded or inundated area and deposition zones because of river path changing and flooding during various satellite image acquisitions [26]. If river inundates the area were taken as erosion and if river moves away from land leaving fluvial deposits there taken as deposition, and as no change if the river maintain its previous course.

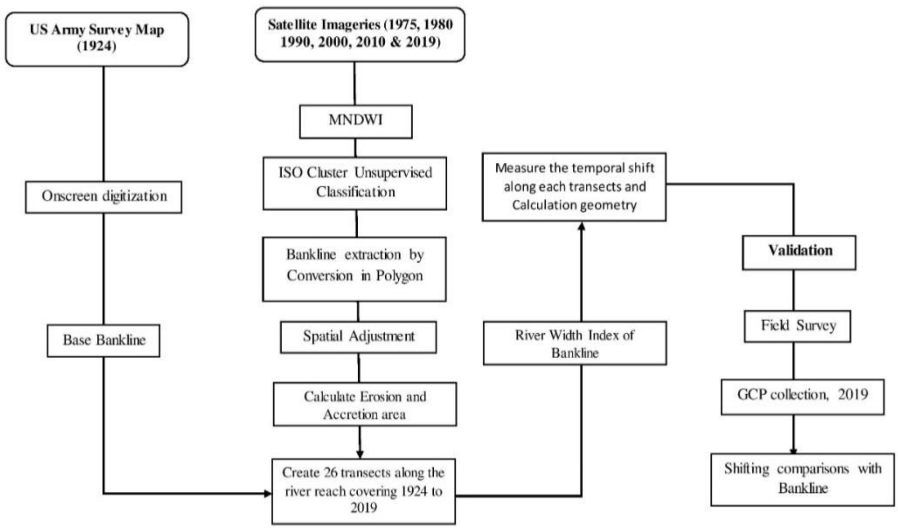


**Fig. 2 Flowchart of the methodology**

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### 4.4 Determining erosion and accretion areas

In this study, the locations of the river bank from 1924 to 2019 period are compared. Due to lack of georeferenced and orthorectified data exactly at ten tears interval, the pattern of decadal changes of bank line can't be described. We have selected the data next to decadal change: 1924-1972 (48 years), 1972-1980 (8 years), 1980-1990 (10 years), 1990-2000 (10 years), 2000-2010 (10 years) and 2010-2019 (9 years). River bank has been positioned outside from the river bank in the past, which is considered as erosion, and if the river bank is shift inside the channel in the past, then it is considered it as accretion [64, 5]. For erosion and accretion measurement (in chute cut off areas), it has been considered that if a chute channel is formed on the right bank side, the entire channel area of the right bank side would increase [40]. Hence, the area lying between the right bank of the present and the earlier channel has been designated as erosion polygon and the area between the present and the earlier left bank was demarcated as accretion polygon and vice versa [40]. After demarcating erosion and accretion polygons, the area of the polygon is calculated through calculating geometry command in ArcGIS software. A detailed field survey has been conducted to familiarize the current mechanisms of the bank erosion and accretion throughout entire reach (fig. 6).

## V. RESULT AND DISCUSSIONS

### 5.1 Mechanism of Channel morphological change involved in bank erosion and accretion

Super impose courses of the bank line from 1924-2019 shows huge changes alongside the course. Along the study section of the Ganga, nine major process of bank erosion and accretion (Table 2) clearly visible. Out of them, the widening of channel has registered highest compare than narrowing of widening and extension of meander bends. To examine the morphological changes of erosion and accretion, 26 cross section are drawn (fig 4) to observe the widening of channel bank, bank line movement and extension of meander bend caused (Table 2) by bank erosion and accretion. The main mechanism of bank erosion and accretion have occurred due to translation, rotation, lateral movement of meander bend, chute cutoff, and complex change of meander bend (fig 3). In 1924-1975, the right bank accretion have occurred due to lateral movement of channel and abounded the old course completely. Left bank erosion in the northern section (fig.7A) and right bank accretion (7C) of study area have caused the meander extension to a larger extent. Due to prolonged erosion in left bank river completely leave his previous course and sifted toward left (fig7). In 1975-1980, due to construction of Farakka barrage, river has progressively eroded left bank and deposit on right bank has develop of several new meander bend. In 1980-1990, extension of meander has also created left bank erosion and right bank accretion to a larger extent. The Chute cutoff and neck cutoff are the main reason of left bank erosion in 1990-2000. During this period erosion is more pronounced than accretion and is the main reason behind channel widening. In 2000-2010, accretion is more active than erosion, and the total amount of accretion is almost triple comparison to erosion (table 6). Neck cutoff and progressive development of new meander bend are commonly visible during this period. In 2010-2019, progressive erosion of both bank have widened the channel and extension of river bank. South-eastern part of the study area has witnessed the frequent channel change due to rotation and complex change of meander bend.

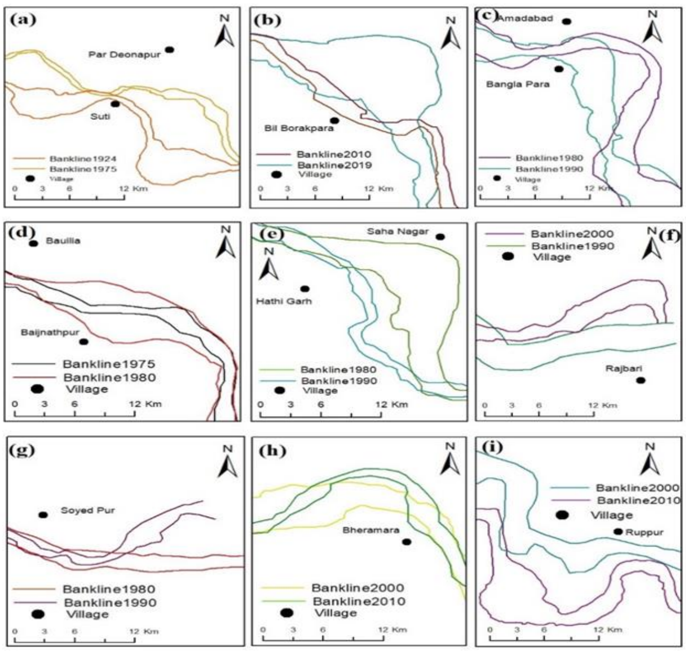


**Fig. 3 Channel dynamic mechanisms of the studied section of the middle lower Ganga river. (a) Bend extension, (b) chute cutoff and development of new channel course,(c) extension of meander bend and development of compound meander, (d) Narrowing of widening, (e) neck cut-off and development of new meander bend, (f) chute cut off and progressive development of meander bend, (g) complex change, (h) rotation, (i) translation**

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**Table 2 Recurrences of the processes of channel morphological change associated with bank erosion and accretion**

| Channel Morphological Change | Year | | | | | |
|---|---|---|---|---|---|---|
| | 1924-1975 | 1975-1980 | 1980-1990 | 1990-2000 | 2000-2010 | 2010-2019 |
| Widening of channel | 6 | 7 | 15 | 6 | 4 | 10 |
| Narrowing of channel | 11 | 9 | 8 | 5 | 15 | 5 |
| Extension of meander bend | 5 | - | 6 | 6 | 12 | 4 |
| Rotation of meander bend | - | - | 1 | 1 | 3 | 1 |
| Complex change | - | 1 | 3 | 1 | 7 | 3 |
| Lateral movement of channel | 3 | 4 | 7 | 4 | 9 | 9 |
| Chute cutoff and new bend development | | - | - | - | 2 | - |
| Chute cutoff | 1 | - | 2 | 1 | 3 | 1 |
| Translation of meander bend | - | - | 1 | 1 | - | - |
| Neck Cutoff | - | - | 1 | 2 | 3 | 1 |

### 5.2. Temporal shift of river bank

Changing bankline position of study area has been measured by 26 fixed cross sections which are created in unequal distance (fig. 4). Locations of cross sections are placed on the basis of visual analysis of major morphometric change of river bank. In left bank, maximum shift in each cross section in 1924-1975 has been cross section X8 and X17 in right bank, which has been 17.90 $km^2$ and 19.53 $km^2$. During this time period river bank laterally has shifted toward left bank, as a result left bank has eroded and right bank has deposited continuously. During 1975-80 highest left bank shifting has occur in cross section no X16, which is 25.60 $km^2$ near to Gondagari village and highest right bank shifting has taken place at X19, which is 22.89 $km^2$ (table 3). After construction of Farakka Barrage, the river has continuously wide-spreading, due to the encroaching of river water; right bank has started erosion with left bank. In the upstream of Farakka Barrage, entire left bank during 1972-1980 has come under bank erosion. Main erosion area comes under Manikchack block, Hiranandapur block, Kakribondha, Jhaubondha and Rajanagar in Kaliyachack-II (Thakur et.al 2011). During 1980-90, highly eroded area comes under cross section X1, X8, X11, X13, X14, X18, X19, X23 and X26 (table 3). The area comes under these cross section are Suti, Bangal Para, Hathi Garh, Gopalpur, Hiranandapur, Bilmaria and Rajbari. In 1990-2000, a huge amount of erosion and channel widening have been found. The highest erosion of right bank and left bank take place along cross section of X26 and X14 respectively. In 2000-10 time period, the rate of bank line shifting has suddenly decreased comparison to the previous decade. During this decade deposition has suppressed erosion for the first time. Highest deposition has taken place in right bank, at cross section X18. After 2010, whole kakribondha, Jhaubona, shimlitola gram panchayat has completely eroded, while Bhutni char, Bhatapara, Majhpara, Ekchariya Diyara has partially shifted.

