Journal of Indian Geomorphology
Volume 7, 2019 ● ISSN 2320-0731
Indian Institute of Geomorphologists (IGI)

Hydro-Geomorphic Analysis of a Meandering Bend of the Ichhamati River at Hugle-Mathpara Region in North 24 Parganas District, West Bengal

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Abstract: *The Ichhamati River is well known for its transboundary flow through India and Bangladesh. A major part of the river traverses through North 24 Parganas District in West Bengal, which mostly comes under the tidal regime. In course of time, the non-tidal course of the Ichhamati has degenerated. However, the lower course of the river remains active throughout the year due to tidal activity. In the middle reach, tidal influence reduces significantly toward upstream along with the presence of a number of angular meandering bends. The study area, located in Baduria and Swarupnagar blocks of North 24 Parganas, is characterised by a meandering bend of Ichhamati that has changed both spatially and temporally. To show the morphological changes in this area, SoI topographical maps and satellite images have been used, complemented by field surveys. Water samples were collected to find out the variation in sediment concentration during flood and ebb tide.*

It is found that the alignment of the Ichhamati meander at Hugle-Mathpara area has changed from curved to angular pattern in the last 100 years. The altered meander configuration can be related with tidal movement in the river. During the same period, the channel width has decreased 2.2 times due to sedimentation. Due to this, the present channel is unable to contain discharge within its banks during high tides. The channel discharge varies significantly during a tidal cycle. There is noticeable tidal asymmetry in the flood-dominant Ichhamati channel that causes deposition of sediment load on the riverbed. Consequently, the natural flow of the river is hindered which may lead to further degeneration of the river in near future.

Introduction

Meanders are result of any river taking a favoured route, determined by channel gradient, cross-sectional area and the ratio of the discharge rate to the carried load. Meanders decrease the stream gradient until equilibrium between the entrainment and transportation capacity of the stream is reached (Charlton, 2008). All natural rivers have a predisposition to deviate from a straight course and increase their sinuosity (Kale and Gupta, 2001). A stream of any volume may develop a meandering course, alternately eroding sediments from the convex side of a bend and depositing them on the concave side (Graf, 1984; Julien, 2002). Once a channel begins to follow a meandering course, the amplitude and concavity of the sinuous loops increase progressively due to helicoidal flow that transports the eroded material toward the inside bend, therefore leaving the convex bend unprotected and vulnerable to lateral erosion (Lewalle, 2006). Meandering also allows any stream to adjust its length.

The tides cause periodic fluctuations in sea level, which diurnally affects the rivers of coastal or estuarine area. Tidal influence varies from river to river. In a coastal setting, tidal currents are unique among the processes responsible for sediment transportation and deposition due to their regularity (Dalrymple and Choi, 1978). The flood tidal current brings sediment into the river channel, while the ebb tidal current carries out sediment to the sea. The Ganga Delta in South Asia, where the tidal flow funnels into various river mouths, is characteristically macro-tidal with spring tidal range of more than 4 m (Bandyopadhyay, 2000; Kale and Gupta, 2001). The position of the Ganga delta at the apex of the Bay of Bengal led to the development of large tidal amplitudes in its coastal part (Chatterjee *et al.*, 2013). This causes the tidal current to move into the interior of the delta twice daily, thus maintaining six large estuaries and a complicated network of creeks and intervening mangrove islands of Sunderbans (Bandyopadhyay *et al.*, 2014). In the Indian part of the delta, the westernmost Hugli and the easternmost Hariabhanga estuaries possess crucial links to the upcountry rivers. The Hugli experiences a time-velocity asymmetry in tidal movement, as the flood tide duration is only 3 hours within a 12.4 hour tidal cycle (Sanyal and Chatterjee, 1995). This causes a net landward movement of sediment (Ghotankar, 1972). Tidal asymmetry is predominant in the creeks and estuaries of the Sundarbans (Chatterjee *et al.*, 2013). This type of asymmetry is expected in the tidal part of the Ichhamati River, which is contributed by the macro-tidal Hariabhanga estuary.

