



Impact of human intervention on assessing downstream channel behaviour of Ichamati River on the lower Gangetic Plain of West Bengal, India

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Abstract

Since the period of human civilization, the hydrological and morphological characteristics of most of the rivers have been intensively modified by human interferences. In this context, the Ichamati River is one of the worst affected distributary channels flowing on the lower Gangetic delta of South Bengal. This tidally active river is streaming on the most densely inhabited district (North 24 Parganas) of West Bengal. The river is gradually decaying over time due to direct and indirect human activities on and along the river. Therefore, the prime aim of this research study is to explain the temporal change of the channel behaviour, especially fluvio-morphological characteristics of the river during 1976–2016. The present study also highlights location-specific causal factors liable for the downstream modification of the channel behaviour. In this research study, channel migration, erosion rate, bank vulnerability zone and channel planform pattern have been assessed using Landsat images of 1976, 1996 and 2016 in remote sensing and GIS environment. Besides, an intensive field survey was conducted for cross-sectional survey of the river. Primary data were gathered from brick kilns through a questionnaire survey for the estimation of sediment extraction rate from the river to prepare the sediment-water budget of the river. This study reveals that the morphological characteristics of Ichamati River have been modified at the human–nature interface and continuous siltation causes gradual upliftment of the riverbed. The channel is gradually narrowing and decaying over time. This study is helpful to understand the current status of the river and helps river scientists for its restoration as well as management planning.

Keywords Ichamati river · Human intervention · Channel behaviour · Bank vulnerability · Sediment-water budget · River decaying

Introduction

The impact of human intervention on a river system emerges as a burning issue in the field of physical geography. About 50% of the Earth's land surface has been altered by human exertion (Hooke et al. 2012; Rhoads et al. 2015). Since the period of human civilization, anthropogenic interferences on the riverine system were started through the activity of crop cultivation along the riverbank (Richards 1982; Sarkar 2004). The impact of human intervention on the river has received scanty attention from researchers and the main focus was given to study the hydrological parameters of the river until 1955 (Strahler 1956; Gilbert 1917). The role of humans to change the channel behaviour was first highlighted by Strahler in 1956 and later this work got ample attention from scientific communities for further research (Gregory 2006). The study was also popularized by Brookes

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(1988); Goudie (2006); Csiki and Rhoads (2010); James and Lecce (2013). William Graf, a river scientist is a pioneer contributor in this field and endows the field of anthropogeomorphology through his research works (Graf 1977, 1979, 1999, 2001, 2006). Several research works such as Fathy (1956); Livesey (1963); Warner (2000); Nilsson et al. (2005); Vandenberghe et al. (2012); Grabowski et al. (2014); Rhoads et al. (2015) and Hazarika et al. (2015) have already been conducted at a global scale to comprehend the human role in response to modification of channel behaviour of large rivers. In case of India, quality researches in this arena have been very few and most of the research have focused on major rivers such as Ganga–Brahmaputra and its main tributaries (Sinha and Sarkar 2009; Dhari et al. 2015; Pal and Pani 2019; Goswami and Patgiri 1999). Previously, researchers have studied channel planform pattern, bar morphology of alluvial rivers, bank erosion vulnerability, channel shifting and migration characteristics of various rivers based on various modelling approaches in remote sensing and GIS environment (Ahmed and Fawzi 2011; Deb and Ferreira 2014; Dhari et al. 2015; Pal et al. 2016; Pal and Pani 2016; Islam et al. 2017; Ophra et al. 2018; Yunus et al. 2019).

The lower Gangetic plain of West Bengal is highly populated and the population density is also very high (904 people/sq. km in 2011, Census of India). Therefore, all the rivers of South Bengal are facing acute stress due to rapid population growth as well as unsystematic human activities along the river. In this context, the Ichamati River is one of the worst affected rivers of South Bengal. The river has degenerating distributaries of the western Ganga–Brahmaputra delta that remains cut off from the source water except for the monsoon season and is chiefly maintained by the groundwater and tides (Rudra 2010). The upper span of the Ichamati river extends from Majdia in Nadia district to Swarupnagar in North 24 Parganas and the lower stretch continues from Swarupnagar in North 24 Parganas to the Bay of Bengal near the Indian Sundarban (Mondal and Bandyopadhyay 2014; Mondal et al. 2016a). The growth rate of the population in North 24 Parganas is the highest (12.04% Census of India 2011) in West Bengal. This huge pressure of population on the riverine process directly or indirectly poses serious threats to channel activity. A few research studies have been highlighted on these issues. Some researchers have concentrated on the study hydrodynamic parameters, psychochemical properties, water quality modeling, riverbank erosion and pool riffle sequence of the Ichamati River (Mondal et al. 2016a, b, c; Mondal and Satpati 2012, 2015). However, human-induced modifications of the channel behaviour and its impact on the riverine processes have received scanty attention from earlier researchers which are the prime focus of the present work.

In recent decades, various unsystematic human activities, for instance, the expansion of brick kilns along the

riverbank, sand mining and construction activities on the riverbed are causing rapid decaying of the river over time. The river discharge, sediment supply and channel planform have been affected by these activities. The study of channel behaviour is a challenging and difficult task because of the complex nature of the fluvial system. Despite that, an attempt has been taken in this research work to study the spatio-temporal change of the channel behaviour at the human–nature interface with the help of geospatial technologies and intensive field survey. The downstream morphological and hydrological characteristics of the river have been illustrated concerning growing human dominance on the river since the last four decades. This study will help to understand the present situation of the river and encourages the river scientists for strategy formulation to control human intervention on the river and save the river from further decaying.

The study area

The study area lies in the lower part of the Gangetic plain of South Bengal. The Gangetic delta was originated by alluvium deposition of the Ganga–Brahmaputra river system in the Quaternary period (Ganguly 1997; Mondal and Satpati 2012). The delta obtained its present configuration during the last Holocene period, as the mean sea level attained its present level since the transgression of the mid-Holocene period throwing accretionary lobes towards the east (Allison 1998; Niyogi 1975; Reaks 1919; Goodbred and Kuehl 2000; Bandyopadhyay et al. 2015). The formation of the entire Bengal basin was started 126 million years ago with the Alpine Himalayan orogeny (Sanyal 1999). The Bengal basin experienced a new tectonic movement during the sixteenth to eighteenth century and tilted towards Dhaka in Bangladesh. As a result, the present flow of the Ganga River started to move along with the Padma River within Bangladesh, leaving Hooghly River as a mere flow of tidal channel (Sanyal 1999). A large volume of water is conveyed through the tidal Hooghly River during the flood season by its tributaries namely the Bhagirathi, Jalangi and Mathabhanga, while the Ichamati River carries only flood water to a limited extent from the Mathabhanga River (O'Mally 1914). In the latter half of the nineteenth century, the off-take point of Ichamati River was gradually disconnected from its parent source due to excessive siltation on the riverbed (Rudra 2010). The riverbed of Ichamati is gradually uplifted to 4.3 m as compared to the riverbed of Mathabhanga River and the river faces acute shortage of water supply during the dry season (Mondal and Satpati 2017). The present study area extends from 22°36'45" N to 22°48'51" N latitude and 88°52'42" E to 88°54'47" E longitude and covers the total geographical area 272.16 sq. km (Fig. 1).

