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Tidal Behaviour and its Relation to Suspended Sediment Concentration in Selected Zones along the Hugli River, South 24 Parganas, West Bengal

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Abstract : *Suspended sediment concentration (SSC) of the Hugli is the key factor behind smooth operation of riverside brick kilns which thrive both solely and partly on supply of riverine sediments. The process of sedimentation depends on tidal behaviour of the river. On the left bank of the Hugli, two 72-km apart stations – Kulpi in the south and Akra in the north – were selected on the basis of concentration of brick kilns. The study aims at understanding the disposition of tidal asymmetry and SSC induced by it, reflecting on the relation between availability of sediment and brick making. Monitoring of tide, analysis of SSC in water samples and dumpy level survey inside the selected brick kilns at the two stations were conducted in pre-monsoon and monsoon seasons from 2017 to 2019. The pattern of rise and fall of the tides remained unchanged for the studied period at the two stations. Asymmetry in terms of duration and velocity of tides was responsible for spatial difference in sedimentation. In this flood dominated channel flood tide travels at a faster velocity and flood phase is shorter than ebb. The sediments travel upstream with tide, recording high SSC at high tide at Kulpi but the load is unable to reach 72 km upstream at Akra. The riverine flow is much effective around the northern station causing high SSC at low tide. Mean SSC was higher in monsoon at Akra and higher in pre monsoon at Kulpi. Kulpi had higher mean SSC in both seasons and higher rate of sedimentation. Steeper incoming water gradient during incoming tide at Kulpi in both seasons brought in huge sediment load causing higher mean SSC at Kulpi. Sedimentation process was controlled by tide around the southern station but tidal effect was dampened by riverine flow around the northern station.*

Key Words: *tidal asymmetry, suspended sediment concentration, brick kilns*

Introduction

Tidal waves are symmetrical and of equal period in continental shelf area but may become asymmetrical as they move towards shallow water due to interaction between wave propagation and the bottom configuration (Paiva *et al.*, 2016*)*. Reduction in estuarine depth increases the tidal

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distortion (Wright *et al.*, 1999; Cavalcante, 2016). The shallow water tidal distortion may cause steep rising or falling limb (Hale *et al.*, 2019) explained by the differences between the periods and velocity of ebb and flood tide, which is called tidal asymmetry (Bolle *et al.*, 2010; Hussain *et al.*, 2014). Asymmetry of tidal waves is dependent on geomorphic characteristics of the estuary and anthropogenic activities like dredging (Speer and Aubrey, 1985). Asymmetry results in flood dominant or ebb dominant estuaries (Dronkers, 1964; Speer and Aubrey, 1985).

The tide of the Hugli is semidiurnal (M_2) in nature (Mukhopadhyay, 2006; Rose *et al.*, 2015). It is a macrotidal estuary (Sen and Bandyopadhyay, 2018) with a wide mixing zone from the mouth to Diamond Harbour (Hospital Point) situated 70 km upstream from the mouth (Nandy and Bandyopadhyay, 2011; Mukherjee *et al.*, 2014). The tidal stretch moves 290 km upstream up to Nabadwip (Nandy *et al.*, 1983). Intense tidal mixing makes Hugli a well-mixed type of estuary up to Diamond Harbour (Sadhuram *et al.*, 2005). An estuary is considered as flood dominated when the flood period is shorter than the ebb period resulting in sediment accumulation (Speer and Aubrey 1985). Range of spring tide of the Hugli varies between 4.30 and 5.00 m and the neap tidal range varies between 1.63 and 2.28 m. Its tidal range increases by 16% up to 70 km from the estuary mouth and decreases thereafter (SoI, 2024). The tidal range attains two maxima — one between the months of March and May and other during September–October (Chakraborty and Sahoo, 2015).

The approximate amount of suspended sediment moving through the Hugli is 328×10^6 t yr^{-1} (Wasson, 2003). South of Akra, sediment also occurs from the Damodar, Rupnarayan and Haldi rivers. The sediment discharge and fluvial runoff follow a seasonal pattern (Chakraborty and Sahoo, 2015). After February, as the flood tide amplitude increases, suspended sediment concentration also increases, and this trend continues up to June (Bose, 1955).

The process of sedimentation depends on the sedimentary behavior of the river which in turn is affected by tidal asymmetry. Suspended sediment concentration (SSC) varies over time and space. Variation in freshwater discharge, tidal characteristics and channel configuration are the controlling factors of suspended sediment concentration (Arora and Bhaskaran, 2013). The sediment flux oscillates with the tidal current (Chugh, 1961). The discharge values measured at Farakka depict that in the monsoon season an average $(3.0\pm1.0)\times10^3$ m^3 s^{-1} with a maximum of 4000 m^{3}s^{-1} of freshwater is discharged through the channel and directs the existing suspended sediment towards the sea (Mukhopadhyay *et al.*, 2006). During the dry season, strong flood current restricts this seaward movement and causes sediment accumulation along the channel (Sen, 1998).

Brick making is one of the oldest industries of West Bengal. Brick kilns situated on the bank of the Hugli in South 24 Parganas district started operating from 1960s. The Hugli brings huge amount of sediments in suspension, containing mostly silt and clay (silty clay is ideal for brick making). Availing this obtainable sediment was the main reason behind the concentration of kilns on the bank of the river. The Hugli-margin embankments of the kilns are cut in the monsoon season.

Figure 1: Components of the brick kiln at Akra in (A) Monsoon season (B) Pre-monsoon season 1. Water inlet 2. Sediment reservoir 3. Reconstructed embankment 4. Drying area 5. Furnace. Blue line in (A) indictes the passage of river water through inlet towards reservoir

Image Source: Google Earth, date of image acquisition: 02 Oct 2018 (Monsoon) 20 Jan 2019 (Pre-monsoon).

The sediment laden river water enters the kiln reservoirs throughout the high-discharge period. The embankments are again re-built in late October–early November. The extra water is pumped out from the reservoirs. Suspended sediment deposited in the monsoon season is then procured and prepared for brick making in the post-monsoon season (Fig. 1A and B). The deposited sediment is heaped at one side of the kiln, which is processed by bullock driven soil processing machine. It is modified by applying sand to avoid cracks upon drying. This mixture is put in a mould and then sun-dried, followed by drying inside the furnace.