The evolution of the Ganga Delta started during the Pliocene-Pleistocene, when the Ganga along with its tributaries entered the Bengal Basin (Goodbred and Kuehl, 2000; Morgan and McIntire, 1959; Mukherjee *et al.*, 2009). It acquired its present form following the last Holocene transgression and the delta building process is still continuing (Oldham, 1870; Reaks, 1919; Fox, 1938; Bagchi, 1944; Niyogi, 1975; Umitsu, 1993; Allison *et al.*, 2003; Goodbred *et al.*, 2003; Bandyopadhyay, 2007). The Ichhamati is a major distributary of the Ganga Delta. Flowing through India and Bangladesh down to the Bay of Bengal, this transboundary river links the mature upper part of the Ganga Delta to the active lower delta. The off-take of the Ichhamati River is located near Majhdia in Nadia district of West Bengal, where the Mathabhanga course bifurcates into two branches — the Churni and Ichhamati. The Ichhamati headwaters remain completely dry during the lean season and receive water only during the monsoons (Bandyopadhyay *et al.*, 2014). In the course of time, the 155 km long non-tidal upper course of the Ichhamati has shrunk considerably due to degeneration (Bandyopadhyay *et al.*, 2015). The Ichhamati has joined the palaeocourse of Jamuna near Tipi in North 24 Parganas District (22.8419°N, 88.8420°E, Fig. 1). Their confluence also marks the approximate northern limit of tidal propagation from the Bay of Bengal at present. About a century ago, the tidal flow used to reach Bangaon in North 24 Parganas District (Addams-Williams, 1919; Reaks, 1919), which is located 48 km upstream from the Jamuna confluence. The 195 km long lower course of the river (from the Jamuna confluence to the mouth of the Hariabhanga estuary) remains active throughout the year due to tidal activity. However, the tidal influence significantly reduces upstream along with the presence of a number of angular meandering bends, which cause reduction of flood tide velocity. A recent study by Mondal *et al.* (2016) revealed the gradual decay of the middle reach of the Ichhamati River.

Study area

The study area is a part of the tidal course of the Ichhamati river. It is positioned almost in the middle part of the Ichhamati course (163 km from the source, 187 km from the estuary mouth). Located at Hugle-Mathpara region in Baduria (western/ right bank) and Swarupnagar (eastern/ left bank) blocks of North 24 Parganas district, the investigated area is characterised by a meander with three sharp angular bends (Fig. 2), the shape of which has changed through time and space.

Physiographically, this area is located

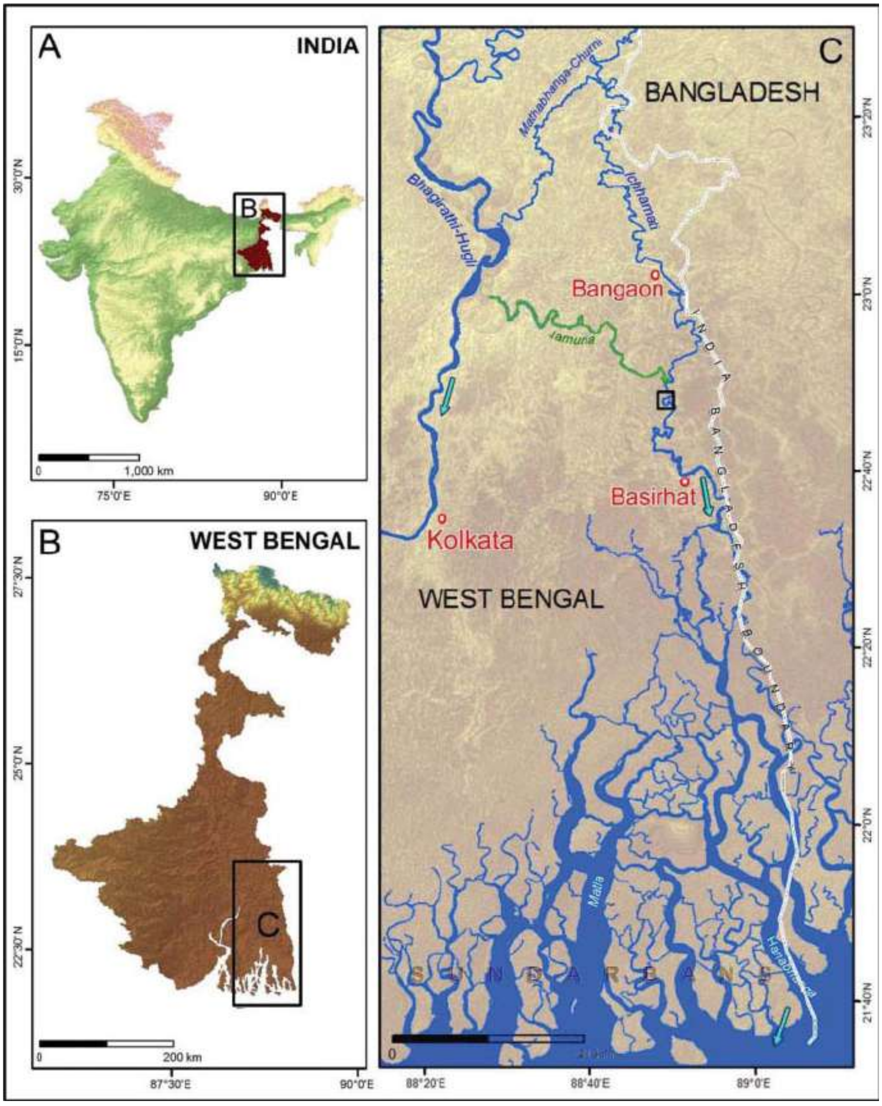

Figure 1. Location map of the study area along with important distributaries in the Indian part of the Ganga Delta. Blue and green watercourses in map C represent rivers and palaeochannels, respectively. The black square in map B represents the concerned area. The arrows indicate principal flow directions. Images: (A and B) SRTM GTOPO30 DEM (1 km), 01.12.1996; (C) 1 arc-second (30 m) SRTM DEM (v-3: Tile n22-e88), February 2000.