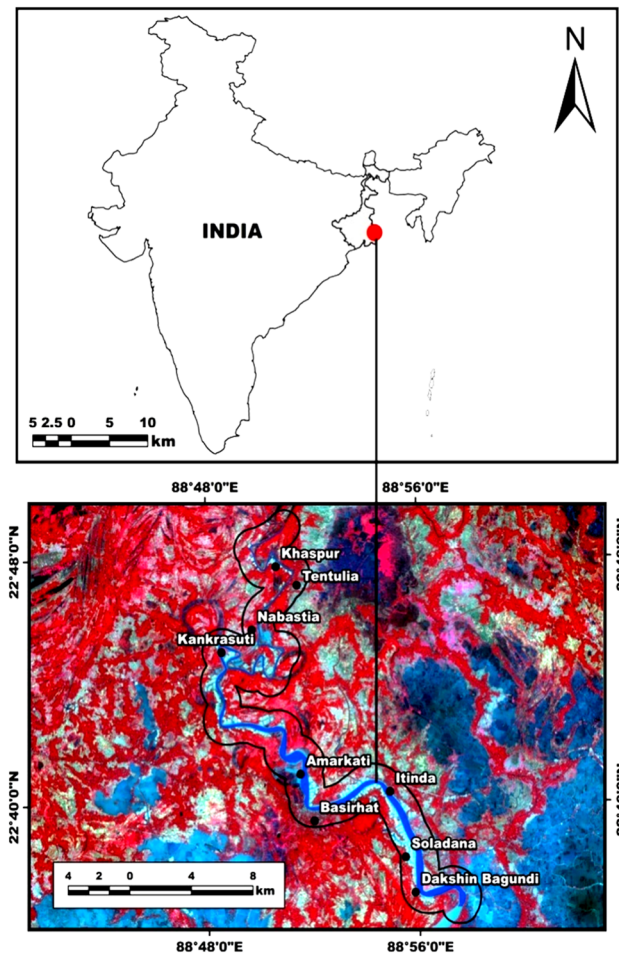


Fig. 1 Location map of the study area

Methodology

To study the channel characteristics of the Ichamati River, various multi-temporal satellite images (Landsat MSS, 1976; Landsat TM, 1996 and Landsat 8 OLI, 2016) were used in remote sensing and GIS environment. As the spatial resolution of multi-temporal satellite images varies with time, the bilinear resample technique was adopted for Landsat MSS image to match the spatial resolution with Landsat TM and Landsat 8 OLI. The details of the dataset used in this study are shown in Table 1.

Table 1 Detailed description of datasets

| Datasets | Description | Resolution | | Path and row | Source |
|----------------|---------------|----------------|---------------------|--------------|---|
| | | Pixel size (m) | Date of acquisition | | |
| Satellite data | Landsat MSS | 60 | 10-Jan-1976 | 148 and 44 | https://earthexplorer.usgs.gov/ |
| | Landsat TM | 30 | 30-Nov-1996 | 138 and 44 | |
| | Landsat 8 OLI | 30 | 06-Jan-2016 | 138 and 44 | |

Change detection of channel characteristics and analysis

The channel shifting was identified from post-monsoon period satellite images of the year 1976, 1996 and 2016. The bank lines of the river were precisely digitized in GIS environment using the on-screen digitization method (Roy and Sinha 2007; Hazarika et al. 2015). The upstream to the downstream section of the river extends from Gopalpur to Dakshin Bagundi and is divided into four equal segments (approximately, 13 km of each segment) based on the position of the river in 2016. Equal numbers of cross sections were created in each segment at an unequal distance from north to south and suitable sites of cross sections were chosen based on visual analysis of satellite images where channel shifting and morphological changes of the river is highest. The shifting of the left bank and the right bank was calculated from the two consecutive years of satellite images through image overlay analysis, and segment-wise mean shifting of the channel was calculated from 1976 to 2016. Each cross section was alphabetically arranged from upstream to downstream. The shifting of the channel shows positive change (+) if the channel progressively widens and the riverbanks move away from each other. The shifting is negative (–) if the riverbanks move towards each other and cause channel narrowing (Fig. 2). The rate of erosion of the river was calculated based on the following formula:

$$\text{Average rate of erosion} = \frac{\text{mean channel shifting (m)}}{\text{time (number of years)}} \quad (1)$$

The bank lines of the river were vectorized using polygon feature and overlay analysis was done for the successive 2 years to identify the zone of erosion and deposition. The zone of erosion was identified when the river was migrating into a new position relative to its older position and the zone of deposition was identified when the channel continuously maintained its actual flow path. There are four zones identified, namely, area under erosion, deposition, unchanged and migrated area in the GIS platform. The method of this entire work is almost identical to that of the previous works of Debnath et al. 2017; Chakraborty and Mukhopadhyay 2015; Hazarika et al. 2015.

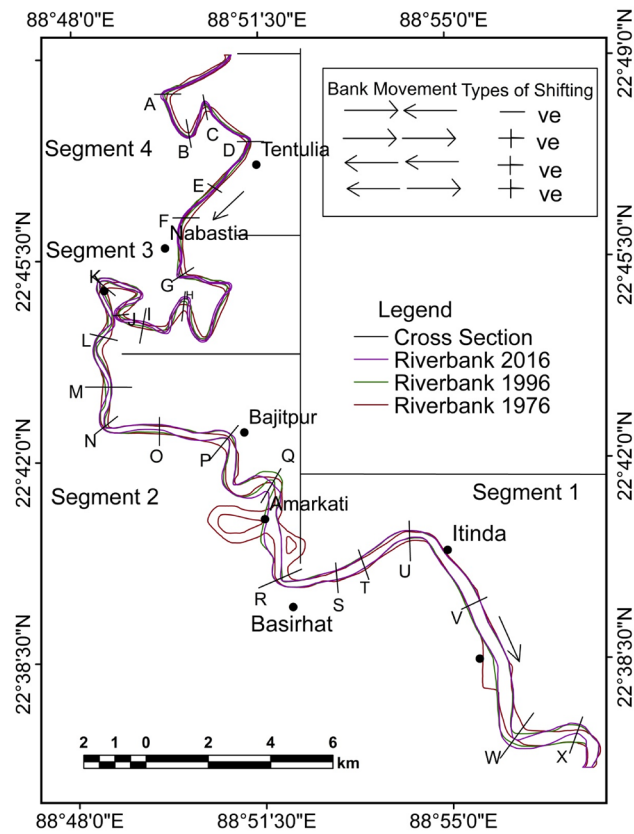


Fig. 2 Assessing the temporal shifting of bank lines using cross sections (1976–2016)

The bank vulnerability zone of the river was prepared based on channel avulsion modeling considering the total amount of erosion and the erosion rate from 1976 to 2016. The rate of the channel avulsion was measured from the channel centreline position in 1955 and 2016, and the avulsion rate was recorded based on cross sections. A 2 km buffer was created from the river and the kriging method using spherical semivariogram model was applied to identify the vulnerable bank zone. In this model, optimal weight is assigned to an unknown value for the calculation of the unknown one. The basic Eq. (2) applied in this study for ordinary kriging is as follows (Pal et al. 2016; Bajjali 2018):

$$K(d) = \frac{1}{2n} \sum_{i=1}^n (Z(x_i) - Z(x_i + d))^2, \quad (2)$$

where d represents the distance between known points, n is the number of samples separated by d , and Z is the attribute value (elevation known points). The equation indicates that semi-variance is expected to increase as d increases.