This paper is intended to enquire about tide-induced sedimentary behaviour of the Hugli by analysing the nature of tide and quantifying the suspended sediment concentration at two stations, selected on the basis of agglomeration of brick kilns (1) Kulpi, predominantly influenced by estuarine conditions and (2) Akra, fundamentally regulated by fluvial conditions, and assess their effects on the mechanism of brick kilns of the two stations. One brick kiln each was selected close to the stations to monitor the volume of sediment moving through the inlet, variation of tide levels and SSC. The present work was carried out in two seasons — pre-monsoon and monsoon. The objectives of the study are to understand the nature of tidal asymmetry by assessing the spatial and seasonal characteristics of tide and to understand the asymmetry-induced suspended sediment concentration within the selected stretch along the Hugli.

Study Area

As stated, the study has been conducted at Kulpi in the south (22°4′39″N, 88°13′30″E) and Akra in the north (22°30′55″N, 88°14′1″E) set apart by 71.7 km on the left bank of the Hugli. The two representative brick kilns for the study were SCG at Kulpi and J. M. Paul at Akra (Fig. 1). Both the stations are situated within the tidal stretch of the river having semi diurnal tide that propagates

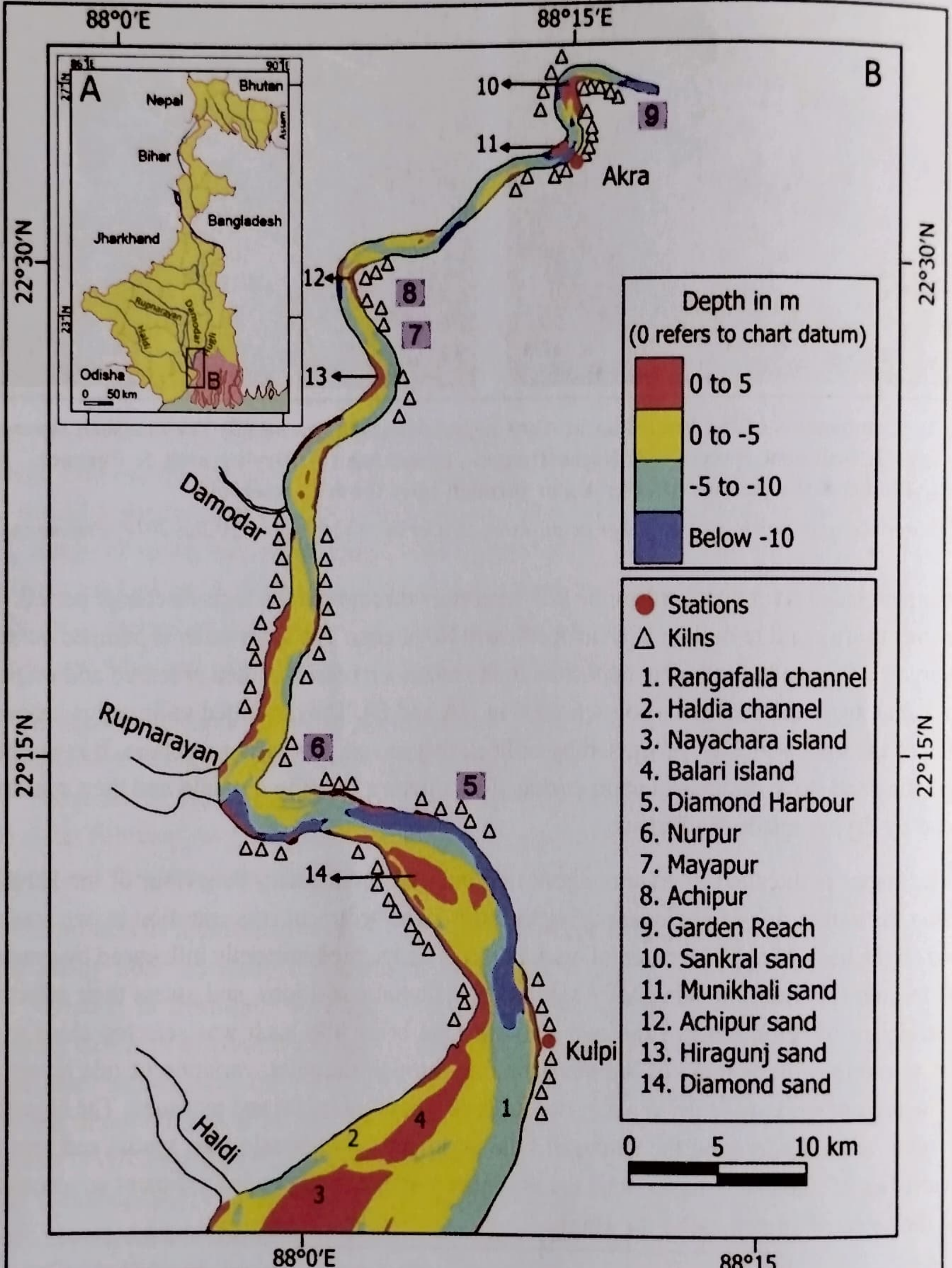

Figure 2: The location of the study area: (A) Location of South 24 Parganas in West Bengal. (B) The Hugli estuary showing the position of the brick kilns and the monitoring stations. Prepared from bathymetric maps of National Hydrographic Office (NHO), compiled from Syama Prasad Mookerje Port data of 2014-15, with later addition and correction up to 2017. Depths are in m reduced to chart datum of 2.82 m below sea level.

from south to north. Between these two, the Damodar and Rupnarayan are the important tributaries that join the Hugli on the right bank (Fig. 2) contributing to the freshwater discharge of the river.

The course of the Hugli is sinuous in nature. Two significant bends are visible along the stretch. Among the kilns, one is located 25.8 km upstream of Kulpi, at the confluence of the Rupnarayan river and the second one is located 10.1 km downstream of Akra. The width of the channel at Kulpi is 4.48 km, which narrows down to 0.92 km at Akra. Depth and breadth of 28 m and 4.68 km was recorded at Khidirpur, located 11 km downstream of Akra (Nath *et al.*, 2004). According to Syama Prasad Mookerjee Port (SMP), annual sediment transported south of Diamond Harbour is 23.68×10^6 t and about 13.20×10^6 t between Diamond Harbour and Nabadwip (Mukhopadhyay *et al.*, 2023). From the vicinity of Garden Reach to Kakdwip, 177 brick kilns were found in 2019 (Fig. 2). In terms of source of sediment used for brick making, the brick kiln at Kulpi thrives on riverine sediment solely, while the brick kiln at Akra uses riverine sediment besides procuring sediment from agricultural fields.