within the reclaimed part of the lower Ganga delta with active tidal influence. The entire region is underlain by young alluvium of the Holocene epoch (Bandyopadhyay *et al.*, 2014). The altitude range of the investigated area is 5–9 m, as found from the 1 arc-second (30 m) SRTM Digital Elevation Model (DEM). Associated with the active tidal course of the Ichhamati, a number of cut-offs can also be found near the study area. The tidal inflow brings substantial amount of silt and clay into the Ichhamati course. The study area is flooded occasionally, especially when excessive downpour occurs in the monsoon season. Flood embankments can be found on both banks of the river.

Due to the presence of fertile alluvial soil, the area is quite rich in agricultural resources. A number of brick kilns are located in this area, which directly rely on the sediment brought in by tidal inflow and monsoon discharge through the Ichhamati course.

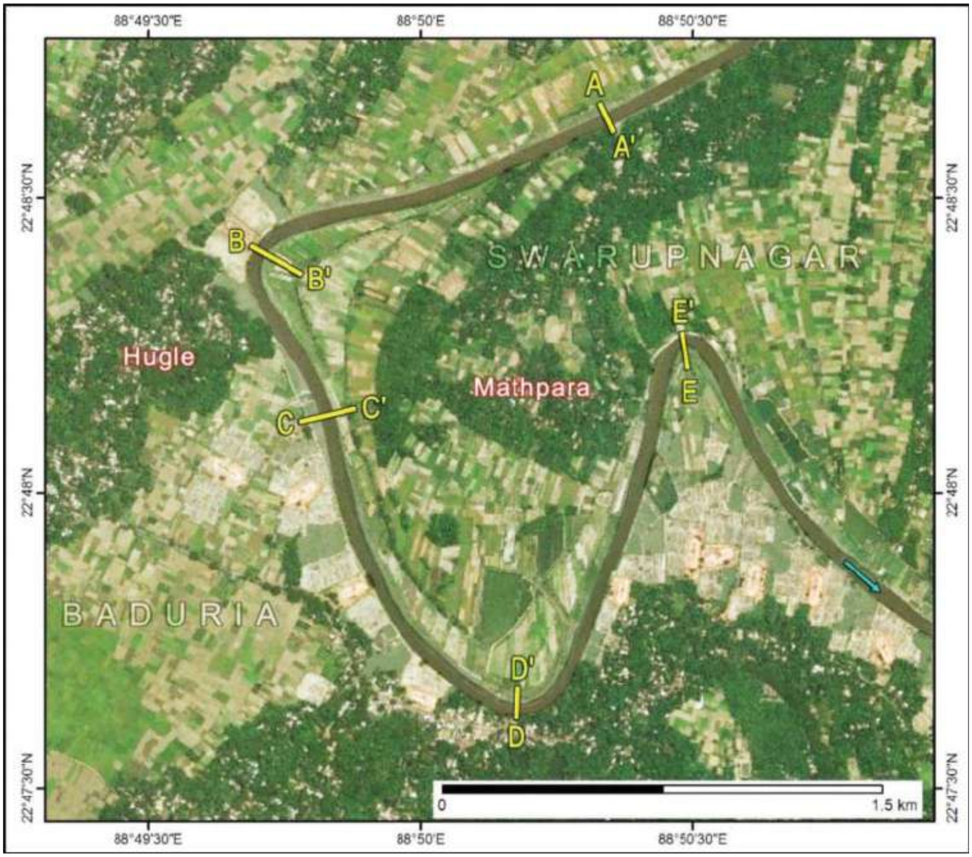

Figure 2. The present configuration of the meandering bend at Hugle-Mathpara region in North 24 Parganas district. Five cross-profiles shown in Fig. 4. are highlighted in the map. The arrow indicates the flow direction of the Ichhamati. Image: Quickbird (Bing Maps), 24.11.2012.

Materials and method

To evaluate spatio-temporal changes in the meander configuration, visual interpretation is done by using Survey of India (SoI) topographical maps and recent satellite images (Table 1). Later on, the change in the meander shape is explained by analyzing the complex tidal flow propagated through the Ichhamati channel.

To assess channel depth, width and riverbed configuration, a number of cross profile surveys were done at a number of locations within the meandering bend. Due to non-availability of SoI or any other bench marks, elevation of the positional pixels of the 1 arc-second (30 m) SRTM DEM (version 3) was used as reference. Velocity of the river during flood tide and ebb tide was measured by current meter, and these measurements were used for calculating the discharge of the channel in different stages of the tidal cycle.