The channel width is considered as the perpendicular horizontal distance between the left bank and the right bank of the river. The channel width, based on cross sections,

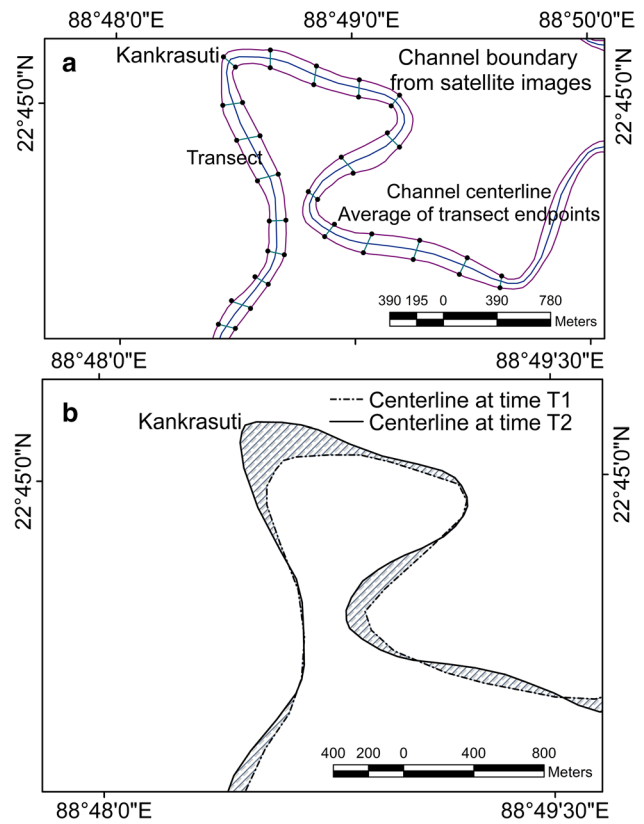


Fig. 3 Determination method of channel activity

and average channel width, based on the segments, were calculated for the year 1976, 1996 and 2016.

Channel activity was determined by measuring the area confined by consecutive channel centrelines that were determined by calculating the area of series of polygons encircled by intertwined, digitized centrelines (MacDonald and Parker 1994). Thereafter, the sum of polygon areas of each bend was divided by the length of the earlier of the two centrelines and the time between the two coverages (Fig. 3). The following formula (Eq. 3) is used to delineate channel activity.

$$\text{Channel activity} = (\text{shaded area}) \div (\text{length of T1 centreline}) \div (T2 - T1) \dots \dots \text{MacDonald and Parker 1994.} \quad (3)$$

Channel activity was calculated during pre-brick kiln and post-brick kiln periods for the comparative study of the river’s response to land-use changes within the meander loop over time.

Field survey and data collection

The field survey was conducted for the cross section survey of the river. The stretch of 52 km from Gopalpur to Dakshin Bagundi was selected for the cross-sectional survey. In this

study, eight cross sections were selected at an irregular distance from the upper to the lower course of the river (Fig. 4; Table 2). Three permanent benchmarks were identified in the study area (Swarupnagar: 4 m, Baduria and Basirhat: 3.14 m) and the respective benchmark was shifted by profile survey near the riverbank in every case of cross profile survey. The depth of the river was measured by modern eco-sounder with the GPS collaboration method. The velocity of the river was measured using Price AA current meter. The

velocity of tidal current and the ebb current was measured on a new moon day during pre-monsoon, monsoon and post-monsoon periods. The velocity was measured at a different depth from a small boat which holds a stationary position at the respective location and recorded the average velocity of the river of that respective place. The weather was calm and the velocity of the wind was mild during the measurement of velocity. The total revolution of the cup of the current meter was measured for 30 s. After that, the following formula was

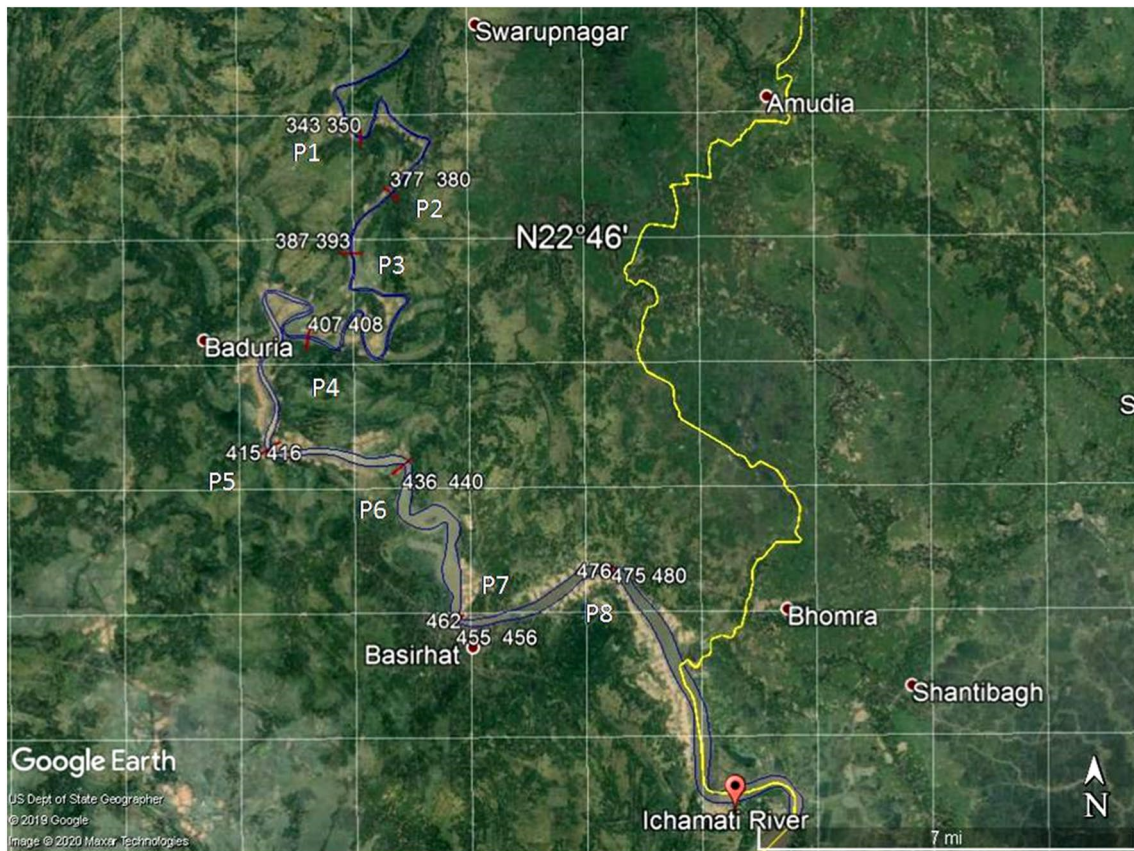


Fig. 4 Location of eco-sounder readings for drawing cross sections

Table 2 Geographical location of cross-sections survey

| Sl. no. | Name of profile | Coordinates | Location | Direction |
|---------|-----------------|---|---------------|----------------|
| 1 | P 1 | 22°47'37.52" N 88°50'12.19" E 22°47'38.60" N 88°50'11.92" E | Ramchandrapur | North to South |
| 2 | P 2 | 22°46'37.52" N 88°50'34.30" E 22°46'39.72" N 88°50'31.59" E | Gokulpur | |
| 3 | P 3 | 22°45'38.56" N 88°49'59.28" E 22°45'39.18" N 88°50'01.38" E | Nabastia | |
| 4 | P 4 | 22°44'24.51" N 88°49'12.91" E 22°44'27.44" N 88°49'13.12" E | Kankrasuti | |
| 5 | P 5 | 22°42'35.58" N 88°48'29.76" E 22°42'37.44" N 88°48'32.24" E | Baduria | |
| 6 | P 6 | 22°39'49.83" N 88°51'50.56" E 22°39'50.42" N 88°51'46.52" E | Bajitpur | |
| 7 | P 7 | 22°39'49.83" N 88°51'50.56" E 22°39'50.42" N 88°51'46.52" E | Basirhat | |
| 8 | P 8 | 22°40'37.77" N 88°54'27.11" E 22°40'44.34" N 88°54'28.85" E | Itinda | |

used, velocity (v) = 0.0069 + RPS (revolution per second) 0.0838. The discharge of the river was measured by using the following formula (Eq. 4):

$$\text{Discharge} = \text{cross-sectional area of flow} \times \text{mean flow velocity.} \quad (4)$$

The rigorous field survey was done from 2017 to 2018 for the collection of primary data from brick kilns to know the production status of bricks in the study area. The total numbers of brick kilns along the river were counted from high-resolution Google Earth image and also verified through questionnaire survey during field investigation. The volume of sediment extraction of each brick kiln from the river was calculated by multiplying the volume of a single mud brick and average production rate of bricks of that respective brick kilns during the survey period. The areal expansion of brick kilns was measured from multi-temporal satellite images using polygon feature in Arc GIS environment. To understand the temporal change of the erosion rate of the river with relation to the areal expansion of brick kilns, the studied reach of the river was divided into four equal segments with an equal number of cross sections in each segment. The average rate of erosion was calculated for each segment for the period of 1976–1996 and 1996 to 2016. Thus, collected primary data were arranged, analyzed and represented in a systematic way to fulfil the aim of the present research.