The bathymetric map of the study area shows that maximum area of the stretch has a depth between 0 and –5 m (Fig. 2). The southern station is located at a depth zone of 0 to 5 m as the station is located on the mudflat, but zones with greater depth can be identified around the station. At the lower part of the studied stretch around Kulpi, a 17.7 km long zone with depth below –10 m can be identified on the left bank of Hugli up to Diamond Harbour. At Diamond Harbour, situated 13 km upstream of Kulpi, the depth and width become 16 m and 0.75 km, respectively. Around Kulpi, the thalweg is close to the left bank of the river. Beyond Diamond Sand, the thalweg shifts to the right bank with depth of more than –10 m. After crossing the large meander bend (18 km diameter) at the confluence of Rupnarayan, the width of the river decreases. Within the 30.1-km long stretch up to Mayapur, maximum depth is found to be within –10 m. In this section, the thalweg follows a zigzag pattern. Opposite to Achipur sand bar the depth increases to more than –10 m. Above Mayapur up to Garden Reach, in the 23.9-km long stretch, the width of the river decreased and majority of the area has a depth between –5 to –10 m. The northern station of Akra is located at a narrow zone with depth more than –10 m as mudflats are ill developed here. In this stretch, distinct thalweg zones of more than –10 m depth are seen to be located close to the left bank of Hugli (Fig. 2).

According to the salinity zonation scheme proposed by Nath et al. (2004), Akra comes under freshwater zone with a very low salinity of 0.052 psu and Kulpi is located in the transitional zone with salinity ranging from 0.5 to 2 psu (Nath *et al.*, 2004). Due to the impact of upland discharge salinity decreases in the monsoon months (Sinha *et al.*, 1997). The absence of brick fields south of Kulpi may be attributable to the increase in salinity downstream. However, the issue of salinity of marine sediment at Kulpi is dealt with proper processing, that substantially scales down the salinity values. Sun drying followed by proper combustion in the furnace at 900 °C can effectively reduce the salinity from 183 ppm to 2.5 ppm (Sobuz *et al.*, 2011).

Material and Methods

Two monitoring stations were set up on the left bank of the Hugli according to agglomeration of brick kilns. Bathymetric maps were procured from the National Hydrographic Office (NHO) to prepare the base map of the estuary covering the study area (Table 1). To monitor the tide with maximum tidal range, the dates of full moon and new moon were selected from the lunar calendar. Generally, the maximum tidal range occurs one or two days before or after new/full moon condition (Table 2).

Survey was conducted at the two stations for two consecutive seasonal cycles, starting from monsoon of 2017 to pre-monsoon of 2019. Tide monitoring and water sample collection were done at the vicinity of the selected brick kilns. Data collection for two consecutive years enabled the calculation of the average tidal level. The span of survey was divided into two seasons — pre-monsoon and monsoon.

Table 1: Data sources

Source	Year	Acquired from	Purpose	Scale/ resolution
Tidal Observatories at Diamond Harbour and Akra	2019	Syama Prasad Mookerjee Port	Calibration of tidal data	—
Bathymetric charts INT 7422 3013, INT 7423 3006	2017	National Hydrographic Office	Width-depth measurement of estuary	1:37,500
Survey of India Topographical maps 79B/2, 79B/4	1958-59, 1967-68	West Bengal State University	Identification of benchmark for calculation	1:50,000

For collecting the data of monsoon season, survey was conducted in September and pre-monsoon data were collected in March-April during both full moon and new moon conditions. The tidal monitoring at the two stations was time-coordinated to avoid any time discrepancy among the stations. Tide monitoring was done following the method of Glen (1979) for a span of 9 hours and data were collected at an interval of 10 minutes. At times when the water level rose/ fell very fast, the interval of data collection was reduced to 5 minutes.

Tide monitoring was conducted in low-to-high-to-low condition at Kulpi and high-to-low-to-high condition at Akra. Data of highest water level from the nearest gauging station (Table 1) was extrapolated to determine the highest water level for the northern station. The actual water level for the whole survey period was calculated thereafter.

Water samples were collected in 1000 ml bottles from a depth of 0.5 m from the surface and at 0.4 m to 4 m distance from the bank of the river according to the condition of tide at one-hour interval for a span of 9 hr. The mouth of the bottle was held facing downstream during incoming tide and upstream during outgoing tide. Precautions were taken to avoid resuspension errors while collecting samples.

Table 2: Details of the dates of the survey

Date of Survey	Season	Phase of moon
06 Sep 2017	Monsoon	Full moon (on 06 Sep 2017)
31 Mar 2018	Pre-monsoon	Full moon (on 31 Mar 2018)
09 Sep 2018	Monsoon	New moon (on 09 Sep 2018)
19 Apr 2019	Pre-monsoon	Full moon (on 19 Apr 2019)

Actual tidal data were collected from SMP for the two tidal observatories situated closest to the monitoring stations of the study area. The observed data of Kulpi was calibrated with the data of Diamond Harbour tidal observatory and for Akra, the tidal data of Akra tidal observatory were used (Table 1).

Whatman Grade-1 filter paper was used for filtering the water samples, in accordance with the very fine texture of the sediment, with particle-diameter ranging from 2–63 µm, representing silt and clay sized particles (Walling, 1983). In this article, the terms highest high and lowest low water levels were used to denote the highest and lowest water levels achieved on the survey dates. Width-depth condition of the inlets (Fig. 6 and 7), which connects the sedimentation reservoir with the river was measured by dumpy level at the two selected brick kilns. Actual depths were determined by adjusting with benchmark values from topographical sheets (Table 1). To assess the volume of sediment entering through the inlet, the Cross-Sectional Area (A) and Wetted Perimeter (P) was calculated following the IWD (2002) methodology. This was applied for the computation of Hydraulic Radius

$$D = WH^{ht} - D^{Min} \qquad \text{Equation 1}$$

Where, D= Depth of channel, WH^{ht}= Water height at high tide, D^{Min}= Minimum depth of the inlet.

$$\text{Cross Sectional Area } (A) = (B+2D)\times D \qquad \text{Equation 2}$$

Where, B = Bed width of inlet channel

Velocity (V) of flow was calculated following Manning's equation.

$$V = R^{2/3}\times S^{1/2}/n \qquad \text{Equation 3}$$

Where, R= Hydraulic Radius, S= Channel Slope, n= Roughness coefficient

$R = A/P$ Equation 4

Where, P = Wetted Perimeter

$P = B + (2 \times 5^{0.5}) \times D$ Equation 5

The volume of water moving in and out of an inlet in a tidal cycle is called the tidal prism. Discharge (Q) was calculated to determine the tidal prism.