In three successive observations during the full moon, third quarter and new moon period, the tidal cycle in the Ichhamati channel was observed. On the basis of these observations, the tidal range is calculated and present tidal limit is marked. One of the most important objectives of this study is to analyse the time-velocity asymmetry in the tidal reach of Ichhamati river. Hence, the flood tide and ebb tide durations were monitored. The readings were taken in the lean season (February and March, 2016) to nullify the effect of direct runoff from the monsoonal rainfall.

To find out the amount of sediment discharge through the tidal Ichhamati course, suspended sediment load is calculated. Subsequently, the results are collated with the tidal observations.

Results and discussion

Changes in meander configuration

The maps and images available for the region show significant alteration in the meander configuration in the last 100 years (Fig. 3). The curved meandering bend is evident from the 1916–18 vector. As seen in the 2016 Quickbird image, a couple of meander scrolls exist on the eastern bank, which represents the century old course of the Ichhamati. In 1973, the Ichhamati used to follow an intensely curved route. Its bend located immediate downstream of the meander apex indicates changing meander configuration from curved to sharp angular pattern. The 2002 and 2016 courses of the Ichhamati exhibit acute bends (each turn produces 60°–85° angle) in all parts of the meander, forming abrupt corners instead of a smooth curvature. At the segments where the bends are formed, the channel has shifted approximately 200–600 m between 1916–18 and 2016 (Fig. 3).

Moreover, the river courses since 2002 are visibly feebler than the previous courses (Fig.

Table 1. Details of used maps and satellite images

Data particulars	Year of survey/ Imaging date	Scale/ Resolution (m)	Sheet ID/ Path–Row/ Tile	Data source
SoI topographical map	1916–18	1:63,360	79B/13	Survey of India (SoI)
Landsat-1 MSS	21/02/1973	80	148-44	United States Geological Survey (USGS)
Quickbird	17/01/2002	1.5	—	Digital Globe (Google Earth)
Quickbird	24/11/2012	1.5	—	Digital Globe (Bing Maps)
Worldview-2	09/04/2016	1	—	Digital Globe (Google Earth)
Shuttle Radar Topography Mission (SRTM)	02/2000	30	v-3 DEM: n22-e88	United States Geological Survey (USGS)
Shuttle Radar Topography Mission (SRTM)	12/1996	1000	GTOPO–30 DEM: u30-n040e060	United States Geological Survey (USGS)

3). It is found that the width of the 1916–18 course near meander apex is 125 m. Similar width can be found for the 1973 channel (119 m), indicating a decrease of only 6 m in 56 years. However, the 2002 and 2016 courses are only 61 m (58 m reduction in 29 years) and 57 m wide (4 m reduction in 14 years) at the meander apex, respectively. This indicates significant reduction of discharge through the Ichhamati course in the last few decades.