Results and discussion

The downstream course of the Ichamati River is characterized by frequent channel avulsion, meanders and oxbow lakes. The self-regulating process response system of the river has been transformed into a control system because of human interventions. The research work is presented in two broad sections. The first section discusses the morphological change of channel behaviour in the last four decades (1976–2016) and the next part deals with the underlying causes responsible for changing the channel behaviour of the river.

Channel behaviour of the Ichamati river

To study the channel behaviour of the river, the rate of channel shifting, channel migration, bank vulnerability and channel width were calculated and discussed in detail below.

Rate of channel shifting

Channel shifting of the Ichamati River has been delineated from 1976 to 1996 and 1996 to 2016. The study reveals that the mean channel shifting of the river from 1976 to 1996

was 89.36 m and from 1996 to 2016, 58.69 m (Fig. 5). There has been a controlled movement of the bank lines at the human–nature interface in the last two decades as shown in Table 3. The rate of channel shifting is comparatively high (4.47 m year^{-1}) from 1976 to 1996 as compared to 1996 to 2016 (2.96 m year^{-1}).

Rate of channel migration

The selected downstream part of the Ichamati River was divided into four equal segments to minutely study the zone of erosion, zone of deposition, unchanged area and historical migrated area. The study reveals that the area under erosion and deposition is 2.28 and 6.7 sq. km, respectively. This high rate of accretion indicates the gradual decaying of the river. The Ichamati River meanders in nature and is characterized by frequent channel avulsion throughout its course. However, the average rate of channel migration is comparatively low (1.5 m year^{-1}) from 1996 to 2016 in comparison to 1976–1996 (4.5 m year^{-1}) (Fig. 6). The Ichamati River receives a mean annual rainfall of 1650.80 mm. The heavy rainfall in the monsoon season increases the velocity and discharge capacity of the river. The rate of erosion is relatively high in the monsoon season due to high discharge. The rate of water discharge at Basirhat and Tentulia is 1010.0 and $58.5 \text{ m}^3 \text{ s}^{-1}$ in the pre-monsoon, 3540.0 and $210.20 \text{ m}^3 \text{ s}^{-1}$ in the monsoon and 1038.0 and $92 \text{ m}^3 \text{ s}^{-1}$ in the post-monsoon periods, respectively (Source: Field Survey in 2018). The Ichamati River has hardly received any water from its parent source of Mathabhanga River during the lean period; therefore, the river faces an acute problem of siltation on the riverbed. The tidal period of the river is 7 h per day which is helpful to carry bed load during this time, but the river faces huge sedimentation on the riverbed due to lack of undercurrent during ebb tide.

Channel avulsion and bank vulnerability

The rate of channel avulsion is not uniform. It varies depending on various natural as well as anthropogenic factors. The bank vulnerability zone map has been prepared based on channel avulsion from 1976 to 2016. In this graphics, the dark shaded areas show high vulnerability (225 m) and the lighter areas show less vulnerability (121 m) (Fig. 7). The rate of channel avulsion is quite high at the meander loops. The average rate of erosion is 4.08 m year^{-1} and the mean channel avulsion rate is 3.84 from 1976 to 2016. The tidally active Ichamati River is highly influenced by monsoon rainfall. Therefore, the rate of erosion increases in the monsoon season as compared to the pre-monsoon and post-monsoon season. During the field investigation, it is observed that the soil composition of the riverbank is mostly medium to coarse sand.

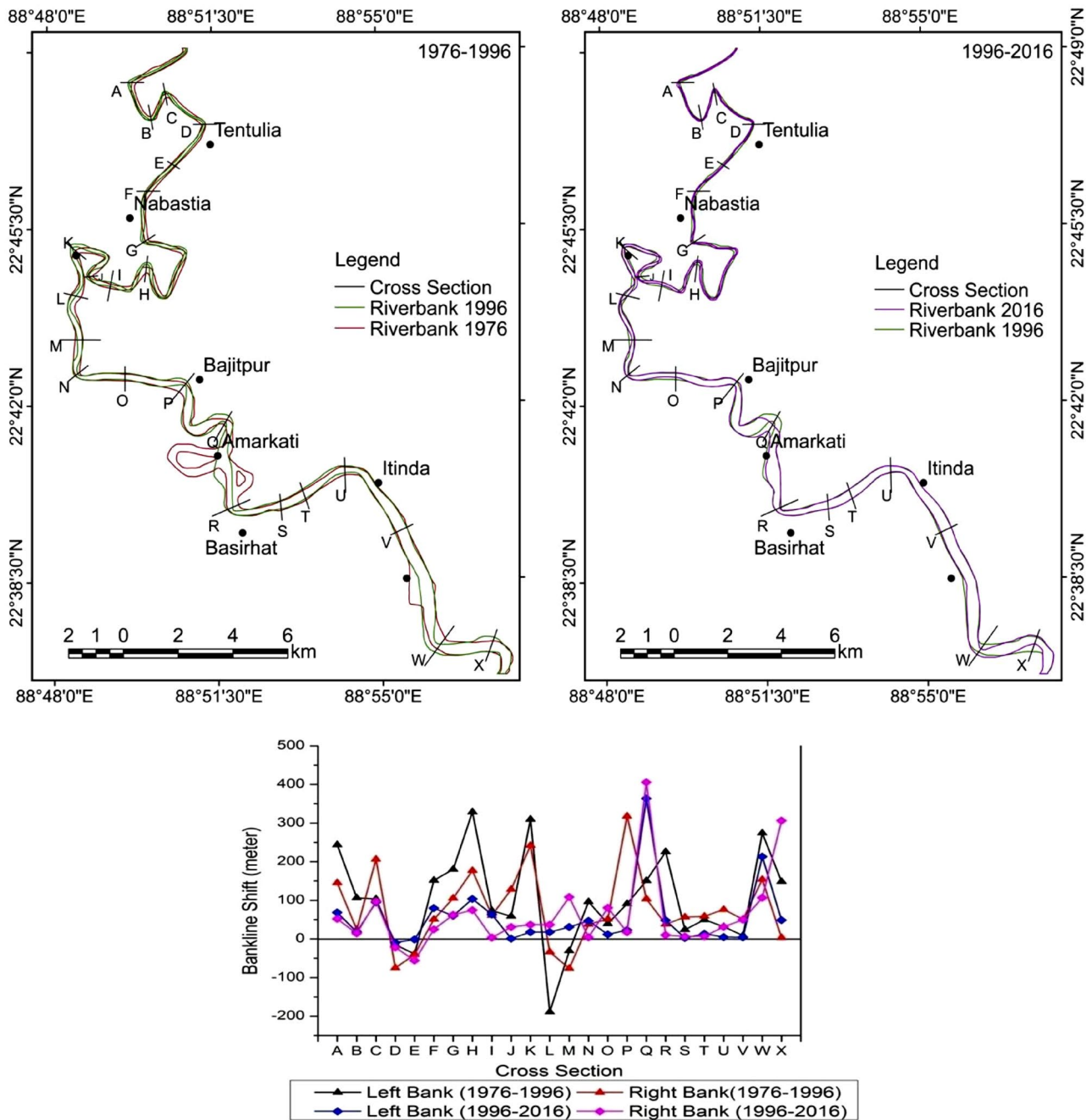


Fig. 5 Shifting of bank lines of Ichamati River (1976–2016)

As the soil cohesiveness of sand is very low, it is easily removed by water flow. Collapse and slumping, undercutting and subsidence, toe erosion, translational slide and lateral erosion are the most common types of bank erosion associated with bank vulnerability. The natural shifting of the river is also controlled by human intervention and locally changed the rate of channel avulsion. The river adjusts with the local environmental factors by the

erosion–accretion process and several meander formation throughout its course.