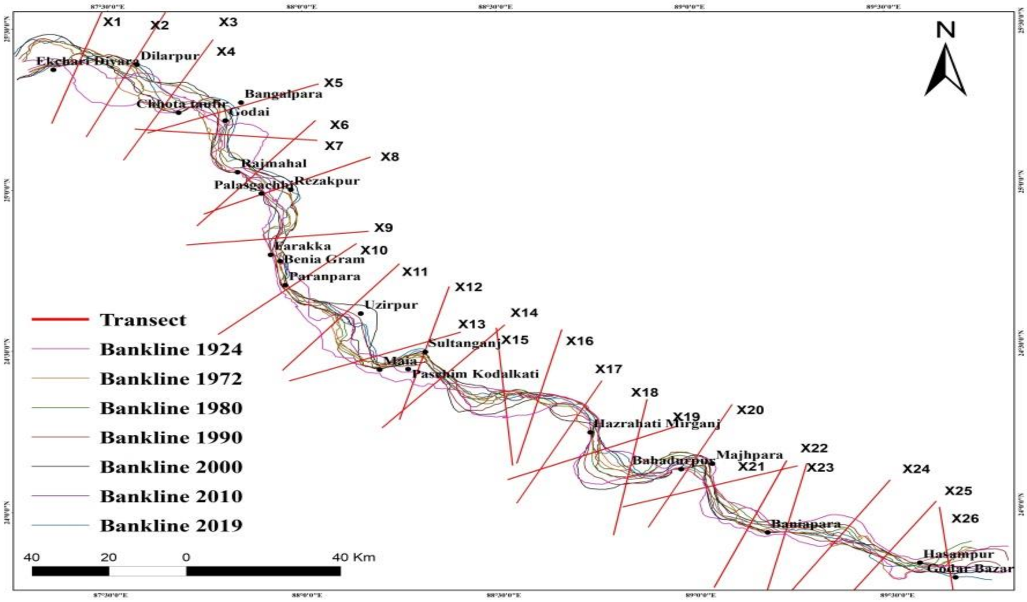


**Fig.4 Location of different cross-section across the superimposed layers of 1924 to 2019 to measure the extent of channel migration.**

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**Table 3 Shifting bank line position along cross-section in different years**

| Cross-Section | 1924-1975 | | 1975-1980 | | 1980-1990 | | 1990-2000 | | 2000-2010 | | 2010-2019 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Right Bank (Km) | Left Bank (Km) | Right Bank (Km) | Left Bank (Km) | Right Bank (Km) | Left Bank (Km) | Right Bank (Km) | Left Bank (Km) | Right Bank (Km) | Left Bank (Km) | Right Bank (Km) | Left Bank (Km) |
| X1 | 4.76 | -4.32 | 2.15 | 1.42 | 0.45 | -1.29 | -1.59 | 0.82 | -1.24 | 0.35 | -1.23 | 0.61 |
| X2 | 6.83 | -3.18 | -0.58 | 0.30 | -0.71 | -0.47 | -0.64 | -0.68 | 3.76 | 2.00 | -0.57 | -0.24 |
| X3 | 1.60 | -4.21 | -0.31 | -3.70 | 0.01 | 1.22 | -0.14 | -2.37 | 0.24 | 4.16 | 1.87 | -0.33 |
| X4 | - 0.50 | 0.93 | -0.13 | -1.80 | 3.02 | -0.31 | -0.04 | -1.08 | 0.35 | -0.49 | 2.39 | -2.12 |
| X5 | - 2.52 | -1.98 | -0.38 | -0.01 | -0.34 | 0.60 | 0.01 | -2.74 | 0.11 | -0.50 | 1.34 | -0.81 |
| X6 | -0.61 | 12.42 | -0.08 | 0.93 | -0.06 | 2.23 | 0.21 | -2.25 | 0.21 | -0.28 | 0.62 | 0.06 |
| X7 | 0.18 | -1.05 | 0.19 | -0.37 | 0.26 | -2.53 | 0.37 | -2.08 | 0.16 | -1.22 | 2.10 | -0.07 |
| X8 | -0.26 | -2.44 | -0.69 | -0.23 | -2.04 | 0.17 | -0.05 | 0.28 | -2.47 | -0.62 | 6.86 | 0.73 |
| X9 | 1.47 | -0.65 | -0.05 | -0.40 | -0.22 | -0.47 | 0.08 | -1.26 | 0.24 | -0.05 | 1.08 | -0.08 |
| X10 | 5.33 | 3.81 | -0.15 | 0.08 | 0.06 | -0.26 | 0.21 | -0.23 | 0.09 | 0.60 | 0.06 | 0.21 |
| X11 | 1.14 | 2.48 | 2.05 | -1.22 | 0.55 | -6.78 | 4.95 | -0.82 | 0.67 | -0.30 | -0.78 | 6.21 |
| X12 | 9.47 | 4.02 | -0.19 | -0.70 | -2.17 | -0.02 | 1.05 | 0.29 | -0.07 | -0.20 | 1.46 | -1.47 |
| X13 | 3.62 | -5.23 | -0.23 | -0.20 | -2.09 | 1.97 | -1.13 | -4.56 | -0.76 | -0.21 | 0.79 | -0.16 |
| X14 | 7.86 | -2.42 | -0.24 | 0.18 | -2.08 | 1.87 | -2.04 | -6.68 | 3.58 | 1.52 | 0.23 | -0.62 |
| X15 | 4.83 | 0.55 | 0.67 | -0.60 | -0.70 | -1.62 | 2.38 | -0.34 | -2.84 | -1.61 | -0.66 | 0.15 |
| X16 | -2.28 | -0.40 | -0.42 | 2.56 | -1.39 | -0.34 | -2.33 | 0.29 | 6.46 | 2.50 | 2.74 | -1.96 |
| X17 | 4.19 | 0.57 | 0.82 | -0.12 | -0.08 | -0.13 | -0.25 | 0.10 | -0.39 | 0.00 | -0.07 | 0.16 |
| X18 | 1.89 | 1.21 | -2.04 | 1.59 | -2.44 | 2.23 | -1.39 | -5.72 | 10.67 | -0.20 | 1.06 | 0.44 |
| X19 | 0.47 | 4.00 | -2.28 | 3.47 | -3.44 | 2.90 | -0.55 | 0.46 | 3.03 | -0.56 | 1.33 | -1.25 |
| X20 | 0.70 | 1.97 | 0.53 | -0.80 | 2.75 | -1.04 | 0.40 | -0.12 | 2.54 | 0.23 | -3.66 | 3.89 |
| X21 | 1.35 | 0.23 | 0.004 | 0.50 | -1.05 | 0.71 | -0.19 | 0.29 | 0.23 | 0.09 | 0.10 | -0.25 |
| X22 | 0.77 | 4.63 | -0.03 | -0.08 | 1.33 | -1.51 | -0.96 | -1.02 | -0.36 | 0.18 | 0.65 | 0.33 |
| X23 | - 0.90 | -1.92 | -2.40 | -0.28 | -1.08 | 0.97 | 0.90 | -1.33 | 0.05 | 0.49 | -0.06 | 0.05 |
| X24 | -0.78 | 7.34 | -1.20 | 1.03 | -0.58 | -1.49 | 0.11 | 0.34 | -0.68 | -1.19 | 2.56 | -0.66 |
| X25 | - 0.62 | 1.18 | 0.59 | -0.25 | 0.43 | -1.17 | -0.40 | 0.07 | -0.49 | -0.22 | -1.25 | -0.03 |
| X26 | 1.00 | -0.28 | 0.33 | 0.41 | -5.98 | 3.43 | -3.18 | 5.63 | -1.29 | 1.69 | -0.12 | 1.34 |

(-) sign indicate erosion of bank line.