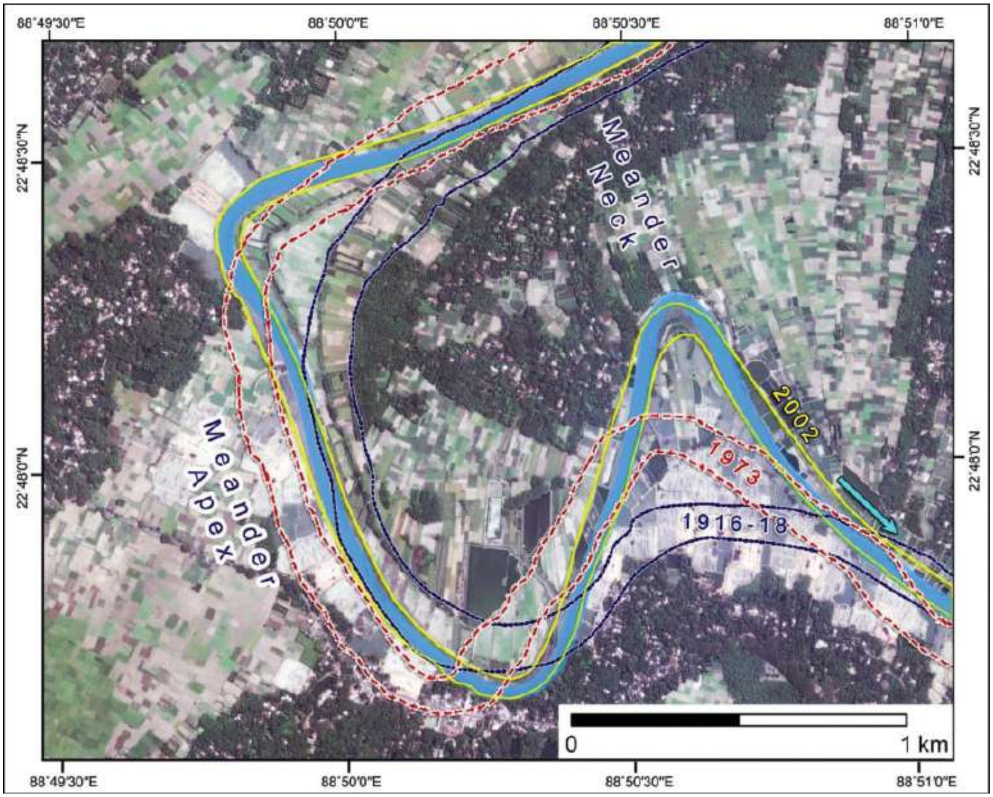

Figure 3. Changing meander configuration of the Ichhamati River at Hugle-Mathpara region in North 24 Parganas District. In the last 100 years, the pattern has changed from curved to angular. The courses of 2002 and 2016 are feeble than the previous courses, indicating recent decrease in discharge amount. The flow direction of the Ichhamati is indicated by the arrow. Sources: 1916–18: SoI topographical map # 79B/13; 1973: Landsat-1 MSS image (Path-148, Row-44), 21.02.1973; 2002: Quickbird (Google Earth), 17.01.2002. Base image: Worldview-2 (Google Earth), 09.04.2016.

The absence of a proper meander neck is another important characteristic of the study area. In a normal situation, a well-developed meander curve of a river represents the shape of a bulb, the upper part of which is identified as the apex and its lower portions come closer to form a neck. Here, the apex is located in between two sharp angular bends and characterized by a nearly straight channel (Fig. 3). Whereas, the downstream segment of the meander pushed the left bank toward north due to continual lateral erosion in the last 100 years. However, this kind of phenomenon is absent in the upstream segment of the meander, which thwarts the formation of a proper neck.

Cross-sectional characteristics and hydraulic parameters

Cross-section surveys were done across five segments of the concerned meandering bend of the Ichhamati river (Figs. 2, 4). The surveyed stretch is approximately 4 km long. Tide levels were monitored at the meander apex (profile C–C′) and assimilated in other profiles of the mentioned stretch to see whether the present channel could contain the incoming tidal discharge or not (Fig. 4). It is very difficult to identify the previous bank levels in the field, as the surrounding landscape is modified by the construction of flood embankments on both sides of the river and encroachment due to increased agricultural activities (Fig. 4, Plate 1).

Among the cross-sections, B–B′, D–D′ and E–E′ were surveyed on the angular bends of the meander (Fig. 2). The other profiles were surveyed on the straight segments of the channel. Channel bed configuration is asymmetric in B–B′, D–D′ and E–E′, with the deepest part located near outer banks (Fig.