$Q = A \times V$ Equation 6

The cumulative volume of water flowing through the inlet was multiplied with the mean SSC of monsoon season to determine sediment volume following Mandal and Chaudhuri (2021).

T^{SSC} = Tidal prism × SSC HT condition

Results and Discussion

Tide and suspended sediment concentration of the pre-monsoon season

The mean peak water level was 6.025 m at Kulpi and 5.72 m at Akra. The mean lowest water level was 0.64 m at Kulpi and 0.93 m at Akra. The difference between mean peak water level between the two stations was larger (0.31 m) than the difference between mean lowest water level (0.29 m). In pre-monsoon season the average lag time of tidal wave was 160 min.

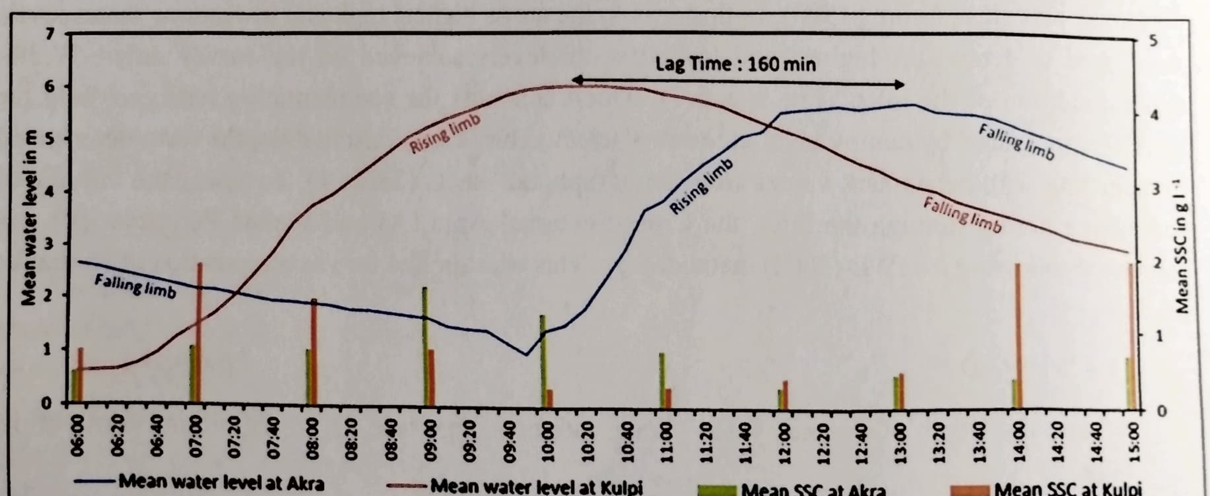

Figure 3: Mean tidal water level and average suspended sediment concentration (SSC) of the two stations for pre-monsoon season. The data of two consecutive years of pre-monsoon season were averaged.

Total mean SSC was high during incoming tide at Kulpi and during outgoing tide at Akra, in both the seasons. At Kulpi, the lowest mean concentration was recorded during the ebb phase (Fig.

3). SSC gradually increased during the flood tide and maximum SSC was recorded at the beginning of high tide. High SSC was recorded at the start and end of the flood cycle. SSC was lowest at the beginning of the ebb phase. At Akra mean SSC was low at the beginning and then it rose gradually till the highest concentration was observed at the first falling limb of the tide. SSC decreased continuously for the next three hours and lowest concentration was marked at the rising limb. With the falling tide, mean concentration rose again. In pre-monsoon season mean SSC was higher at Kulpi (Table 3), calculated with total mean SSC of one incoming cycle and total mean SSC of two incomplete outgoing cycles experienced at the beginning and end of the survey period respectively. The pre-monsoon and monsoon seasons show spatial and temporal variation of total mean SSC at the two stations. High discrepancy in total mean SSC can be noted between the two stations (10.94 g l^{-1}in Kulpi and 6.09 g l^{-1} in Akra) in the pre-monsoon condition.

Table 3: Total Average SSC in g l^{-1} in pre-monsoon and monsoon seasons at two stations

Pre-monsoon				Monsoon			
Kulpi		Akra		Kulpi		Akra	
Incoming	Outgoing	Incoming	Outgoing	Incoming	Outgoing	Incoming	Outgoing
6.39	4.55	1.46	4.63	6.2	2.1	1.59	5.58

Tide and suspended sediment concentration of the monsoon season

The average lag time of highest high tide for monsoon season was 130 min, which was 30 min less than the pre-monsoon period. At both the stations, no major seasonal difference was noticed in the pattern of rise and fall of the tidal wave. However, in monsoon season the mean peak water level was 6.36 m at Kulpi and 6.27 m at Akra (Fig. 4), which was higher than the pre-monsoon levels. The seasonal difference in highest water level was more pronounced in Akra than Kulpi.

Total mean SSC was lower in monsoon at both the stations (Table 3). Total mean SSC values were 8.3 g l^{-1} and 7.17 g l^{-1} at Kulpi and Akra respectively in monsoon season. At Kulpi mean SSC was maximum at the rising limb. The concentration decreased steadily, and the mean lowest concentration was marked at the rising limb. Another high concentration was identified at the second falling limb of the tide. At Akra mean SSC was maximum at the second falling limb and mean lowest concentration was marked at the rising limb. The pattern of occurrence of mean highest and lowest SSC values along with rising and falling tide was similar to the pre-monsoon season.

The tidal force significantly deceases upstream due to riverine discharge (Chacko and Jayaram 2017, Jayaram *et al.*, 2021). The seasonal variation of peak tidal level at Akra is due to the effect of fluvial discharge in monsoon season.