(+) sign indicate accretion of bank line.

### 5.3 Mechanisms behind the cutoff bank

Essentially, two sorts of mechanism have been engaged with a cutoff of the river bank of the examination zone, these are: liquefaction and flowage of bank materials and shear disappointment. The cycle of liquefaction happens generally in the normal levee deposited area where the grouping of sand and residue particles is high. The mechanism of chute cutoff involves the building of a natural dam which locally forces water to overflow across the floodplain. And due to difference of hydraulics action in upstream and downstream of the natural dam, the returning flow plunges over the riverbank and back into the channel. The plunging water can result in bank incision, creating a headcut that propagates upstream until it forms a chute [8]. During the flood silt and sand become highly saturated and air compressed pores space of these saturated banks. After recession of floodwater the release of trapped air pressure help to bowl shaped and slab failure (fig 6a) of cohesive bank due to liquefaction and flowage failure. On the other hand; shear failure is frequently visible in study section of river bank, due to the inhomogeneous composition of bank materials. The bank materials, which are marginally strong, bring about a turned advance like shear failure (fig 5). In the study section of the river, distribution of natural levees are frequently visible. 'Majority of the failures occurred as a result of the current undermining of the natural levee deposits, due to large block of natural levee sediments are shearing-off and tilting into river' [7]. In northern section of the study reach, upper layer of bank material is predominated by silty clay and lower layer is predominated by sand and sandy clay, these type of bank material encourage undercutting toe erosion as a result of the upper layer overhanging on lower layer, when the gravity exceeds the shear strength of the bank and the cantilever bank failure occurs. It is observed from satellite image that the change of thalweg position in every flood event almost in every year is also another reason of bank erosion of study area. Apart from that after construction of Farakka barrage the river has witnessed the huge morphological changes in upper and lower segment of the barrage.


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**Fig.5 Lithology of right bank of Ganga river near (a) Bhutni Char village (b) and near Suti village (Source: Sabyasachi Sarkar, field work 2019)**


**Fig. 6 Bank failure or bank erosion of the studied section of the middle-lower Ganga river, a bowl shaped failure due to liquefaction around Chotataufir village, b slab failure of cohesive bank material around Rezzakpur village, c shearing of blocks around Bhutni Char village, d rotated shear failure around Godai village, e rotated step like shear failure around Maia village, f cantilever Bank failure around Hazrahati village (Source: Sabyasachi Sarkar, field work 2019)**

### 5.4 Bank erosion and accretion dynamics (1924–1975)

Erosion and accretion can be detected through the spatial and temporal variation in the study reach [14]. Erosion and accretion are identified by overlapping of bank line of two different periods. It has been observed in the present study that due to shifting of the bank lines, the bank areas are subjected to erosion and the earlier channels get filled-up by sediment deposition. Hence the bank area lost due to erosion and gained due to sediment deposition are measured from the area layers separately for the right and the left bank of the river. The bank lines of 1924 and 1975 have been traced from US Army map service and Landsat MSS image. During this period, the sinuosity index of study area is 1.062, which indicate the river near to straight. Due to low water discharge in the study reach, there are huge number of bar deposited in the middle and lower course of the study reach (fig. 7B & C). Erosion has occurred in mainly left banks of the reach in the upper section or near about Kosi confluence region of the study course (fig.7A).Total amount of deposition and erosion have been identified by overlapping river banks of both years and showing in column chart (fig.13a & 14a).

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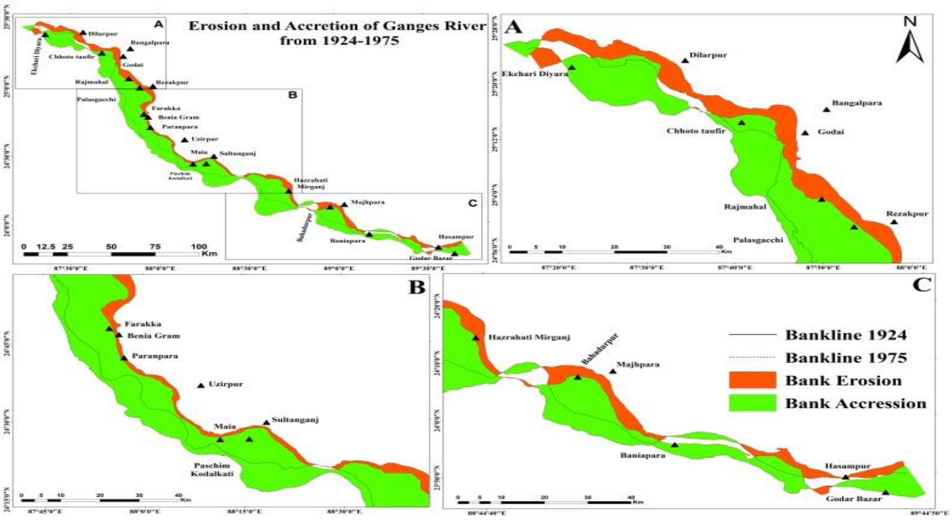


Fig. 7 Erosion and accretion between 1924 to1975.

Throughout this time frame, left bank erosion is more evident in comparison to right bank. About 503.25 $km^2$ area has eroded from the left bank at the rate of 9.87 $km^2$/year (table 5); whereas the 194.81 $km^2$`of the right bank has eroded with the rate of 3.82 $km^2$/year (table 4). A massive accretion has been observed in right bank near to Kosi confluence (fig. 7 A) and near the Jamuna confluence (fig. 7C) of the study reach. Channel expansion occurred at some locations, notably Dilarpur, Godai, Rezzakpur in India and Hazrahati, Majpara and Hasampur in Bangladesh. Meander shifting and meander translation occurred in Chhototaufir, Palshgachi and Manikchack in India; Maia, Bahadurpur, sultanganj and Paschim kodalkati in Bangladesh. The amount of left and right bank accretion is considerably- 771.21 $km^2$ and 463.64 $km^2$, with the rate of 15.12 $km^2$/year and 9.09 $km^2$/year. It's clearly showing that the left bank accretion is almost double in spatial scale, intensity and rate in comparison to right bank. Table 6 depicts that the total amount of deposition area is 1234.86 $km^2$ and erosion area is 698.07 $km^2$ during 1924-1975. The rate of deposition is 24.21 $km^2$/year and the rate of erosion is 13.69 $km^2$/year. In consideration of rate, deposition is almost double in comparison to erosion. The difference between erosion and deposition is 536.79 $km^2$ (Table.6).

### 5.6 Bank erosion and accretion dynamics (1975–1980)

Lateral erosion is the major reason of channel migration. In this period the rate of annual erosion on the left bank has been higher than that of right bank. Erosion occurred in the most of the study area along upper reach to lower reach. During 1975-1980, total amount of right bank erosion is 29.17 $km^2$ (table 4) and left bank erosion is 370.54 $km^2$ (table 5). The rate of right bank erosion is 5.84 $km^2$/year and left bank erosion is 74.11 $km^2$/year; which clearly shows that the left bank erosion is more pronounced in comparison to right bank. Deposition has mainly occurred in middle and lower reach of the channel (8B & 8C). The total amount of left and right bank deposition is 430.57 $km^2$ & 49.61 $km^2$. The difference between erosion and accretion is 80.47 $km^2$. During this time period erosion is more pronounced than deposition (table 6). Total amount of erosion is 399.71 $km^2$, and accretion is 480.18 $km^2$. At Five locations in each portion (near Dilarpur, Bangalpara, River Block, Kala Diayara, Godai in India and near Uzirpur, Bilmaria, Juniadha, Chandgram in Bangladesh), channel widening characteristics of river is highly conspicuous (fig.8) due to presence of large meander bars. Sharma (2005) found similar type of channel widening along Brahamputra River in Assam.