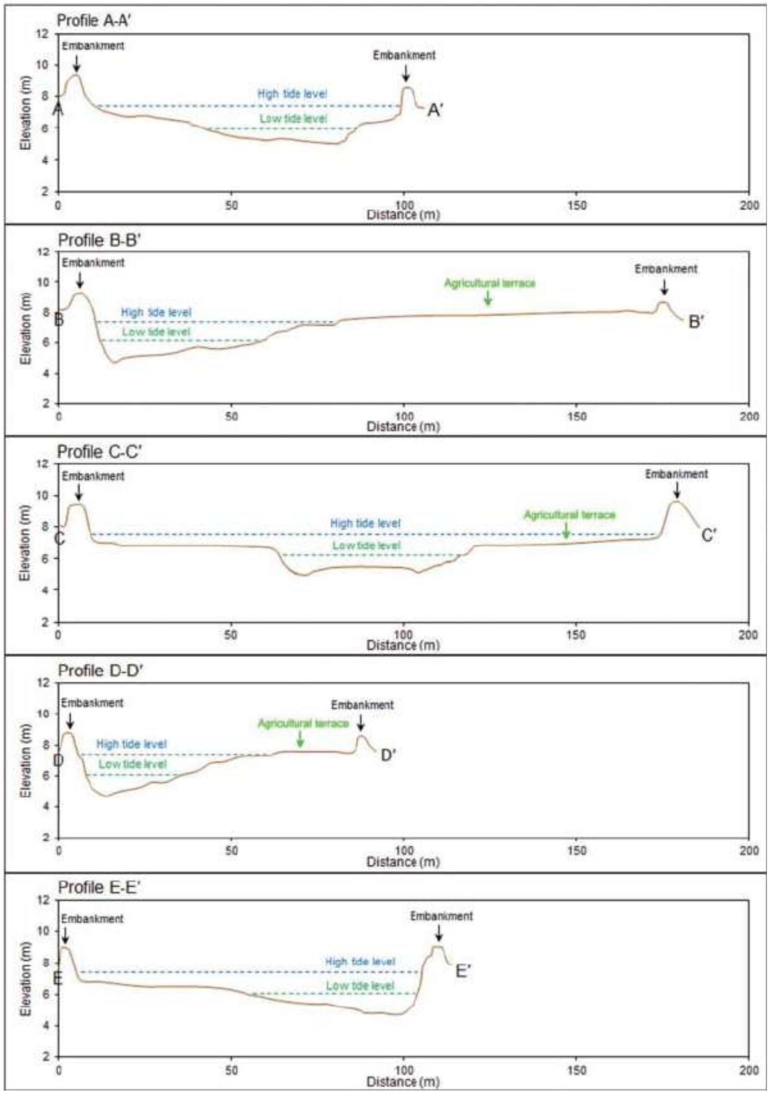

Figure 4. Five cross-profiles across the Ichhamati River at Hugle-Mathpara region. The locations of the profiles are shown in Fig. 2. The tide levels were observed during the full moon on 22–23 February 2016. The profiles (right bank on the left and left bank on the right), were surveyed on 22.02.2016.

4). Bankfull width of the channel does not vary much within the surveyed stretch and ranges between 49–57 m (Table 2). Despite noticeable tidal activities, the present channel is quite shallow (deepest point of 2.9 m found at B-B′ cross section) and subjected to overspill during high tide. During bankfull stage, at any location of the studied meander, the average depth and bankfull cross-sectional area of the channel is less than 2 m and 100 m^2 respectively (Table 2). For this reason, the present channel is unable to hold the discharge within its banks during high tides. However, the spill-over discharge is obstructed by the flood embankments on both banks (Plate 1).

During the new moon on 9–10 March 2016, the average detected velocity of the flood and ebb currents were 0.57 ms^{-1} and 0.33 ms^{-1} at the meander apex, respectively (Table 2). With the overbank flow during the high tide, the cross-sectional area increased by more than twice as compared to the bankfull stage. As found from subsequent calculations, the inflow at high tide level is about 5 times higher than the outflow at low tide level (Table 2).

Tidal observations

Tidal levels were monitored at the meander apex (C–C′ profile) during the full moon (22–23 February 2016), last or third quarter (2–3 March 2016) and new moon (9–10 March 2016) periods (Fig. 5).

Observations revealed that the tidal range was maximum (1.80 m) during new moon at Hugle-Mathpara (Fig. 5). The tidal range was 1.66 m during full moon condition. During the last quarter, the range (0.6 m) was significantly less than the spring tide periods. The highest tidal bore was detected during the new moon (0.42 m), while the lowest tidal

Table 1. Hydraulic parameters of the tidal Ichhamati channel at Hugle-Mathpara region in North 24 Parganas District

Hydraulic parameters	Cross-sections				
	A–A'	B–B'	C–C'	D–D'	E–E
Bankfull channel width: W_b (m)	55	51	57	49	50
Mean channel depth at bankfull stage: D_b (m)	1.2	1.9	1.4	1.9	1.6
Maximum channel depth at bankfull stage (m)	1.8	2.9	1.9	2.7	2.2
Bankfull cross-sectional area: A_b (m^2) = $W_b \times D_b$	66.0	96.9	79.8	93.1	80.0
Channel width at high tide level*: W_h (m)	–	–	163	–	–
Mean channel depth at high tide level*: D_h (m)	–	–	1.1	–	–
Cross-sectional area at high tide level*: A_h (m^2) = $W_h \times D_h$	–	–	179.3	–	–
Average velocity of flood tide inflow*: v_h (ms^{-1})	–	–	0.57	–	–
Discharge at high tide level*: Q_h (cumecs) = $A_h \times v_h$	–	–	102.2	–	–
Channel width at low tide level*: W_l (m)	–	–	52	–	–
Mean channel depth at low tide level*: D_l (m)	–	–	1.2	–	–
Cross-sectional area at low tide level*: A_l (m^2) = $W_l \times D_l$	–	–	62.4	–	–
Average velocity of low tide outflow*: v_l (ms^{-1})	–	–	0.33	–	–
Discharge at low tide level*: Q_l (cumecs) = $A_l \times v_l$	–	–	20.6	–	–

*Tidal observations during the new moon on 9–10 March 2016 (maximum detected tidal range) at the meander apex (C–C' profile) bore was identified during the last quarter (0.12 m).

Time-velocity asymmetry

The tidal course of Ichhamati is subjected to asymmetry in the duration of flood and ebb currents, as found from the observations at Hugle-Mathpara (Fig. 5). During full moon, duration of the rising segment of the tidal curve is 2 hours 35 minutes, while duration of the falling segment is 10 hours 15 minutes. This translates into an asymmetry ratio of 1:3.97 between flood tide and ebb periods. During new moon, the flood tide duration was only 3 hours within a 12 hours 50 minutes tidal cycle, translating into a flood-ebb duration ratio of 1:3.28. This ratio is comparatively low during the neap tide in the last quarter (1:2.26 for a tidal cycle of 12 hours 40 minutes).