Change of channel width

The average channel width of the Ichamati River was 261.67 m in 1976, 186.92 m in 1996 and 149.68 m in 2016. The change in average channel width from 1976 to

Table 3 Details of bank line shifting of Ichamati River

| Variables | 1976–1996 | | 1996–2016 | |
|---|-----------|------------|-----------|------------|
| | Left bank | Right bank | Left bank | Right bank |
| Mean bank line shifting (m) | 100.98 | 77.72 | 55.24 | 62.13 |
| Rate of bank line shifting (m year^{-1}) | 5.04 | 3.89 | 2.76 | 3.10 |

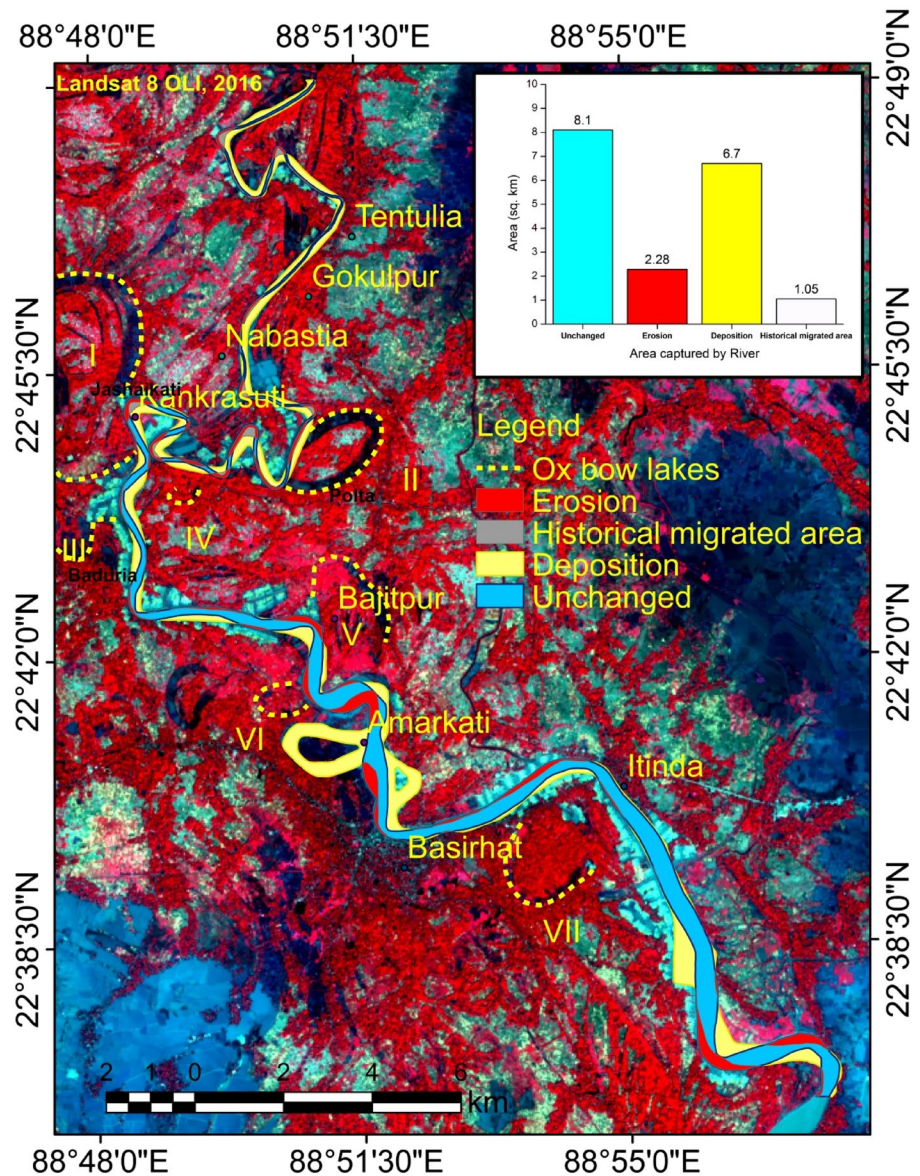
1996 is -3.73 and $-1.86 \text{ m year}^{-1}$ from 1996 to 2016. The segment-wise change of channel width has been calculated and is recorded in Table 4. The study reveals that the channel width has been gradually decreasing

since 1976. The narrowing of the river channel is more prominent in segment 3, which is -125.2 m . The rate of decrease of channel width was -2.0 m year^{-1} in Segment 1, $-3.05 \text{ m year}^{-1}$ in Segment 2, $-3.13 \text{ m year}^{-1}$ in Segment 3 and $-3.01 \text{ m year}^{-1}$ in Segment 4 during 1976–2016.

Major factors responsible for channel behaviour modification at the human–nature interface

Human activities play a significant role in changing channel behaviour and affect morphological as well as hydrological characteristics of the river. In this part, various types of human interventions on the river have been identified and discussed in detail.

Fig. 6 Historical channel migration of Ichamati River (1976–2016)