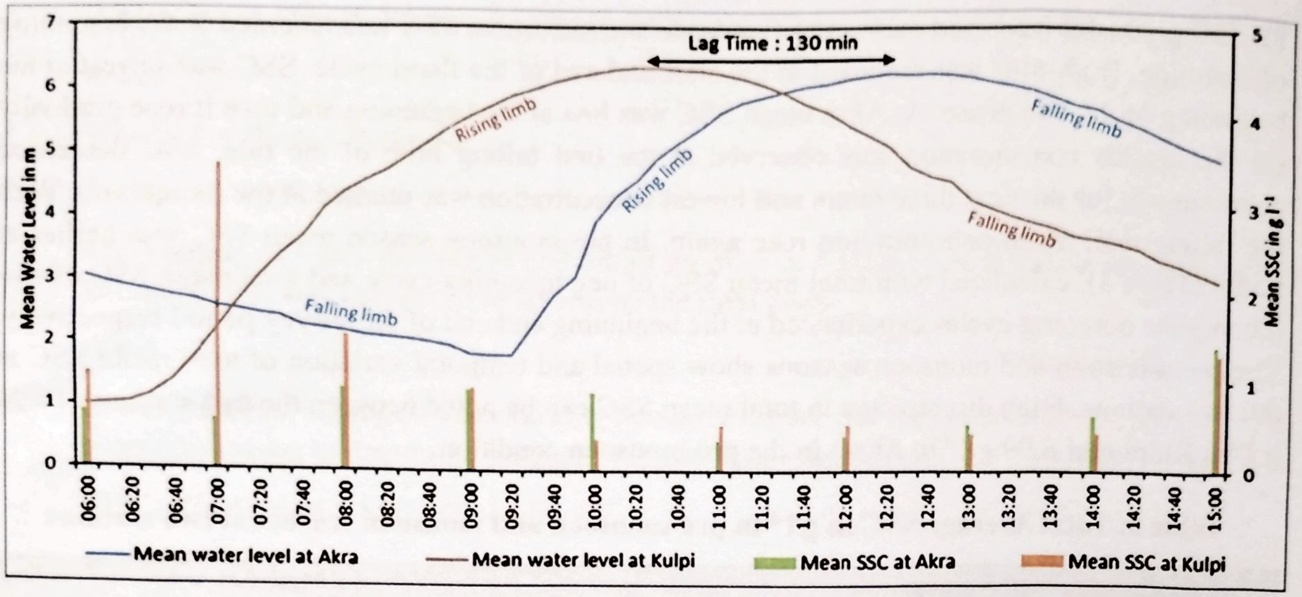

Figure 4: Mean tidal water level and average SSC of the two stations for monsoon season. The data of two consecutive years of monsoon season were averaged.

The spatiotemporal pattern of SSC can be cast in terms of the following observations — (1) Mean suspended sediment concentration was higher in monsoon season at Akra and higher in pre-monsoon season at Kulpi. (2) Mean SSC was higher at the southern station in both the seasons. (3) Total mean SSC was high during incoming tide at Kulpi, but high during outgoing tide at Akra. These observations affirm the seasonal and spatial variation of SSC. Fluvial discharge-induced sediment influx and resuspension aided by strong wind are associated with incidence of high SSC in monsoon (Chacko and Jayaram, 2017). The source of sediment is mainly estuarine around Kulpi, of which a share is getting deposited, and rest is going back to the sea. With high velocity of incoming tide, huge amount of sediment travels upstream but lower velocity ebb flow brings back lesser amount of sediment in suspension. When the progressive high tide reached Akra, SSC decreased. The smaller tidal range and gentle gradient of water during incoming tide at Akra (Fig. 5) supports the fact that, the volume of the sediment-laden tidal water decreases as the progressive tide moves upstream. The source of sediment at Akra is mainly riverine, reflected in low SSC at Akra at incoming tide. The reverse condition is noticed at outgoing tide, when the riverine flow and tidal flow are in the same direction. Variation of freshwater discharge, tidal variation and channel geometry plays pivotal roles in the variability of SSC (Pitchaikani *et al.,* 2018). Higher discharge during flood tide enhances the sediment carrying capacity (Banerjee *et al.*, 2013). As the width and depth reduced drastically upstream, the asymmetry of tidal current resulted in deposition of sediment along the course of the river. While the water is receding, the flow of tidal water over the intertidal areas may bring huge amount of sediment in suspension. High mean SSC during outgoing tide at Akra could be related to the above statement.

Range, rising rate and falling rate of tide

Mean range (Table 4) of the tide was larger in the monsoon season at both the stations and larger at Kulpi in both the seasons. The change in the levels of low water were larger in the monsoon season while levels of high water remained almost same in both the seasons at Kulpi, pointing at the dependence on regional freshwater discharge (Hale *et al.*, 2019). Tidal range changes as the tidal wave propagates inland (Rose *et al.*, 2015) with mainly friction amplifying the range (Wang *et al.*, 2002).

Table 4: Seasonal variation of tidal characteristics at Kulpi and Akra

Date	Pre-monsoon Season						Date	Monsoon Season					
	Kulpi			Akra				Kulpi			Akra		
	Range (m)	Rising rate ($m\ hr^{-1}$)	Falling rate ($m\ hr^{-1}$)	Range (m)	Rising rate ($m\ hr^{-1}$)	Falling rate ($m\ hr^{-1}$)		Range (m)	Rising rate ($m\ hr^{-1}$)	Falling rate ($m\ hr^{-1}$)	Range (m)	Rising rate ($m\ hr^{-1}$)	Falling rate ($m\ hr^{-1}$)
31 March 2018	5.31	1.27	0.64	4.60	1.42	0.62	6 Sept 2017	5.26	1.17	0.77	4.4	1.39	0.49
19 April 2019	5.43	1.49	0.55	4.80	1.62	0.45	9 Sept 2018	5.62	1.38	0.74	5.06	1.60	0.66
Average	5.38	1.38	0.59	4.70	1.52	0.54	Average	5.44	1.28	0.76	4.73	1.50	0.57

Source : Calculated from the data acquired from primary survey

Due to the asymmetry of tide when the water is drawing out from the northern station, another wave of high water comes in, resulting in small tidal range at Akra. The range of tide is > 5 m at Kulpi. Akra is under mesotidal and Kulpi is under macrotidal range (Table 4). Slow falling rate compared to rising rate at the two stations in both pre-monsoon and monsoon seasons confirmed the flood dominance in the selected stretch.