At the monitoring station, the average velocity of the flood current was 1.7 times greater than the ebb current during the new moon (Table 2). During the full moon and last quarter, the differences were 1.6 times (0.54 ms^{-1} for flood current and 0.33 ms^{-1} for ebb current) and 1.3 times (0.43 ms^{-1} for flood current and s^{-1} for ebb current), respectively. Along with duration, asymmetry can also be noticed for the incoming and outgoing tidal discharge.

Suspended sediment load

Suspended sediment load of the Ichhamati channel varies significantly during the tidal cycle. For the observed periods of full moon and new moon, average suspended sediment load during flood tide were 3 and 3.1 times greater than the ebb flow period, respectively (Table 3). Whereas, in the last quarter, average suspended sediment load was 2.1 times greater during the incoming tide as compared to the ebb.

Total suspended sediment load for the entire flood tide and ebb tide phases are predicted for all observation periods (Table 3). As water level of the Ichhamati constantly fluctuates due to tidal activities, bankfull stage

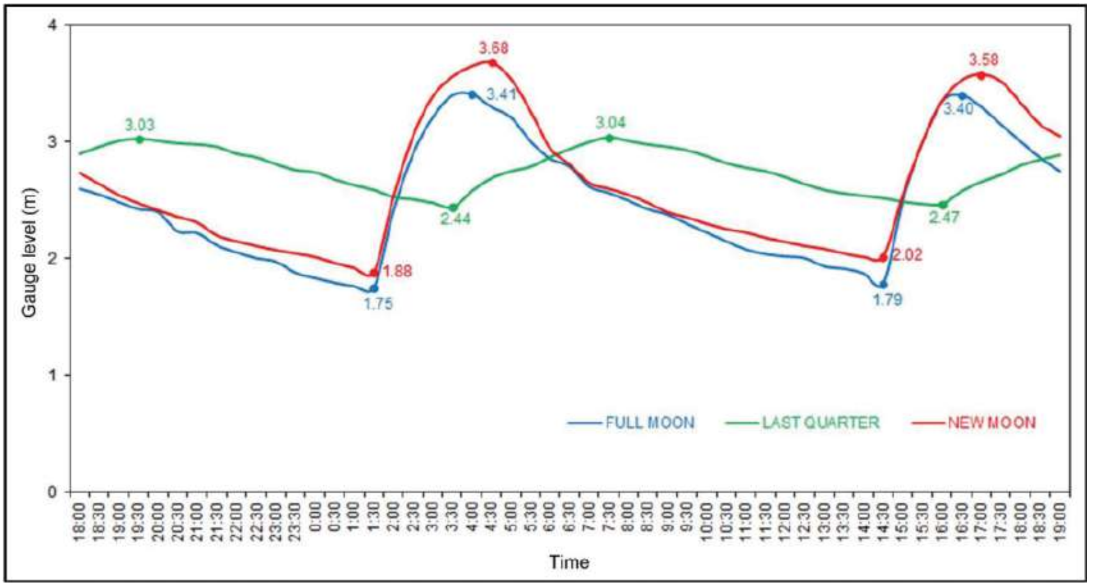

Figure 5. Tidal curves observed at the meander apex of the Ichhamati river at Hugle-Mathpara. Observation periods: full moon on 22–23 February 2016, last quarter on 2–3 March 2016, new moon on 9–10 March 2016.

Plate 1. The tidal Ichhamati course at Hugle-Mathpara region in North 24 Parganas District. (A) The first angular bend of the meander during ebb tide (viewing upstream), location of profile B–B'. (B) Overbank flow at a straight segment of the tidal Ichhamati during high tide (viewing upstream), location of profile A–A'. (C) Exposed banks during ebb tide (viewing downstream), location of profile C–C'. Date of photographs: 10 March 2016.

of the river at the meander apex is considered for the estimation. Estimated bankfull discharge level varies due to the difference in velocity of the flood and ebb currents. It is found that the estimated suspended sediment load during outgoing ebb flow would be much lesser than the incoming flood flow, and the discrepancy is significantly greater during the spring tides (Table 3). This results into trapping of sediment in the tidal course of the Ichhamati, which may cause the channel to clog up in the near future.

Tidal extent

The upstream extent of tidal flow in the Ichhamati river is marked on the basis of the tide gauge data obtained from Basirhat station in North 24 Parganas district (148 km upstream from the Hariabhanga estuary mouth) and tidal observations in the study

Table 3. Suspended sediment load movement at the meander apex (profile C–C') of the Ichhamati River at Hugle-Mathpara region in North 24 Parganas District

Observation periods		Average suspended sediment load (mg/L)	Estimated total suspended sediment load# (tonnes)
Full moon (22–23 February 2016)	High tide	676	286.0
	Low tide	226	219.6
Last quarter (2–3 March 2016)	High tide	557	267.2
	Low tide	262	211.6
New moon (9–10 March 2016)	High tide	716	
	Low tide	231	

Considering fixed water level at bankfull stage

area (39.2 km upstream from Basirhat). As the river mostly follows a sinuous course on the upstream segment of Basirhat, the velocity of tidal inflow is significantly low and tidal range gets reduced significantly.