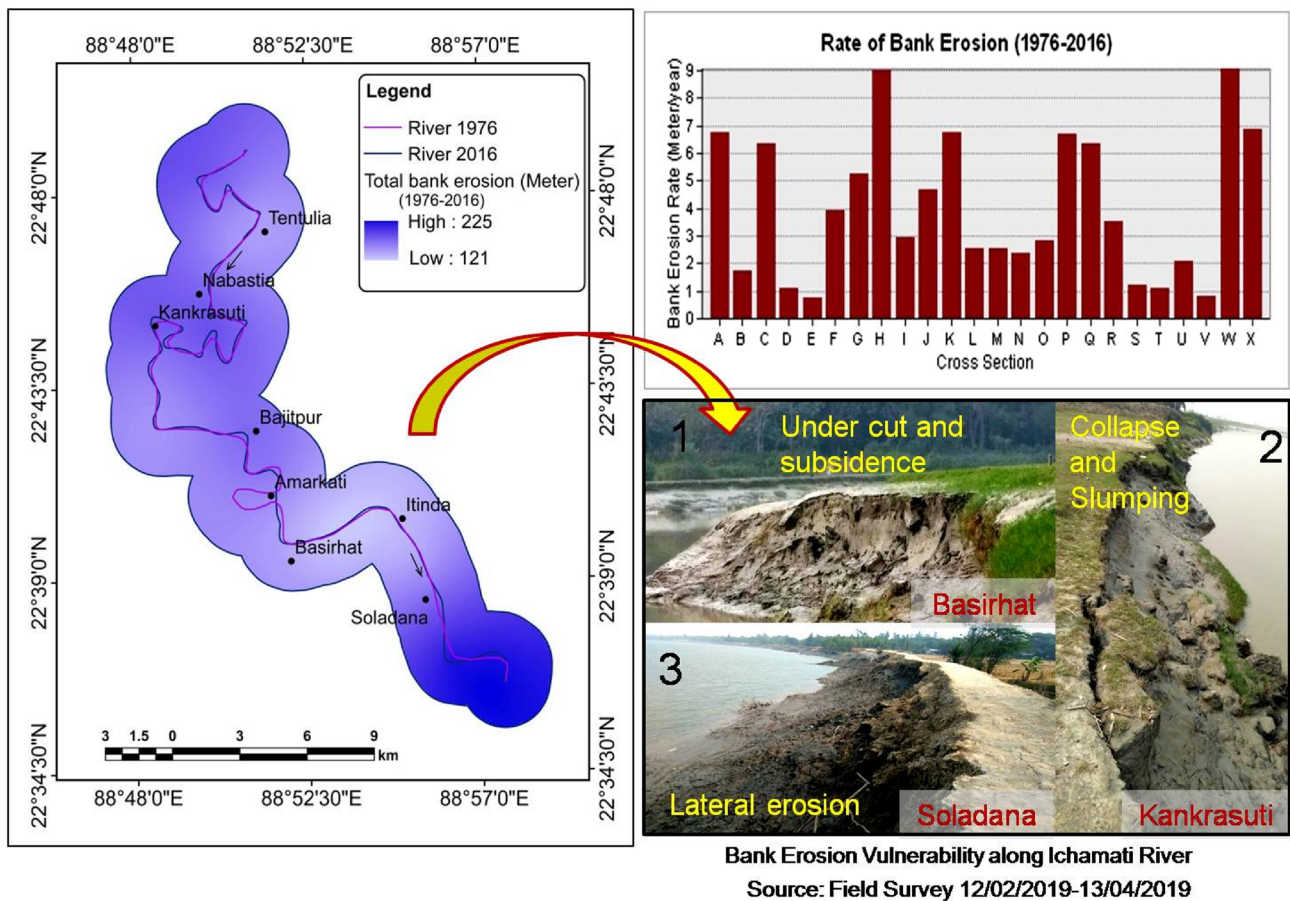


Fig. 7 Bank vulnerability zone based on channel avulsion modeling from 1976 to 2016 using kriging method

Table 4 Temporal variations in channel width (1976–2016)

| Channel width (m) | 1976 | 1996 | 2016 | 1976–1996 | 1996–2016 | 1976–2016 |
|-------------------|--------|--------|--------|-----------|-----------|-----------|
| Segment 1 | 387.98 | 384.32 | 307.76 | – 3.66 | – 76.56 | – 80.22 |
| Segment 2 | 288.75 | 196.73 | 166.66 | – 92.02 | – 30.07 | – 122.09 |
| Segment 3 | 204.72 | 104.48 | 79.52 | – 100.24 | – 24.96 | – 125.20 |
| Segment 4 | 165.23 | 62.15 | 44.79 | – 103.08 | – 17.36 | – 120.44 |

Growth of brick kilns and its impact on the channel behaviour

There are nearly about 208 brick kilns on both sides of the river course which have a direct or indirect impact on the channel behaviour. Brick kilns are rapidly expanding along the riverbank depending on the sediment supply, source of freshwater, availability of cheap labour, transport facility and huge demand of brick in this densely populated region. The growth of brick kilns is regulated by the Pollution Control Act of 1986. According to the act, the setup of any brick kilns must be ensured at a range of 200 m away from a major river and habitable area. However, mushrooming expansion of brick kilns has been observed over time due to

lack of effective implementation of the law. The mobility of the bank line is controlled by pre-delineated limits of brick kilns. The areal growth of brick kilns and mean channel shifting from 1976 to 1996 were 5.4 sq. km and 89.35 m, respectively, and 10.9 sq. km and 58.69 m, respectively, from 1996 to 2016. Segment-wise rate of bank erosion was calculated in response to spatial growth of brick kilns of that respective segment. The analysis reveals that the rate of erosion continuously decreases with the expansion of the brick kilns over time. The mean rate of riverbank erosion was 5.5 m year⁻¹ during 1976–1996 and reduced to 3.1 m year⁻¹ during 1996–2016 (Fig. 8). The rate of channel migration is also locally controlled by the growth of brick kilns. The correlation value between segment-wise expansion of brick

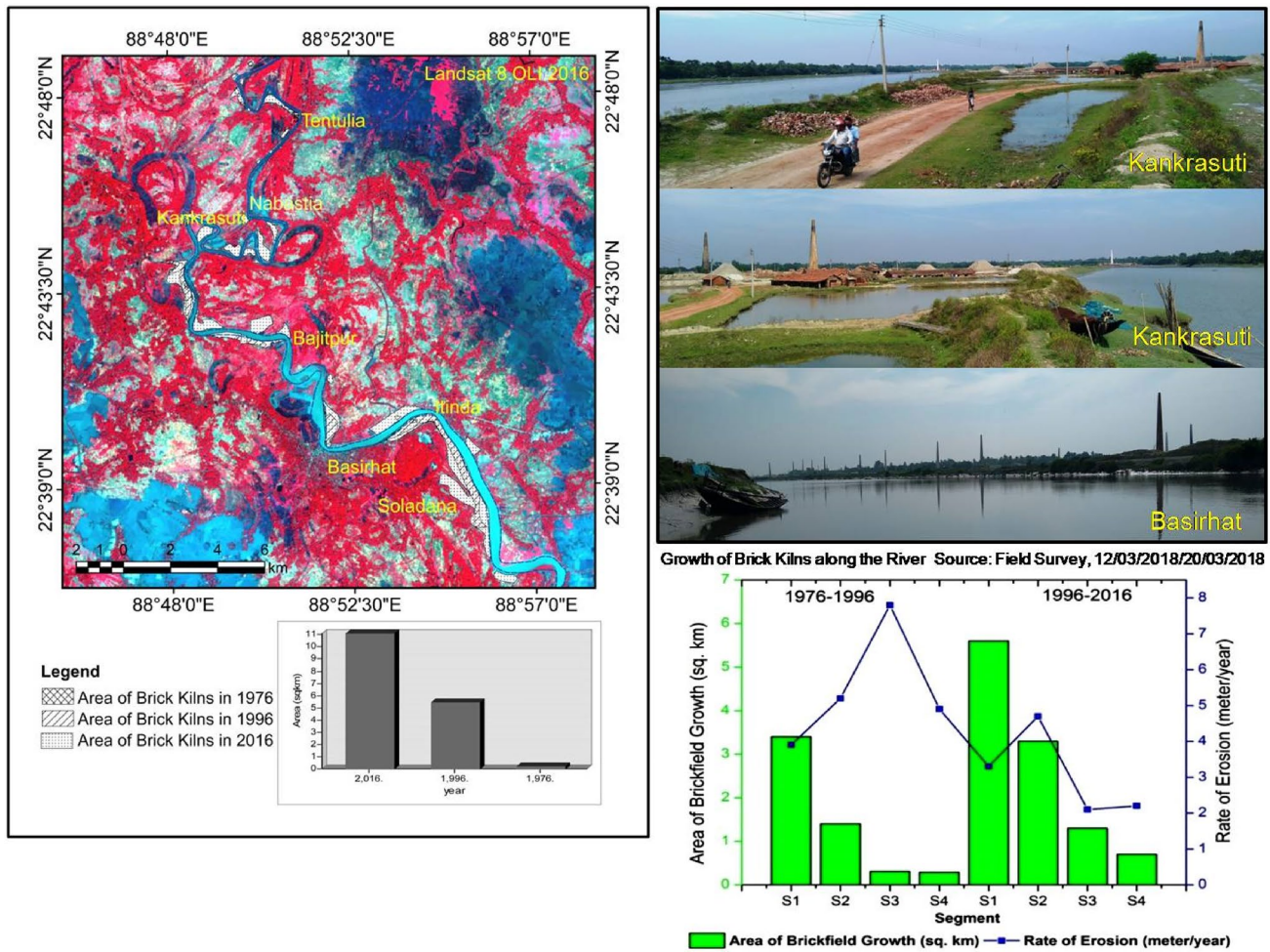


Fig. 8 Expansion of brick kilns with relation to rate of erosion (1976–2016)

kiln area and mean channel shifting was positive: $r = 0.39$, $r^2 = 0.15$ from 1976 to 1996, whereas the correlation value was negative: $r = -0.6$, $r^2 = 0.4$ from 1996 to 2016. Therefore, the growth of brick kilns has some local influence in controlling the natural shifting of the riverbank.