Asymmetry of tidal wave

Non-linear propagation of tidal wave produces M_4 (lunar quarter diurnal) tide from M_2 (lunar semidiurnal) tide, which has a period of ½ the period of M_2 tide. Due to the effect of friction M_6 (sixth diurnal) tide is generated from M_2 tide with a period $^1/_3$ of the period of M_2 tide (Bosboom and Stive, 2023). The tidal asymmetry is discussed in terms of vertical tide, which is the difference in duration of ebb and flood currents and horizontal tide referring to difference between velocity of ebb and flood currents. If the duration of flood current is shorter than duration of ebb current it leads to stronger peak flood current, causing flood dominance or flood asymmetry (Walton, 2002; Cavalcante, 2016; Hussain *et al.*, 2014). Net seaward transport of sediment would take place in case of ebb dominance. In flood asymmetry, transport of sediment is directed towards land (Nandy and

Bandyopadhyay, 2011; Coe and Frey, 2016). Asymmetry in duration is related to velocity asymmetry causing shorter duration of flood tide with stronger velocity and longer ebb duration with weaker ebb currents (Toublanc *et al.*, 2015). Most progressive waves can generate higher degree of asymmetry during a tidal cycle (Ward *et al.*, 2018). Flood dominance of vertical tide increases landward as the falling rate (Table 4) of the southern station (0.63 m in pre-monsoon, 0.59 m in monsoon) was higher than the falling rate of northern station (0.57 m in pre-monsoon, 0.54 m in monsoon).

Water surface gradient

In the water surface gradient diagram, Kulpi is placed at the left end and Akra is on the right end of the x axis. Lines joining hourly water levels at the two stations show the gradient of water surface with tide (Fig. 5). Among the survey dates (Table 2), the data of 31 Mar 2018 for pre-monsoon season and the data of 9 Sep 2018 for monsoon season have been considered for depiction of water surface gradient. Water surface gradient for other dates of a season was similar in terms of slope.

Water surface gradient in pre-monsoon season

During the 9-hr monitoring period, the first 30 min experienced unidirectional movement of tidal water (moving towards sea) from both the stations. For the next 3 hr 30 min water movement was bi-directional, as incoming tide directed the water upstream from the southern station and water was receding towards the sea from the northern station. In the next 3 hr water movement was also bi-directional, when water was receding from downstream station Kulpi and rising at northern station Akra. During the last 2 hr the stretch experienced unidirectional movement as ebb phase prevailed at both the stations. Water surface gradient was steepest during the flood cycle at 10:00 hr (bidirectional flow). The gradient became most gentle during the ebb cycle at 7:00 hr and at the second cycle of outgoing tide at 12:00 hr.

Water surface gradient in monsoon season

During the 9 hr monitoring, the initial 3 hr experienced bi-directional movement of tidal water, when water was receding (moving towards sea) from the northern station and rising (moving upstream) at the southern station. For the next 1 hr 30 min water movement was unidirectional (moving upstream), as water was rising at both the northern and southern stations. In the next 2 hr 30 min, water movement was again from two directions, when water was still moving upstream at the northern station, ebb phase had already initiated at the southern station. For the last 2 hr, the flow was unidirectional, as ebb tide was being experienced at both the stations. Steepest water surface slope was observed at the middle of the flood cycle at 9:00 hr (landward gradient). Steepness was maintained for the rising phase till 10:00 hr (bi-directional flow). At 11:00 hr, at the initiation of the ebb cycle tidal gradient was most gentle (unidirectional flow). As the ebb phase continued, the

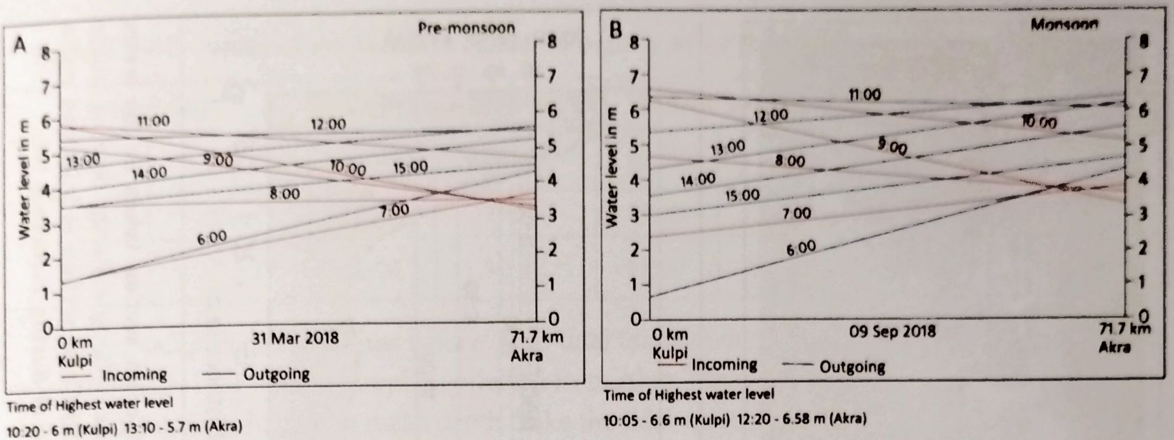

Figure 5: Water surface gradient between the two stations for (A) pre-monsoon and (B) monsoon season. Date of survey: 31 Mar 2018 and 9 Sep 2018.

gradient also increased (bi-directional flow), but it marginally decreased at the end of the survey at 15:00 hr. (unidirectional flow). Steep slope of incoming water carried huge amount of sediment in suspension, but lesser amount of sediment went out to the sea (Kanga *et al.*, 2020). The spatial variation of SSC is also reflected in the amount of sediment available for brick making.

The water surface gradient of pre-monsoon and monsoon season was steep when incoming tidal cycle initiated at Kulpi. Steepest but a reversed slope was identified at the fag end of the incoming tidal cycle. Gentle slope could be found in the middle of the incoming cycle at Kulpi when water was still receding from Akra. The water slope became gentle when the second outgoing cycle started at Kulpi. The first incoming cycle at Akra and the second outgoing cycle at Kulpi initiated almost at the same time. Steep upstream gradient and higher rising rate were maintained throughout the incoming tidal period at Kulpi (Fig. 5). During the incoming cycle at Akra, the water surface slope was gentler than Kulpi. This deciphers the phenomenon of higher SSC at incoming tide at Kulpi.

Bore tide is an important characteristic of tide at the upstream station of Akra. Width reduction had stronger effect on tidal amplitudes than depth. The decreasing width of the Hugli estuary caused convergence of tidal energy (Khojasteh *et al.,* 2021), and tidal amplitude increased along the channel. Due to short rising period, steep vertical tidal waves were generated, that takes the form of a wall while travelling upstream. This phenomenon is called the tidal bore (Bosboom and Stive, 2023; Mukhopadhyay *et al.*, 2023). Reduction of depth upstream and large tidal range encouraged the formation of tidal bore (Bowers and Roberts, 2019). Such high-velocity steep waves can transport abnormal amount of sediment within a short time. Occurrence of tidal bore is a common phenomenon in Hugli estuary. The lower part of estuary does not show signs of bore formation (Roy-Biswas and Sen, 2023). Thus, the effect of bore is profound at Akra but not felt at Kulpi.