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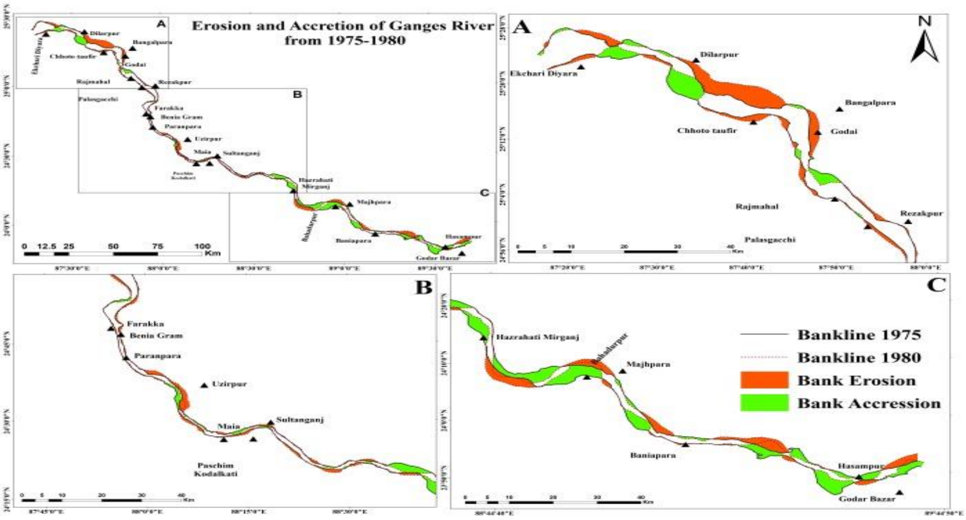


**Fig. 8 Erosion and accretion between 1975 to1980.**

**Table 4 Total amount of right bank erosion and accretion**

| Year | Erosion($km^2$) | Accretion ($km^2$) | Difference (E-A) ($km^2$) | Erosion Rate ($km^2$/year) | Accretion Rate ($km^2$/year) |
|---|---|---|---|---|---|
| 1924-1975 | 194.81 | 463.64 | 268.82 | 3.82 | 9.09 |
| 1975-1980 | 29.17 | 49.61 | 20.43 | 5.84 | 9.92 |
| 1980-1990 | 613.57 | 209.24 | 404.33 | 61.36 | 20.92 |
| 1990-2000 | 216.12 | 271.26 | 55.14 | 21.61 | 27.13 |
| 2000-2010 | 189.57 | 244.48 | 54.91 | 18.96 | 24.45 |
| 2010-2019 | 247.31 | 116.02 | 131.29 | 27.48 | 12.89 |

### 5.7 Bank erosion and accretion dynamics (1980-1990)

Erosion and deposition are common hydrological processes that create changes in the riverbanks and its associate area [14]. The landform along river channel has frequently changed due to channel shifting. The bank line of study reach has shifted during 1980-1990 in different position (fig. 9).

During this decade, total amount of right bank erosion is 613.57 $km^2$ and left bank is 230.50 $km^2$. The rate of right bank erosion is 61.36 $km^2$/year and left bank is 23.05 $km^2$/year; which show that during this period the intensity and the spatial extent of right bank erosion is more powerful than left bank. An area of 87.08 $km^2$ on the left bank has been accreted and 209.24 $km^2$ of right bank accreted during this period; with the rate of 20. 92 $km^2$/year and 8.71 $km^2$/year (table 4 & 5). Due to construction of Farraka barrage, huge amount of water logging accelerates river bank erosion and reachs almost 26.17% in comparison to the previous decade. Nearly 8.72% of accretion has decreased during this decade comparing to previous decade. Total amount of erosion during this decade is 844.07 $km^2$ and deposition is 296.33 $km^2$.The difference between erosion and deposition is 547.75 $km^2$. Most pronounced bank erosion due to compound band development is observed between Ekchari Diyara to Godai in India and Bilmaria to Ruppur villages in Bangladesh. Apart from that several erosional pocket can be seen in some location, especially Jalangi, Narsinghapur, Hazarhati Mirazganj (India) and Maia, Putia, Bilborakpara, Yusufpur, Abeder Ghat, Juniadha, Mirazanagar and Laidaha (Bangladesh).

### 5.7 Bank erosion and accretion dynamics (1990-2000)

Erosion and deposition are the natural hydrological processes that make geomorphological changes in the river corridor and its adjacent areas. River bank erosion is one of the main causes of channel shifting processes; which leads landform changes along the river banks. Bankline of 10 years from 1990-2000 are drawn from the Landsat-TM and Landsat-ETM imagery (table 1). Changes of the river bank position are identified through the overlapping of bankline of two different years. River bank of the study reach has been sifted in different position.

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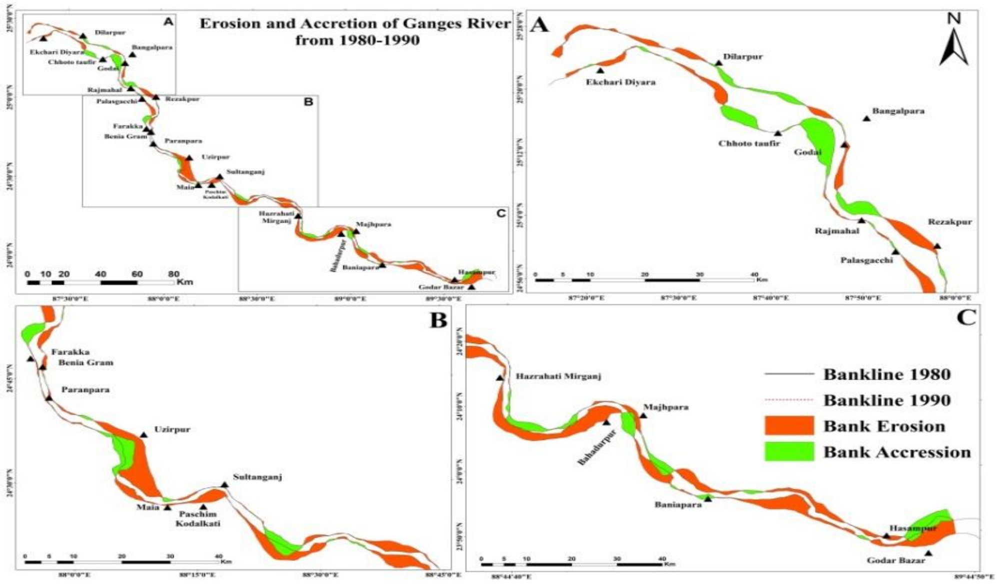


**Fig. 9 Erosion and accretion between 1980 to 1990.**

About 271.26 $km^2$ right bank area is deposited at the rate of 27.13 km2/year, which is the almost double compared to left bank that is, 112.72 $km^2$ with the rate of 11.27 $km^2$/year (table 4 & 5). Erosion rate of right bank during this period is 21.61 $km^2$/year and left bank is 24.46 km2/year; and this depicts left bank has eroded more than right bank. The total amount of erosion is 460.69 $km^2$ and deposition is 383.98 $km^2$. The difference between erosion and deposition is 76.70 $km^2$. Rate of erosion suddenly decreases when compared to the previous decade which is 26.77 % in 1980-90 and 14.66% in 1990-2000. The rate of erosion becomes almost half during this decade. As a result, the deposition rate increases from 8.72% of 1980-90 to 11.30% of 1990-2000.

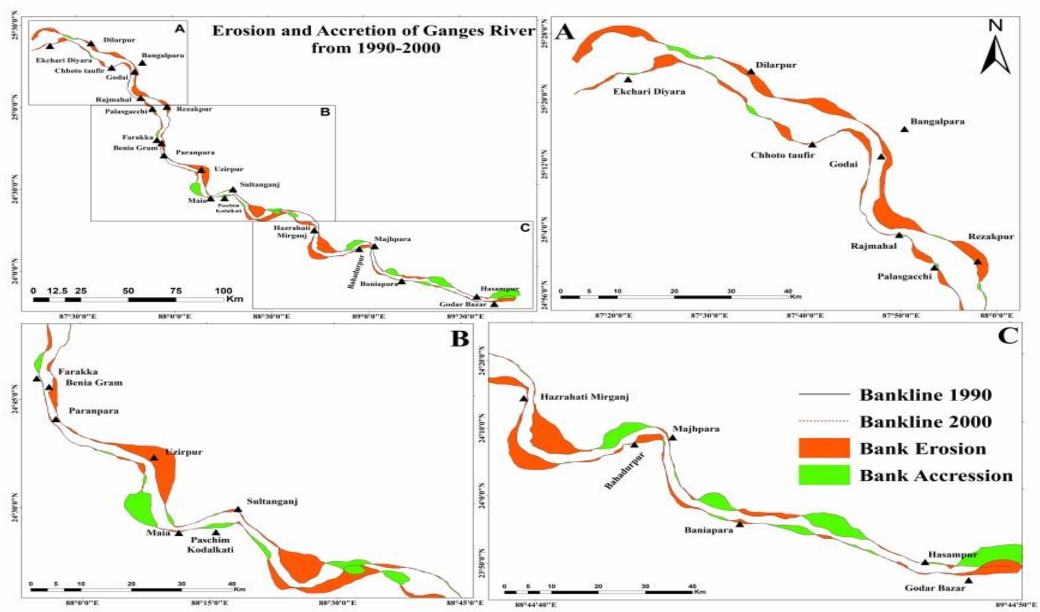


**Fig. 10 Erosion and accretion between 1990 to 2000.**

A group of bank erosion pocket has appeared on the left bank due to northward migration of the bankline at the central part of the study reach from Manihari village and Mathurapur village. Meander extension can be seen near Katha Diyara, Kesharpur Sukhsena, Rezzakpur village in India (Fig. 10A) and Uzirpur, Sultanganj, Mohanganj, Char Khidirpur Paschim, Chilmari, Khayer Hat and Bahadurpur in Bangladesh (Fig. 10B & C).