Collection of sediment and its impact on the Ichamati River

The production of bricks depends on various natural as well as socioeconomic factors such as rainfall, sediment supply, availability of freshwater, labour force and demand of bricks in local areas. During the field survey, it is observed that the average production rate of bricks in the study area is 58.5 lakh year⁻¹ during 2017–2018. 117 brick kilns produced bricks less than the average rate of production and 49 brick kilns that produced bricks more than the average rate of production (Fig. 9). Several sediment reservoirs have been dug along the riverbank to store sediment. During high tide, tidal water enters into these reservoirs through the inlet system and

drain out into the river through the outlet system during low tide. The rate of siltation on the riverbed is much higher than the extraction rate of sediment from the river. The carrying capacity of the river decreases due to excessive sediment load. As a result, large size river chars appear in the river, especially during low tide (Fig. 10). Sediment is extracted from these chars by local brick kilns and used as a source of raw material for brick production. To estimate the overall rate of sediment extraction from the riverbed, water and sediment budget of the Ichamati River from Gopalpur to Dakhin Bagundi has been prepared based on the quantitative analysis of the questionnaire survey data and presented accordingly in Table 5. The study shows that 22.45% of tidal water is extracted by brick kilns in a day, which is 3.28% of the total discharge of the river.

Construction of embankment, bridge pillars and its impact on the river

The riverbank of Ichamati is protected by both concrete and earthen embankment. The construction of embankment

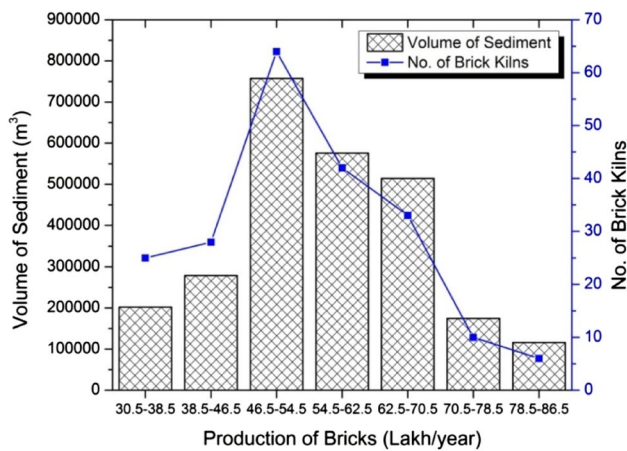


Fig. 9 Volume of sediment used and production status of bricks in brick kilns

holds water within the channel and a huge amount of dissolved sediment presence in river water gradually silted on the riverbed. Besides, construction of three major bridges over the river and their concrete pillars on the riverbed (Kalanchi Bridge in Gaighata area, Tentulia bridge at Swarnpurnagar area and Basirhat bridge at Basirhat town) have also affected the flow and velocity of the river. As a result, the rate of sedimentation increases on the riverbed and the riverbed is gradually uplifted over time. To estimate the upliftment rate of the riverbed, a temporal survey was conducted to draw cross profiles of the river in some selected places. The survey reveals that the average cross-sectional area of the river decreased from 486.53 to 433.35 sq. m from 2013 to 2018. The depth of the river (Gopalpur to Dakhin Bagundi) also decreases with time. The cross profile survey shows that the average depth of the river was 3.9 m in 2013 and 3.45 m in 2018. The rate of riverbed upliftment was estimated as 9 cm year⁻¹ from 2013 to 2018 (Fig. 11; Table 6). The decrease of river cross-sectional area is an indicator of river decaying.

Unsystematic land use and its impact on the Ichamati River

In the study area, 70% of the annual rainfall was recorded in the monsoon season (June to September). The Ichamati River carries freshwater. Therefore, farmers depend on the canal’s water directly connected with the river and available groundwater sources for irrigation in the dry season. At Tentulia, the tidal input in the river is $292,896 \times 10^4$ L. There are 25 (HP 24.5) river pumps between Tentulia and Kalanchi. These pumps jointly withdraw a huge amount of water ($10,071 \times 10^5$ L water per day) from the river which decreases the overall discharge capacity of the river (Mondal and Satpati 2019). The discharge capacity of the river is

very less in the dry season because of excessive pumping of river water for irrigation purpose. As the river discharge is not sufficient enough to carry out the excess sediment load, it further increases sedimentation on the riverbed. Besides, continuous human encroachment through expansion of fisheries, waste dumping activities and illegal construction on the riverbed are some common problems affecting the riverine processes.

The human-induced obstructions in the neck cutoff process

Ichamati River forms several meanders and cutoffs throughout its course. The cutoff formation has been interrupted by human-made obstructions in various places. For example, the Kankrasuti–Faridkati meander loop in Baduria block is chosen for a case study. The narrow passage of the meander neck is protected by local brick kiln owners of Faridkati for their vested interest of land. The distance between two necks was 135.96 m in 1976, 82.66 m in 1996 and 14 m in 2016 (Fig. 12). The rate of erosion was 2.66 m year⁻¹ from 1976 to 1996 and 3.44 m year⁻¹ from 1996 to 2016. The study shows that the rate of erosion increased in the last two decades (1996–2016). If the rate of erosion remains the same, there is a possibility of neck cutoff within 10 years from 1996, but this meander neck is protected by anti-erosion layers. The formation of neck cutoff allows the river to flow into a new course, leaving the loop as an abundant part of the channel. Therefore, it hampers the production of brick inside the meander loop due to the lack of sediment supply and creates the problem of a land dispute between the local people of Faridkati and Kankrasuti. If the meander neck joined, the brick industry within the meander loop would collapse, being isolated from its original place. Therefore, the present brick kiln owners of Faridkati are always trying to protect this narrow passage of meander neck for their vested interest of land.

In the Kankrasuti–Faridkati meander loop, the channelization of river water through canals has been increasing after 2005. It has reduced the consistent flow velocity of running water and decreased the rate of channel erosion. The cutoff formation process has lengthened indirectly due to these channelization activities at the meander loop. To understand the controlled movement of the meander loop at the human–nature interface, the channel activity has been calculated for pre-brick kiln and post-brick kiln situation in the GIS platform. The mean channel activity was 8.1 m year⁻¹ during 1976–1996 when the land within the meander loop was primarily used for agricultural activities, but after 1996, the land was used for brick production, pisciculture and agricultural purposes. As a result, the mean channel activity has been reduced in the last two decades (1.76 m year⁻¹). The study reveals that the channel activity has been decreasing in



Fig. 10 Sediment deposition on riverbed and extraction of sediment by brick kilns

the post-brick kilns period (1996–2016), which is an indication of human dominance on natural channel mobility.