Basirhat) during the new moon, whereas, in the last quarter, the flood current extended only up to Bhenkutia (51.9 km upstream from Basirhat). These places are located upstream of the Ichhamati-Jamuna confluence.

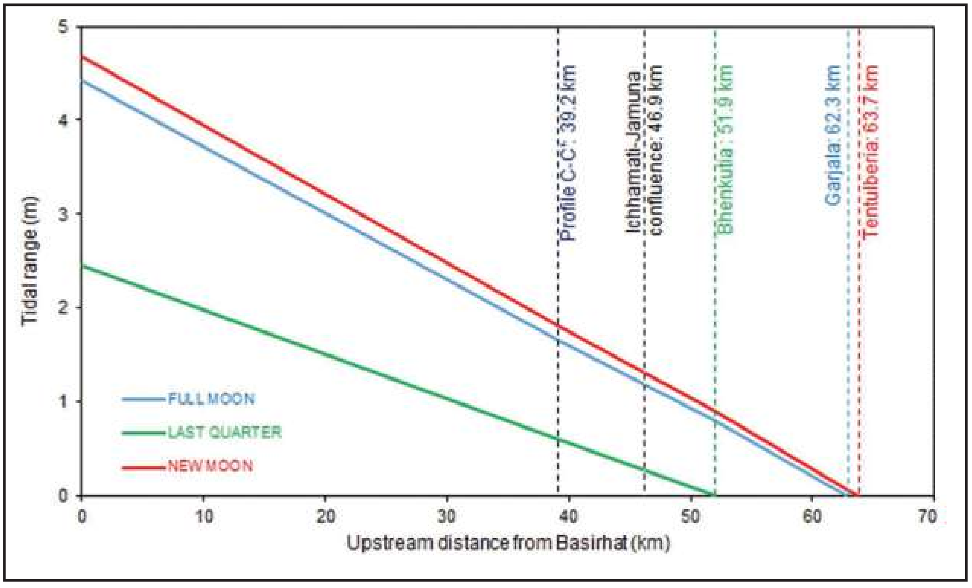

Figure 6. Upstream tidal extent of the Ichhamati River in North 24 Parganas District. Observation periods: Full moon on 22–23 February 2016, last quarter on 2–3 March 2016, new moon on 9–10 March 2016.

The tidal range was maximum during the new moon and lowest during the last quarter (Fig. 6). The tidal flow is estimated to have reached Tentulberia (63.7 km upstream from

However, considering the present channel configuration of the Ichhamati, the actuals may vary.

Conclusion

The alignment of the Ichhamati meander at Hugle-Mathpara has changed significantly in the last 100 years (curved to angular bends). Conspicuous channel shifting has occurred only at the bends due to lateral erosion. During the same period, the channel width has also decreased about 2.2 times due to the sedimentation. Because of the channel shrinkage, the Ichhamati is unable to contain flood-tide discharge within its banks. The tidal sedimentation and subsequent shrinkage of channel can be linked to the degeneration of the upper course of the Ichhamati. Since the Ichhamati headwaters receive discharge only during the monsoons, the deficient lean season flow from the upstream is unable to flush out the deposited sediments brought in by incoming flood tides. Consequently, the channel cross-sectional area is getting decreased. Therefore, in spite of flood embankments erected on both of the Ichhamati banks, the region may become susceptible to frequent flooding if direct runoff from upstream coincides with spring tides during the monsoon season.

The channel discharge varies significantly during spring tidal cycle and the present banks get submerged during high tides. Due to lack of contribution from the upcountry, this part of the Ichhamati is flood-tide dominated. There is a noticeable time-related asymmetry in the tidal flow of the Ichhamati river (flood-ebb tide ratio of more than 1:3 during the spring tide) that causes inequality in sediment transportation toward upstream and downstream. Due to this asymmetry, sediment accumulates on the Ichhamati bed. At least 20% of the estimated suspended sediment load brought in by incoming tidal current gets deposited on the river bed. Not only has this reduced the discharge carrying capacity of the channel, but the tidal current also gets obstructed. During spring tides, the tidal current is estimated to have reached Tentulberia in North 24 Parganas district, which is located 31 km downstream from the tidal limit (Bangaon) mentioned in the century-old literatures. Going by the present pattern of sedimentation, it can be assumed that along with channel shrinkage, the extent of tidal propagation will further reduce in the future.

Acknowledgement

We wish to acknowledge the assistance of Mr. Tapas Das Adhikary, Mr. Imran Hossain and Mr. Yudhisthir Das during the field visits. We also express a deep sense of gratitude to Dr. Madhab Mondal for sharing some tide related information.

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Date received : 23 September 2018
Date accepted after revision: 17 July 2019