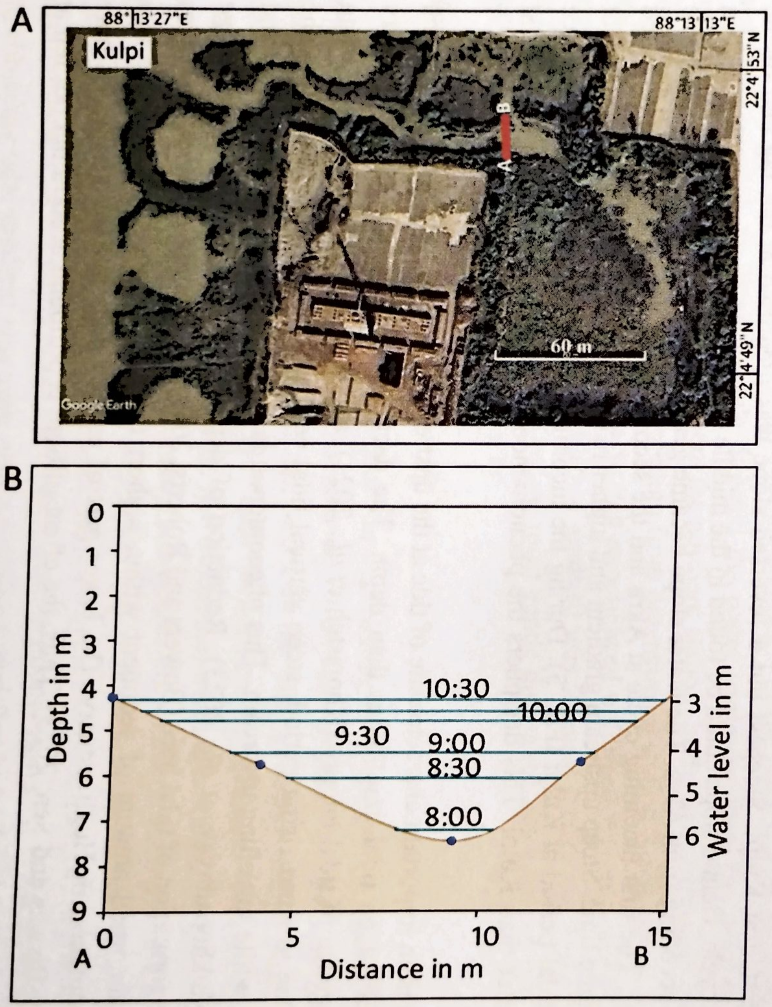

Figure 6: (A) Location of cross section taken at the water inlet at Kulpi (image source: Google Earth, Date of acquisition: 21 Dec 2021). (B) Cross section of inlet and water height at half hourly interval during incoming tide.

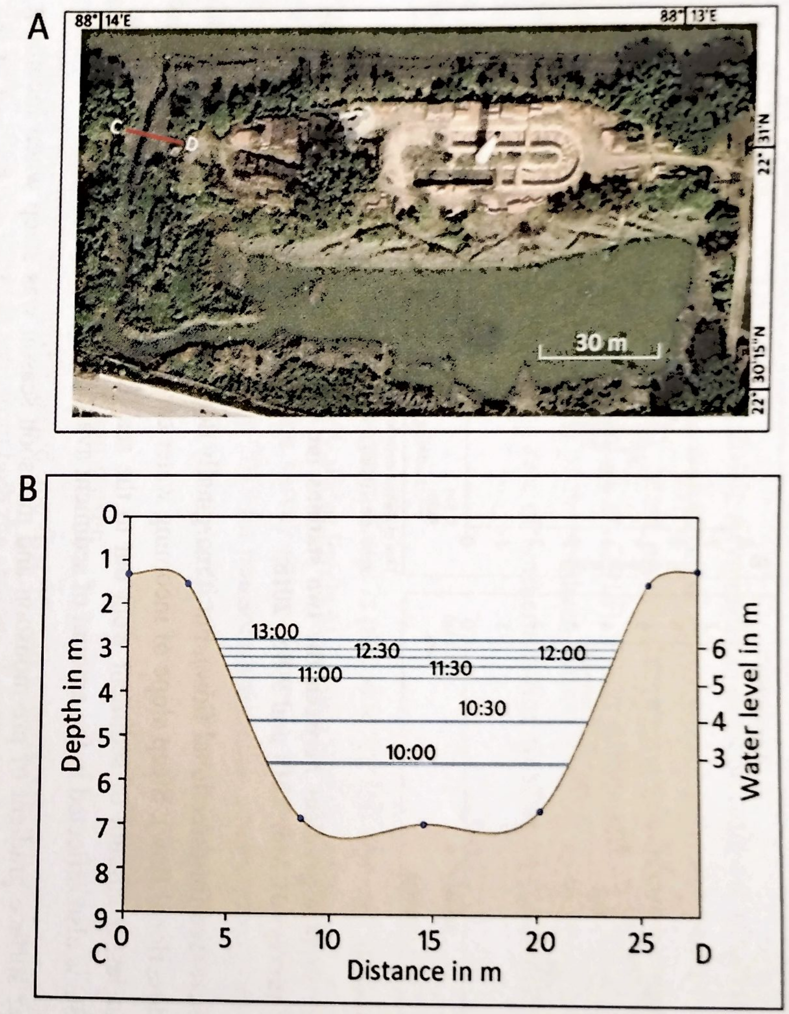

Figure 7: (A) Location of cross section taken at the water inlet at Akra (image source: Google Earth, date of image acquisition: 26 Jan 2020). (B) Cross section of inlet and water height at half hourly interval during incoming tide.