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**Table 5 Total amount of left bank erosion and accretion**

| Year | Erosion ($km^2$) | Accretion ($km^2$) | Difference (E-A) (km2) | Erosion Rate ($km^2$/year) | Accretion Rate (km2/year) |
|---|---|---|---|---|---|
| 1924-1975 | 503.25 | 771.21 | 267.96 | 9.87 | 15.12 |
| 1975-1980 | 370.54 | 430.57 | 60.04 | 74.11 | 86.11 |
| 1980-1990 | 230.50 | 87.09 | 143.42 | 23.05 | 8.71 |
| 1990-2000 | 244.56 | 112.72 | 131.85 | 24.46 | 11.27 |
| 2000-2010 | 91.76 | 550.77 | 459.01 | 9.18 | 55.08 |
| 2010-2019 | 221.76 | 90.50 | 131.26 | 24.64 | 10.06 |

### 5.8 Bank erosion and accretion dynamics (2000-2010)

In this period, river reach has been digitized from the orthorectified Landsat-ETM and the sinuosity index increases from 1.09 (2000) to 1.26 (2010). It indicates that the increase of meander bend (Fig. 11A, B, and C). An area about 189.57 $km^2$ of right bank has eroded at the rate of 18.96 $km^2$/year whereas 91.76 $km^2$ of the area of the left bank has eroded at the rate of 9.18 $km^2$/year. The rate of bank accretion is higher than bank erosion (table 6), which can be seen in different sites of the study reach (fig.11). Rate of accretion has changed in comparison to the previous decade by more than 13.40%; which is the highest among all the study decade. An area of 550.77 $km^2$ of left bank has been deposited; whereas, 244.48 $km^2$ of the area of right bank has deposited during this time period. Total amount of accretion is almost thrice in comparison to erosion (table 6), of which maximum magnitude of deposition had been observed between Benipur and Majhpara village (fig.11). Due to the north eastward extension of meander bends and lateral migration of channel; the right bank accretion has occurred chiefly in four pockets of study reach (fig.11). Within these four pockets, two pockets are located in down-stream of the study reach; another two are located in upstream of the study reach (fig.11A & 11C). Several extensive depositional pocket in left bank also can be seen both up and down stream of Farakka Barrage; among these pocket Milik Gacch, Baijhnathpur, Ajolarambari, Panchanandapur and Islampur in India and Beniagram, Biswanathpur, Indra Narayanpur, Putia, Tranagar, Filip Nagar and Charjukhori in Bangladesh are notable. Meander translation, nack cut-off of meander and creation of Ox-bow lake is the main reason of making these several extensive depositional pocket.

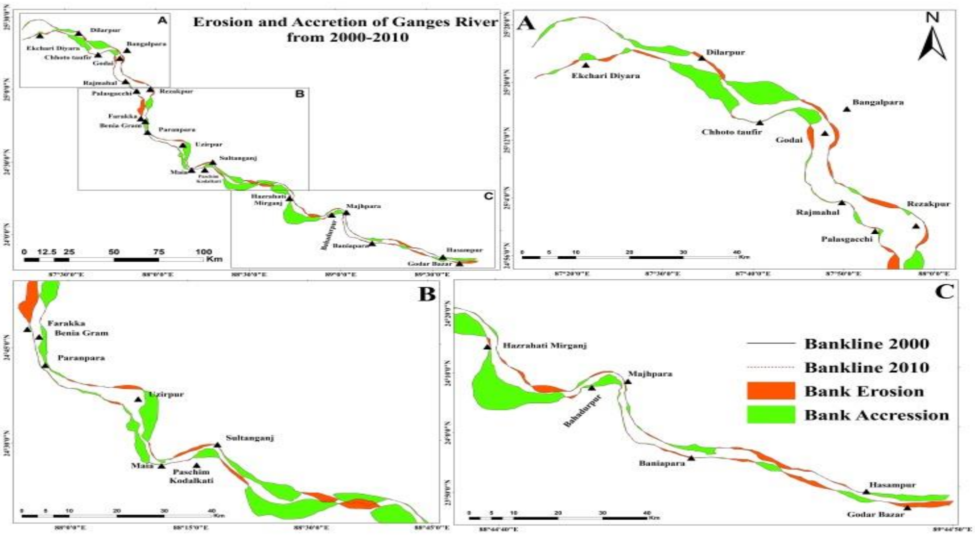


Fig. 11 Erosion and accretion between 2000 to 2010.

### 5.9 Bank erosion and accretion dynamics (2010-2019)

The variation in bank movement may be attributed to a number of factors including flow regulation, changes in sediment load, and monsoonal floods of large magnitude [18, 22, and 54]. However, it has been reported that measuring bank movement over shorter periods of time exhibits greater scatter than those over 100-200 year as channel migration is episodic in nature [55]. In figure 13 bank line, erosion and deposition are shown in different colors for 2010 and 2019. In these decade huge amount of the areas in different blocks of Dakshin Chandipur, Manikchack and Dharampur Gram panchayet are badly affected by erosion. The total amount of erosion is 469.07 $km^2$ and deposition is 206.52 $km^2$. The difference between erosion and deposition is 262.55 $km^2$. Statistics shows that accretion is much pronounced than erosion. Rate of erosion is 52.12 $km^2$/year and the rate of deposition is 22.95 $km^2$/year (table 6). Accretion rate of right bank is much higher than that of left bank (table 4 & 5). Erosion rate of right bank is also slightly higher than that of left bank (table 4 & 5). In the North-

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eastward shifting of river channel there are five major meander bends that have developed near the village of Bangalpara, Khanpur, Moharajpur, Bagha and Lalpur in upstream of Farakka and six: Uzirpur, Maia, Sultanganj, Yusufpur, Hazrahati Mirazganj, and Majhpara in downstream of Farakka.

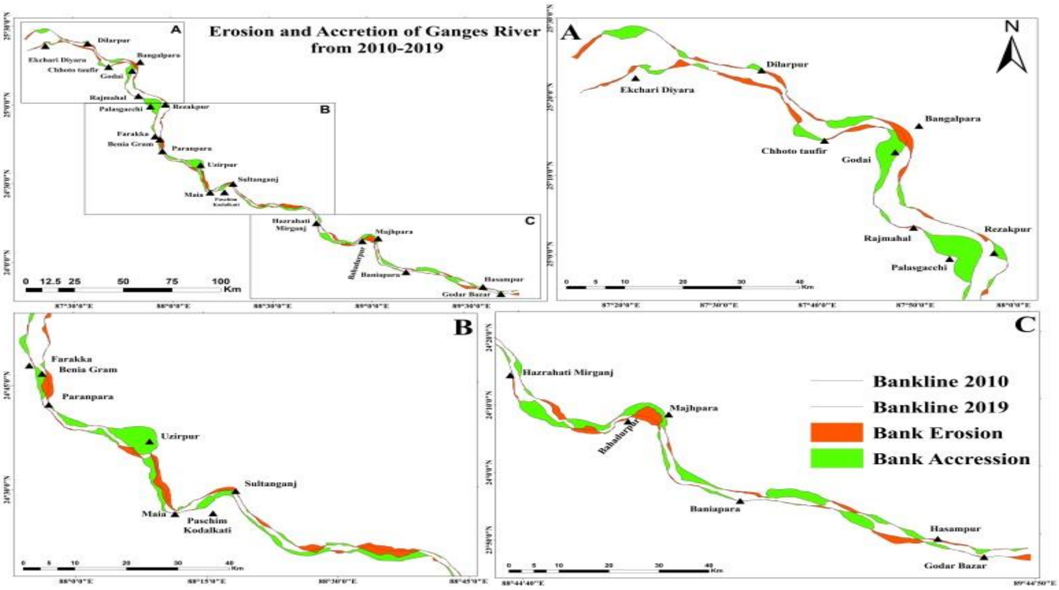


**Fig. 12 Erosion and accretion between 2010 to 2019**

**Summery**

Over the time period erosion, accretion and human interventions the Ganga river has witnessed significance morphological changes. However it has been very difficult work to quantify morphological changes of an active alluvial river like Ganga. A practical approach to detect the long-term morphological changes of Padma River is analysing by multiple satellite image [23]. Table 6 and fig 13a &14a show the total amount of erosion and accretion over the period. Average rate of erosion and accretion are also shown in fig. 13b & 14b.