Conclusion

The hydrological and morphological characteristics of the river have been changed by human intervention over time. In recent decades, unsystematic growth of brick kilns, extraction of sediment, sand mining and channelization activities have been decreasing the flow and discharge capacity of the

river. The study reveals that 22.45% of tidal water has been extracted from the river per day which constitutes 3.28% of the river discharge. The depth as well as the cross-sectional area of the river has been gradually decreasing from 2013 to 2018 as a result of rapid siltation on the riverbed. The rate of riverbed upliftment is 9 cm year^{-1} , which indicates gradual decaying of the river with time. The morphological characteristics of the river have also been modified due to mushrooming expansion of brick kilns along the downstream part of the river. The rate of average channel shifting has been decreasing due to the expansion of brick kilns,

Table 5 Water and sediment budget of the Ichamati River from Gopalpur to Dakhin Bagundi

| | |
|---|---|
| Rate of discharge | 3540 m ³ /s or 3,540,000 L |
| Total tidal period | 7 h |
| Total incursion of tidal water | 3,540,000 × 3600 = 12,744 × 10 ⁶ 12,744 × 10 ⁶ × 7 h = 89,208,000,000 L/day |
| The volume of a single brick | 2.34375 × 10 ⁻⁰³ m ³ |
| Average rate of production in a brick kilns | 60 × 10 ⁵ |
| Total number of brick kilns in the study area | 208 |
| Total production in the study area | 1248 × 10 ⁶ |
| Volume of sediment used | (2.34375 × 10 ⁻⁰³) × (1248 × 10 ⁶) = 2,925,000 m ³ or 2925 × 10 ⁶ L (22.45% of tidal water/day) |
| Percentage of total discharge | 3.28% |

Calculated by the researcher based on field survey data from October 2017 to February 2018

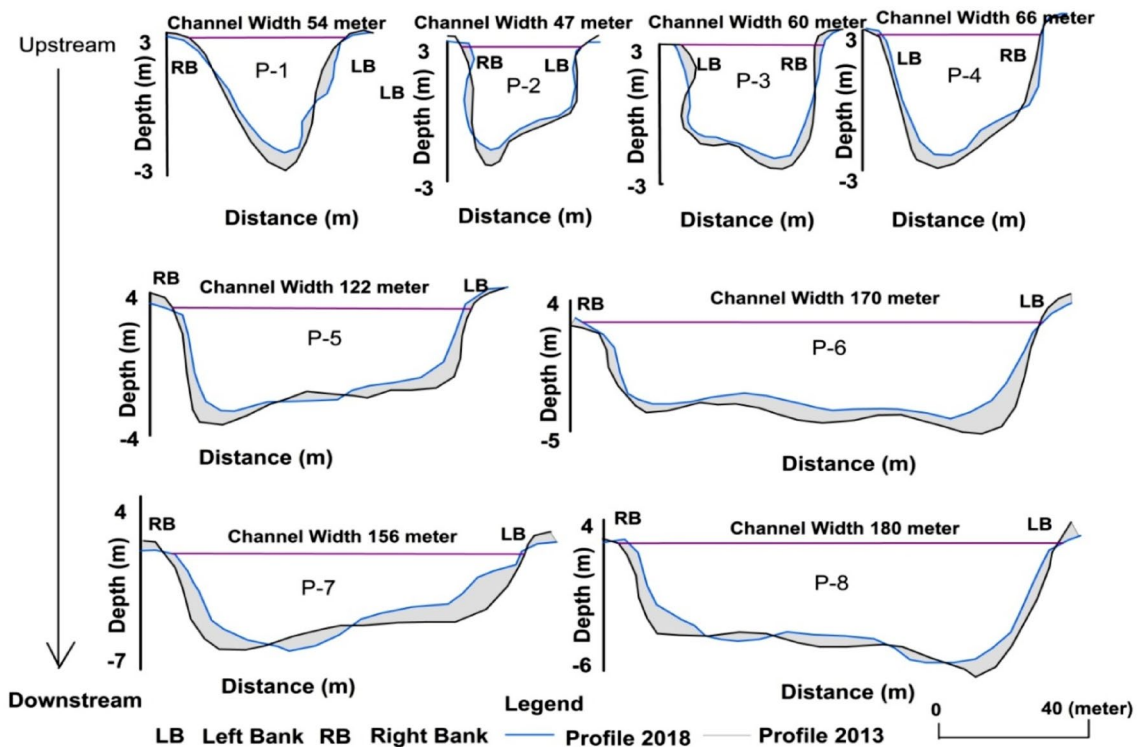


Fig. 11 Spatio-temporal changes of the river cross profiles (2013–2018)

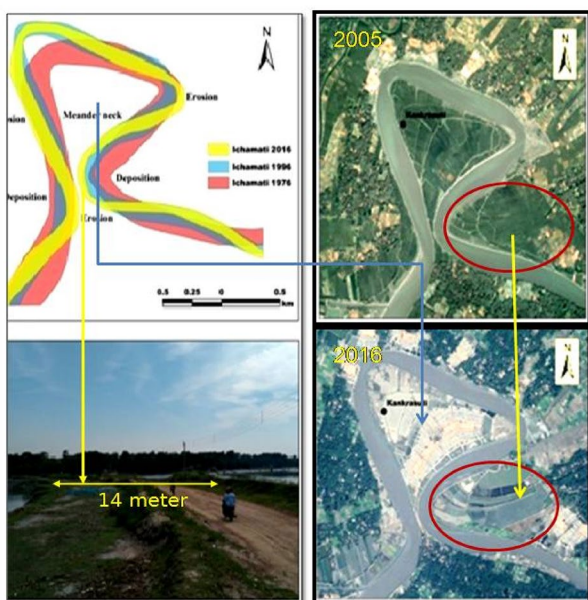
89.36 m from 1976 to 1996 and 58.69 m from 1996 to 2016. The rate of erosion was also reduced from 5.5 m year⁻¹ to 3.1 m year⁻¹ during 1976–1996 and 1996 to 2016 respectively. The mean channel activity at the Kankrasuti meander loop was reduced from 8.1 m year⁻¹ (1976–1996) to 1.76 m year⁻¹ (1996–2016) with time due to various land use activities within the meander loop. The rate of channel avulsion is locally controlled and varies due to human-imposed barriers at various places. The mean channel width was also reduced from 261.67 m in 1976 to 149.68 m in 2016. The interruption in river flow due to the construction

of bridge pillars and embankments has affected the fluvial process of the river. All these activities collectively affect the hydrological and morphological behaviour of the Ichamati River. It is not possible to take immediate control over these activities, but proper planning and management strategies urgently need to be implemented to save the river from decaying. It is noteworthy to mention that more in-depth study incorporating various hydraulic parameters, tidal magnitude and morphological attributes are essentially required for the advanced level study of the channel behaviour on the lower Gangetic plain.

Table 6 Cross section-wise area and depth of the Ichamati River

| CS | Distance (km) (from Goplapur) | Average Depth (m) | | Cross-sectional area (m ²) | |
|-----|----------------------------------|-------------------|------|--|------|
| | | 2013 | 2018 | 2013 | 2018 |
| P 1 | 4.16 | 2.5 | 2.3 | 135 | 124 |
| P 2 | 9.40 | 2.6 | 2.2 | 122 | 103 |
| P 3 | 11.71 | 2.7 | 2.3 | 162 | 138 |
| P 4 | 20.62 | 2.9 | 2.4 | 184 | 158 |
| P 5 | 29.28 | 3.7 | 3.2 | 427 | 390 |
| P 6 | 33.46 | 4.8 | 4.2 | 850 | 714 |
| P 7 | 39.53 | 6.5 | 5.9 | 967 | 920 |
| P 8 | 44.48 | 5.8 | 5.1 | 1044 | 918 |

Field survey from 2013 to 2018



Human intervention at meander loop **Channelization of river water**

Fig. 12 Human intervention at Kankrasuti–Faridkati meander loop

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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