Table 5: SSC values of the samples collected before/ after the incidence of bore tide at Akra

6 Sept 2017		31 March 2018		9 Sept 2018		19 April 2019	
09:00	1.1 g l^{-1}	10:00	1.22 g l^{-1}	10:00	1.3 g l^{-1}	9:00	1.79 g l^{-1}
9:52	Bore	10:15	Bore	10:10	Bore	9:45	Bore
10:00	1.17 g l^{-1}	11:00	1.30 g l^{-1}	11:00	0.37 g l^{-1}	10:00	1.24 g l^{-1}

Water samples collected just before/ after tidal bore contained high SSC (Table 5). SSC values range from 0.3–1 g l^{-1} in the samples collected from Akra. Meandering channel, location of bars and shoals and drastic reduction in mean depth make the tidal wave propagation more complex (Brooks, 1965; Dronkers, 1986). Change in sediment transportation pattern was affected by interactions between tide and bathymetry (Bolle *et al.*, 2010).

Estimation of sediment volume at the brick kilns

The width-depth, alignment of the inlet (Fig. 6, 7) with respect to the river controls the amount of river water entering the sedimentation reservoir.

Tidal prism of Akra is smaller than Kulpi at high tide condition (Table 8). Reckoning of sediment volume rendered these observations – (1) Volume of sediment entering the kiln reservoir through the inlet in the monsoon season was higher at Kulpi. (2) Volume of sediment deposited inside the reservoir was higher at Kulpi.

The brick making process is almost same in the brick kilns at Kulpi and Akra. Kulpi relies only on riverine sediment for brick making, but lesser sediment availability at Akra entailed the brick kiln owners to opt for other sources of sediment other than the river. To maintain profitable production sediment is bought from agricultural field or industries.

Conclusions

There was negligible variation in the rise and fall pattern of tide in the pre-monsoon and monsoon seasons in the studied reaches of the Hugli. The difference in values of the ranges between the two stations at Kulpi and Akra is significant. Constriction of width along with short rising period forms tidal bore at Akra. Such phenomenon is absent in the downstream station of Kulpi, where the channel is wider. However, long-term tidal dataset is required to fully understand the nature of the tide. Spatial variation of SSC had been confirmed by the fact that Akra showed lesser mean SSC than the southern Kulpi in both the studied seasons. Progressive nature of tide, time-velocity asymmetry and the width-depth configuration of the studied stretches controlled the spatial variations in SSC. The asymmetry of vertical tide at a station was also affected by asymmetry at a downstream station. Width reduction affects the tidal range and ultimately the amount of SSC. Akra recorded lower sediment volume entering the reservoir through the inlet in one incoming cycle

Table 6: Calculation table for sediment volume entering through the inlet of SCG kiln at Kulpi

Time	Water level in m	Bed slope in degree (s)	Depth of channel in m (D)	Bed width of channel in m (B)	Cross-sectional area in m^2 (A)	Wetted perimeter in m (P)	Hydraulic mean depth in m (R)	Mannings Ruggedness co-efficient (n)	Velocity in m/s $=R^{2/3}*S^{1/2}/n$	Discharge in cumec (Q=A×V)	Volume m^3	Cum Volume m^3
08:00	3.29	0.0045	1.745	3	11.325	10.80	1.05	0.025	2.77	31.36	56444.1	56444.1
08:30	4.58	0.0045	3.035	3	27.527	16.57	1.66	0.025	3.76	103.60	186475.4	242919.5
09:00	5.19	0.0045	3.645	3	37.507	19.30	1.94	0.025	4.18	156.73	282108.4	525027.9
09:30	5.73	0.0045	4.185	3	47.583	21.72	2.19	0.025	4.53	215.40	387724.6	912752.5
10:00	6.00	0.0045	4.455	3	53.059	22.92	2.31	0.025	4.70	249.13	448431.6	1361184.1
10:30	6.25	0.0045	4.705	3	58.389	24.04	2.43	0.025	4.85	283.09	509560.6	1870744.7

Table 7: Calculation table for sediment volume entering through the inlet of J. H. Paul kiln at Akra

Time	Water level in m	Bed slope in degree (s)	Depth of channel in m (D)	Bed width of channel in m (B)	Cross-sectional area in m^2 (A)	Wetted perimeter in m (P)	Hydraulic mean depth in m (R)	Mannings Ruggedness co-efficient (n)	Velocity in m/s $=R^{\wedge 2/3}*S^{\wedge 1/2}/n$	Discharge in cumec (Q=A×V)	Volume m^3	Cum Volume m^3
10:00	3.22	0.0017	1.20	10.25	15.180	15.62	0.97	0.025	1.62	24.57	44220.0	44220.0
10:30	4.38	0.0017	2.36	10.25	35.329	20.80	1.70	0.025	2.35	82.94	149286.2	193506.3
11:00	5.23	0.0017	3.21	10.25	53.510	24.61	2.17	0.025	2.77	148.14	266653.4	460159.7
11:30	5.58	0.0017	3.56	10.25	61.837	26.17	2.36	0.025	2.93	180.93	325667.5	785827.1
12:00	5.85	0.0017	3.83	10.25	68.595	27.38	2.51	0.025	3.04	208.70	375655.8	1161482.9
12:30	5.98	0.0017	3.96	10.25	71.953	27.96	2.57	0.025	3.10	222.86	401143.3	1562626.3
13:00	6.1	0.0017	4.08	10.25	75.112	28.50	2.64	0.025	3.15	236.39	425502.2	1988128.4

Table 8: Calculation table for total sediment volume entering through the inlets at Kulpi and Akra

	Kulpi	Akra
Tidal Prism	1870744.7 m^3	1988128.4 m^3
SSC HT condition	6.2 g l^{-1}/ 6199.25 m^3	1.183 g l^{-1}/ 1183 m^3
Tidal Prism × SSC HT condition	11597214.2 kg/11597.21 m^3	2351955.931 kg/ 2351.95 m^3

in a day and lower sediment volume deposited inside the reservoir in the monsoon season in a year. At Kulpi, the effect of river flow is negligible. The sedimentation process is guided by tidal flow. Riverine flow is stronger than tidal flow at Akra and its effect is observed in the amount of sedimentation. High velocity sediment-laden incoming tide had higher SSC at Kulpi while unidirectional tidal and riverine flow at outgoing tide had higher SSC at Akra. Seasonal dominance of freshets control the seasonal variation of SSC at Akra. Production of brick got affected mainly by local SSC values. Only a fraction of the huge marine sediment load reaches the upstream station, causing low volume of sediment. The lower volume of sedimentation at Akra leads the brick kiln owners to procure sediment from sources other than the Hugli. Temporal variation in SSC, a lowering trend of sedimentation in particular, is a concerning issue for brick making industry. Rate of sedimentation has recorded small decrease from 2018 to 2019 in both the stations. Analysis of long-term dataset is required for in-depth analysis of temporal variation.

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