**Table 6 Total amount of Bank Erosion and Accretion**

| Year | Total Erosion ($Km^2$) | Total Accretion ($Km^2$) | Difference (E-A) ($Km^2$) | Rate of Erosion (km2 /year) | Rate of Accretion (km2 /year) |
|---|---|---|---|---|---|
| **1924-1975** | 698.07 | 1234.86 | 536.79 | 13.69 | 24.21 |
| **1975-1980** | 399.71 | 480.18 | 80.47 | 79.94 | 96.04 |
| **1980-1990** | 844.08 | 296.33 | 547.75 | 84.41 | 29.63 |
| **1990-2000** | 460.69 | 383.98 | 76.70 | 46.07 | 38.40 |
| **2000-2010** | 281.33 | 795.26 | 513.92 | 28.13 | 79.53 |
| **2010-2019** | 469.07 | 206.52 | 262.55 | 52.12 | 22.95 |

In the study stretch of the river Ganga, erosion and accretion is most active and significant issue. Highest amount of erosion has occurred during 1980-1990 which is 844.08 $km^2$, and the highest rate of erosion has also occurred in 1980-1990 which is 84.41 $km^2$/year. On the other hand, the highest amount of deposition (1234.86 $km^2$) has occurred during 1924-1975, but highest per year deposition has occurred during 1975-1980, which is 96.04 $km^2$/year. Total amount of accretion is ultimate high in 1924-1975, which is decreased continuously after 1975. In 1924-1975, erosional and accretion rate of left bank is 9.87 $km^2$ and 15.12 $km^2$, after construction of Farakka barrage which is increased almost 7 times in erosional work (74.11 $km^2$) and 6 times in accretion work (86.11 km2), river try to readjust with new riverine morphology; and it again decreased after 1980. In right bank, both erosion and accretion rate is very low till 1980 (table 4), but after 1980 both erosion and accretion in right bank increased several times. Result indicates that Farakka barrage (1974) has triggered huge amount of sediment deposited alongside of the river.

Finally it can be said that hydrological and morphological change of river are naturally controlled through the erosion and accretion process. In study reach, water level and discharge are in general high in wet season and they are low in dry season. So, erosion and deposition with other hydrological parameter also vary seasonally.

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## VI. CONCLUSIONS

The study is mainly based on satellite images and the satellite based image digitizes data considering their limitations. This study investigates the rate and amount of bank erosion and accretion processes of Ganga River in different time periods. This paper has used geospatial techniques to quantify the channel characteristics of Ganga river from Kosi confluence to Padma confluence in India and Bangladesh over 96 years. Using toposheet and Landsat data from 1924 to 2019 and spatial analysis technique within GIS, this study has quantified channel characteristics of 327 km of Ganga system including middle (from Kosi confluence to Rajmahal hill) reaches and lowers (Rajmahal hill to Padma confluence) reaches.

Over the years, under the combined impact of erosion, accretion and anthropological interventions of human being, the large anabranching of Ganga river has experienced significant hydro-morphological changes in the study reach. However, accurate analysis and quantification of hydro-morphological changes of tropical and alluvial river like Ganga is a challenging and tedious task. Channel planform maps of study area over 96 years reveal that the river has witnessed expansion and contraction as well as adjustment to its planform during the study decade. Analysis of both banks shows that each bank whether it is right or left has a particular stretch where movement is very low and high. For example, left bank movement is very high in the area ahead of the Kosi confluence from Dilarpur to Rezzakpur in upstream of Farakka and Paranpara to Majhpara in downstream of Farakka. The right bank erosion is found at Ekchari Diyara to chotataufir in upstream and Udirpur to Godar Bazar in down-stream of farakka barrage. The erosion and the accretion are not continuous in nature but they are combine of large and small pockets. Statistical data of erosion and accretion of both bank show that 1662.36 $km^2$ of land has eroded along left bank and 1354.27 $km^2$ has accreted along right bank that suggesting the pattern of accretion and erosion do not balanced here. Meander theory can establish the relationship between bank curvature with erosion and accretion. It is the fact that erosion and deposition of the study area are highly controlled by flood flow and on the Padma (downstream of Farakka barrage) and annual average flow, indicating the effect of barrage.

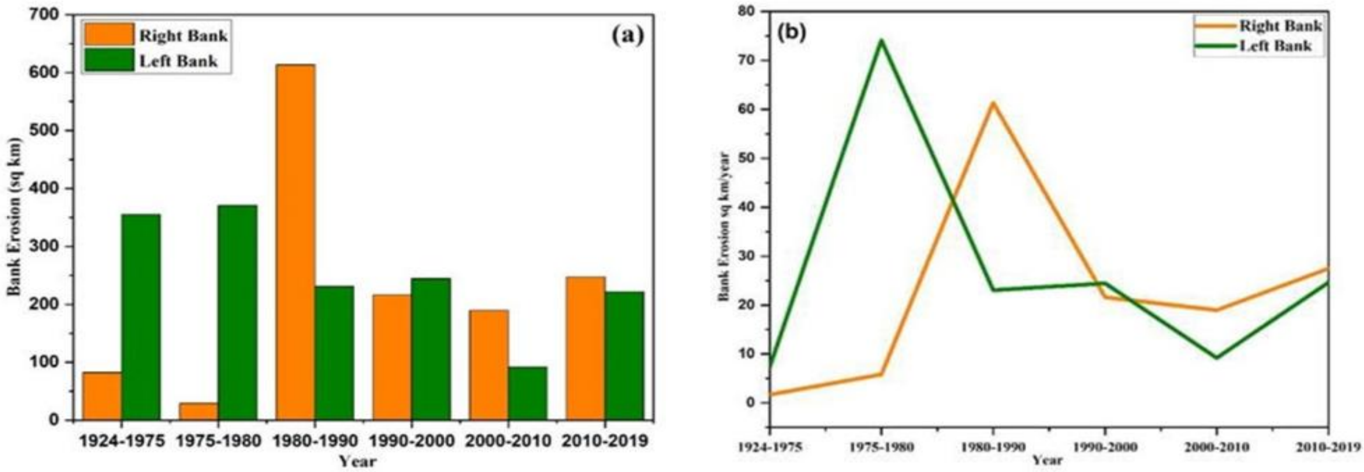


**Fig. 13 Amount of bank erosion of the studied section of Ganga river a total bank erosion and ( b) average rate of bank erosion**

Alluvial rivers are dynamic geomorphic entities as they freely change their channel position and morphology in order to adjust themselves horizontally or vertically in response to spatio-temporal variations in sediment and water discharge [40]. Bank erosion and accretion phenomena of any alluvial river indicate the level of channel adjustment. The lower portion of the study reach (after Farakka barrage) is significant dynamic in nature. Basically, the section of the study reach, the Ganga river is unconfined in nature as the river migrates vigorously resulting in erosion and accretion along the river bed and channel. During 1924-2019, river Ganga underwent lateral migration towards northeast, which is pronounced along the upper and middle portion of the study reach. During 1975-1980, the river has migrated towards southeast due to meander bend development (fig.9); it has further extended in the succeeding periods. In the study it has been observed that the left bank accretion has taken place owing to the south-eastward migration of the river bank, while the left bank erosion has occurred due to north-westward migration of the channel; for right bank, it is vice versa. Although, bank erosion and accretion are also determined by meander bends extension, translation, and rotation as well as chute and neck cutoff in the study area.

The overall pattern of bend development process and bank line shifting of channel suggest the continuously widening of the river channel and shifting north-westward of upper segment and south-eastward of lower segment of Farakka Barrage. Channel widening is more evident in upper segment of Farakka in comparison to lower segment. In general, the whole channel shifting process can be grouped into two stages: in the first, before the of construction Barrage during the period of 1924 to 1975 which is dominated by natural process; and in the second, during the period of 1975 to 2019, it is

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controlled by anthropological processes and reeled the continuous migration of bank line. Rate of bank erosion depends on bank material and discharge quantity. The mean erosion rate being highest in 1980-1990 is obvious because of newly construction of Farakka barrage, river responds immediately to the increase in human intervention in the early 1980's. In first stage (1924-75), the average sinuosity is 1.07 whereas it has increased in second stage (1975-2019) to 1.37. Because of this reason river shifts towards left and erodes huge settlements such as Bangitola, Dakshin Chandipur,Manikchack, Uttar Chandipur, Dharampur, Panchanandapur I & II, Hamidpur, Rjanagar, Hiranandapur, Gopalpur etc and land area.

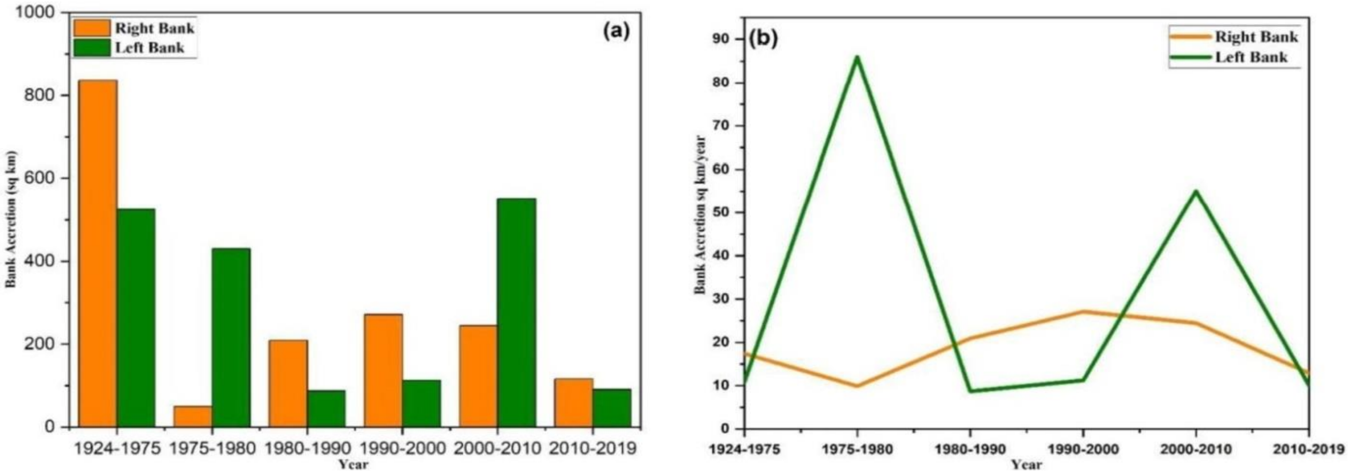


**Fig. 14 Amount of bank accretion of the studied section of Ganga river (a) total bank accretion and (b) average rate of bank accretion**

Localized bank protection method cannot be solution for long-term due to lack of continuous maintenance of protection work. "Decreasing water pressure from the left bank of upstream of barrage by diverting water flow from eroding channel, as suggested by group of expert, may be the only permanent solution under the existing condition" [59]. Till that desired diversion of flow achieving by continuously dragging of river channel. Diversion of water through Bhagarathi-Hoogly channel reduces dry season water flow in Padma, and sediment deposited behind the barrage and it releases during pick of monsoon when barrage gate are open. The result of database created during this study specially erosion and accretion area, cross-section and digital elevation model of flood plain can be used for further hydrographic and bankline prediction analysis of study stretch. Hence, this study become very much helpful for monitoring, analyzing and interpreting the river stretch for future studies.

### Ethical Statement

We have no conflict of interest to disclose. This Manuscript has not been published and is not under consideration for publication elsewhere.

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## Reference

[1] Abbas. N., Subramanian, V., Erosion and sediment transport in the Ganges river basin (India.) *Journal of Hydrology*, 69, 1–4, PP 173-182.1984. https://doi.org/10.1016/0022 1694(84)90162-8

[2] Ahmed A.A., Fawzi A., Meandering and bank erosion of the River Nile and its environmental impact on the area between Sohag and El-Minia, Egypt. *Arabian Journal of Geoscience*, 4, 1–11, 2011.

[3] Ahmed, K.S., & Mafizuddin, M., (Eds.). Riverbank Erosion, Flood and Population Displacement in Bangladesh. *REIS-JU, Dhaka*, pp. 61–72, 2014.

[4] Bartley, R., Keen, R.J., Hawdon, A.A., Hairsine. P.B., Disher, M.G., & Kinsey-Henderson, A.E., Bank erosion and channel width change in a tropical catchment. *Earth Surface Processes and Landforms*, 33, 2174–2200. 2008.

[5] Bhakal, L., Dubey, B., Sarma, A.K., Estimation of bank erosion in the river Brahmaputra near Agyathuri by using geographic information system. *Journal of the Indian Society of Remote Sensing*, 33(1), 81–84. 2005.

[6] Baki, A.B.M., Gan. T.Y., Riverbank migration and island dynamics of the braided Jamuna river of the Ganges–Brahmaputra basin using multi-temporal Landsat images. *Quaternary International*, 263, 148–161, 2012.

[7] Brice, J.C., Stream channel stability assessment. Report FHWA/RD-82/021. *US Department of Transportation Federal Highway Administration, Washington*, DC. 1982.

[8] Coleman, J.M., Brahmaputra river: Channel processes and sedimentation. *Sedimentary Geology*, 3(2–3), 129–239. 1969.

[9] Constantine J.A., Stephen R., Thomas D., A mechanism of chute cut-off along large meandering rivers with uniform floodplain topography. *GSA Bulletin*, 122 (5-6): 855–869. doi: https://doi.org/10.1130/B26560.1, 2010.

[10] Dad, M.M. A Study on the River Course Shifting Pattern in Bangladesh M.Sc Engg. Department of Water Resources Engineering, Bangladesh University of Engineering and Technology, Dhaka, Bangladesh. 1977.

 DOI : 10.35291/2454-9150.2022.0011 

[11] Das S., and Pal S., Character and Cardinality of Channel Migration of Kalindri River, West Bengal, India. *International Research Journal of Earth Sciences*, 4(1):13-26, 2016.

[12] Das, S., Delineation of Channel Migration Zone and Its Change in Post Farakka Barrage, a Case in Kalindri River of Eastern India. *Journal of Geography, Environment and Earth Science International*, 14(3): 1-10, 2018.

[13] Dewan. A., Corner. R., Saleem. A., et. al., Assessing channel changes of the Ganges-Padma River system in Bangladesh using Landsat and hydrological data. *Geomorphology,* 276 257–279. 2016. http://dx.doi.org/10.1016/j.geomorph.2016.10.017

[14] Eaton, B.C., Millar, R.G., & Davidson. S., Channel patterns: braided, anabranching, and Single thread. *Geomorphology*, 120, 353–364, 2010.

[15] Ety, N.J., Rashid, M.S., Spatio-temporal variability of erosion and accretion in Ganges River using GIS and RS: a comparative study overlapping Rennell's map of 1760s. *Environ Dev Sustain* **22,** 3757–3775, 2020. https://doi.org/10.1007/s10668-019-00317-4.

[16] Florsheim, J.L., Mount, J.F, and Chin, A., Bank erosion as a desirable attribute of rivers. BioScience, 58(6), 519–529. 2008.

[17] Garcia, M.H., Bittner, L., Nino, Y., Mathematical modeling of meandering streams in Illinois: A tool for stream 64. 1994.

[18] F.D. Shields, Jr., Simon, and Steffen, L.F., Management and engineering. Unpublished report, University of Illinois, Urbana, IL, Us. 49.

[19] Galay, V.J. (1980). River channel shifting on large rivers in Bangladesh. *International Symposium on River Sedimentation*, Beijing, China, pp. 543–562. 1999.

[20] Harijan. N, Kumar. A., Bhoi. S., Tare, V., Course of river Ganga over a century near Kanpur City based on remote sensing data. *J. Indian Soc. Remote Sens*. 31 (1), 1–4. 2003.

[21] Heitmuller, F.T., Channel adjustments to historical disturbances along the lower Brazos and Sabine rivers, south-central USA. *Geomorphology,* 204, 382–398, 2014.

[22] Hossain, M.A., Gan, T.Y., Baki, A.B.M., Assessing morphological changes of the Ganges river using satellite images. *Quat. Int.* 304, 142–155, 2013.

[23] Hossain. M.M., Shifting characteristics of the Ganges in Bangladesh. *REIS-JU, Dhaka*, pp. 61-72, 1991.

[24] Hussain, M., Chen, D., Cheng, A., and Wei, H., Stanley, D., Change detection from remotely sensed image: From pixel-based to project object based approaches. *ISPRS Journal of Photogrammetry and Remote Sensing,* 80, 91-106, 2013.

[25] Kalam, M.A., Hoque. N., Erosion trend study of the Ganges river course using remote sensing techniques. *Asia Pac. Remote Sens. J*. 8 (1), 43–50.1995.

[26] Khan, H., Khalil, S., Kazmi, S., Umar, M., Shahzad, A., & Farhan, S., Identification of River Bank Erosion and Inundation Hazard Zones Using Geospatial Techniques – A Case Study of Indus River near Layyah District, Punjab, Pakistan. *Geoplanning: Journal of Geomatics and Planning*, 4(2), (2017). 121-130. doi:10.14710/geoplanning.4.2.121-130

[27] Khan, A.U., Rawat, B.P., Quaternary geology and geomorphology of a part of Ganga basin in parts of Bareilly, Badaun, Shahjahanpur and Pilibhit district, Uttar Pradesh. Hyderabad: G.S.I. 1992.

[28] Kummu, M., Lu. X.X., Rasphone. A., Sarkkula. J., Koponen, J., Riverbank changes along the Mekong River: Remote sensing detection in the Vientiane–Nong Khai area. *Quaternary International,* 186(1), 100–112, 2008.

[28] Knighton, A.D., Fluvial forms and processes. pp. 206–236 London, 1984.

[29] Lane, S.N., Richards, K.S., Linking river channel form and process: Time, Space and Causality revisited. *Earth Surface Process and Landforms*, 22, 249-260.1997.

[30] Leopold, L.B., Wolman, M.G., Miller, J.P., Fluvial processes in geomorphology. Dover publications, New York, 1964.

[31] Li, L., Lu, X., Chen, Z., River channel change during the last 50 years in the middle Yangtze river, the Jianli reach. *Geomorphology,* 85, 185–196. 2007.

[32] MacDonald, T.E., Parker, G., Leuthe, D.P. (1991). Inventory and analysis of stream meander problems in Minnesota. St Anthony Falls Laboratory. University of Minnesota, Minneapolis, MN, USA.

[33] Mani, P., Kumar, R., Chatterjee, C., Erosion study of a part of Majuli River- Island using remote sensing data. *Journal of the Indian Society of Remote Sensing*, 31(1), 12–18, 2003.

[34] Mannan A., Sheikh A.H., The shifting of the Ganges river (the Padma) and its morphological effect within the Rajshahi district. Rajshahi Univ. Stud. Part B XII, 61–79, 1984.

[35] McFeeters, S.K., The use of the normalized difference water index (NDWI) in the delineation of open water features. *International Journal of Remote Sensing*, 17, 1425–1432. 1996.

[36] Mirza, M.M.Q. (Ed.)., The Ganges Water Diversion: Environmental Effects and Implications. *Springer Science + Business Media Inc*., Dordrecht, the Netherlands, 2004.

[37] Morisawa, M., Hack, J.T., Tectonic geomorphology. In Proceedings of the 15th annual Binghamton geomorphology symposium. Boston. 1985.

[38] Motta, D., Abad, J.D., Langendon, E.J, Gracia, M.H., A simplified 2D model for meander migration with physically-based bank evolution. *Geomorphology.* 10:163-164, 2012.

[39] Mukherjee, K., Pal, S. Channel migration zone mapping of the River Ganga in The Diara Surrounding Region of Eastern India. *Environment Development and Sustainability,*1–23, 2017. DOI:10.1007/s10668-017-9984-y.

[40] Mukherjee, R., Yadav, R.B., Biswas, S.S., Pal. R. Bank erosion and accretion dynamics explored by GIS techniques in lower Ramganga river, Western Uttar Pradesh, India. *Spat.Inf. Res.* 2016. https://doi.org/10.1007/s41324-016-0074-2

[41] Pal, R., Biswas. S.S., Pramanik, M.K., Mondal, B., Bank vulnerability and avulsion modeling of the Bhagirathi-Hugli river between Ajay and Jalangi confluences in lower Ganga Plain, India. *Modeling Earth Systems and Environment,* 2(2), 65. 2016.

[42] Parua, P.K., Fluvial geomorphology of the river Ganga around Farakka. *J. Inst. Eng. India* 82, 193–196. 2002.

[43] Pan, S., Application of remote sensing and GIS in studying changing river course in Bankura district, West Bengal. *Int. J. Geomatics Geosci*. 4 (1), 149–163, 2013.

[44] Pati, J.K., Lal, J., Prakash, K., Bhusan, R., Spatio-temporal shift of western bank of the Ganga river, Allahabad City and its implications. *J. Indian Soc. Remote Sens.* 36, 289– 297. 2008.

[45] Philip, G., Gupta, R.P., Chattacharya, A., Channel migration studies in the middle Ganga basin, India, using remote sensing data. *Int. J. Remote Sens.* 10 (6), 1141–1149, 1989.

[46] Posner, A.J., Duan, J.G., Simulating river meandering processes using stochastic bank erosion coefficient. *Geomorphology,* 163–164, 26–36, 2012.

[47] Rahman, M.L., Ashrafuzzaman, A.K.M., River geometry and bankline movement of the Ganges river in Bangladesh. *J. NOAMI* 21 (2), 19–31, 2004.

[48] Randle, T.J., Channel migration model ror Meandering River. University of Colorado, Denver, 2004.

 

[49] Rinaldi, M., Recent channel adjustments in alluvial rivers of Tuscany, central Italy. *Earth Surface Processes and Landforms*, 28, 587–608, 2003.

[50] Rozo, M.G., Nogueira, A.C.R., Castro, C.S., Remote sensing-based analysis of the plan form changes in the upper Amazon river over the period 1986–2006. *J. S. Am. Earth Sci.* 51, 28–44, 2014.

[51] Sahu, A.S., Identification and mapping of the waterlogged areas in Purba Medinipur part of Keleghai river basin, India: RS and GIS methods. *International Journal of Advanced Geosciences*, 2(2), 59–65, 2014.

[52] Sarker, M.H., Impact of Upstream Human Interventions on the Morphology of the Ganges-Gorai System. In: Mirza M.M.Q. (eds) The Ganges Water Diversion: Environmental Effects and Implications. *Water Science and Technology Library*, vol 49. 2004.. https://doi.org/10.1007/978-1-4020-2792-5_4

[53] Sarma, J.N., Bora, D., Goswami, U., Change of river channel and bank erosion of the Burhi Dihing river (Assam), assessed using remote sensing data and GIS. *Journal of the Indian Society of Remote Sensing*, 35, 93–100, 2007.

[54] Sharma, J.N., Fluvial process and morphology of the Brahmaputra River in Assam, India. *Geomorphology* 70, 226–256, 2005.

[55] Shields, Jr. F.D., Simon, A., Steffen, L.J., Reservoir effects on downstream river channel Migration. Environ. Conserv. 27 (1), 54–66, 2000.

[56] Sinha, R., Ghosh, S., Understanding dynamics of large rivers aided by satellite remote sensing: a case study from lower Ganga plains, India. *Geocarto Int*. 27 (3), 207–219, 2012.

[57] Surian, N., Channel changes due to river regulation: The case of the Piave River, Italy. *Earth Surface Processes and Landforms*, 24, 1135–1151,1999.

[58] Thoma, P.D, Gupta, C.S, Bauer, E.M., Quantifying river bank erosion with scanning laser altimetry. *International Archives of the Photogrammetry, Remote Sensing, Annapolis*, 34(3/W4), 169–174, 2001.

[59] Thakur, P.K., Laha, C., Aggarwal, S.P., River bank erosion hazard study of river Ganga, upstream of Farakka barrage using remote sensing and GIS. *Nat Hazards* , **61**, 967–987, 2012. https://doi.org/10.1007/s11069-011-9944z

[60] Thorne, C.R., Geomorphic analysis of large alluvial rivers. *Geomorphology;* 44:203-219, 2002.

[61] Winterbottom, S.J., Medium and short-term channel planform changes on the rivers Tay and Tummel, Scotland. *Geomorphology*, 34, 195–208, 2000.

[62].Yang, C.T., On river meanders. Journal of Hydrology, 13:231-253, 1971.

[63] Yang, X., Damen, M.C., J, Van., Zuidam, R.A., Satellite remote sensing and GIS for the analysis of channel migration changes in the active Yellow river delta, China. *JAG 1* (2), 146–157, 1999.

65. Yao, Z., Ta, W., Jia, X., Xiao, J., Right bank erosion and accretion along the Ningxia- Inner Mongolia reaches of the Yellow river from 1958 to 2008. *Geomorphology*, 127, 99–106, 2011.

66. Yao, Z., Xiao, J., Ta, W., Jia, X,. Planform channel dynamics along the Ningxia–Inner Mongolia reaches of the Yellow River from 1958 to 2008: analysis using Landsat images and topographic maps. Environ Earth Sci. 70**,** 97–106, 2012. https://doi.org/10.1007/s12665-012-2106-0

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