Coastal Dynamics and Sediment Transport in parts of Hooghly Estuary

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Abstract- The present study shows various morphological processes and their impacts on the movement of sediment in a complex dynamic coastal zone like Hooghly Estuary and Sagar Island. This is an area where eustatic, isostatic and tectonic forces control the significant geomorpholoical changes in a combine manner. Sediment transport is very important phenomena in this particular study area. With the help of satellite imageries, GIS techniques and a lot of numerical modelling with engineering parameters the study has given a fruitful result. There is a constant movement of sediment in this zone. Analysis of sediment samples indicates sand and clay are found togetherly. Cohesivity of sediments is affected by the seasonal salinity variations near the mouth of the estuary. It is seen that in saline water fine sand is more cohesive while silt may have non-cohesive properties in fresh water.

Keywords- *Estuary;Eustatic; Isostatic; Tectonic; Cohesivity*

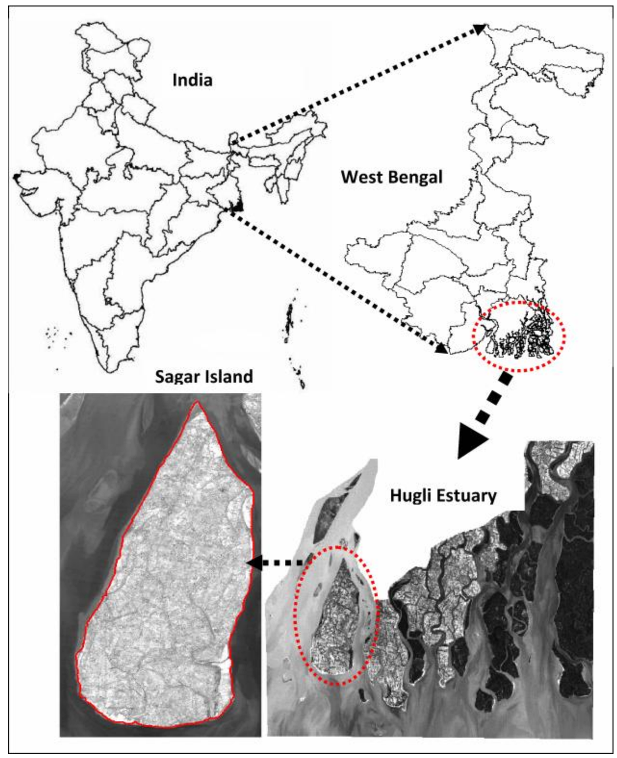
I. INTRODUCTION

The morphometric setting of the Hooghly estuary and Sagar Island is the product of continuous fluvial sedimentation in a series of para-deltaic lobe progradation systems developed on the western shelf margin areas and eastern troughs of the Bengal basin tectonic frame, over the entire Holocene period, under the combined influences of eustatic, isostatic and tectonic forces. The study area extends between 21º29'54"N and 22º19'26"N latitudes, and 87º46'13"E and 88º58'49"E longitudes (Fig. 1).

All the delta and sub-delta lobes with alluvial plain surface are produced by Subarnarekha, Rasulpur, Kaliaghai-Kangsabati, Rupnarayan-Silabati, Damodar and Ganges Rivers, outbuilded rapidly into the open water when the main transgression waned after 7000bp [1]. The average submergence rate reduced from 1.2m/1000yr in 7000b.p to 0.85m/1000yr in 3000b.p. The decrease in the submergence rate coincided with a change from open muddy estuaries to tidal wetlands [2].

The Hooghly estuary is characterised by a broad expanse of onlapped fluviomarine coastal plain. Since past 200 years, the Hooghly estuary is the abandoned part of the lower deltaic plain of the Ganges-Brahamputra delta. From early phase of this century, it is passing through a destructive phase.

The Hooghly estuary lies at the extreme southern part of Indo-Gangetic plain. The Quaternary sediments is underlain by the Tertiary sediments reflecting a huge deposition in a subsiding tectonic trough. The Quaternary sediments of the Bengal plain constitute the flood plain deposits and deltaic deposits and consists of the Newer alluvium (Recent to Sub-Recent) and Older alluvium (Pleistocene) Groups.



The sea level has been a major constraint on the Late Quaternary evolution of the Ganges-Brahmaputra delta. The postglacial transgression is recorded by the presence of marine shell layers (7000-6500 yrs b.p) found at a depth of 11-18m near Khulna, Bangladesh [7].

A. *Geological Setting*

The Sagar and the adjacent Islands, lying on the southern part of the Bengal Basin, are now covered by the Recent-Sub Recent alluvium underlain by thick sediments of Tertiary Period. The basement of the Bengal basin is a part of the eastern edge of the Indian plate, which is being subducted beneath the China plate along the Sunda subduction zone and Naga-Lushai orogenic belt. Whereas, the tectonic and depositional history of the Bengal basin has been controlled by several movements during Cretaceous-Tertiary periods, the basement and basin stratigraphy also controlled the space for sediment accommodation, sediment supply, sediment by-passing of the Ganga-Brahmaputra delta head ("swatch of no ground channel").

B. Objectives of the Study

1. To understand the sediment transport mechanics and the hydrodynamics of the Hooghly estuary.
2. To model the growth, migrations and the stabilities of the channels in the estuarine region using prediction analysis.
3. To model the total sediment load transported through the Hooghly estuary using numerical methods, satellite imageries, and GIS studies.

II. METHODOLOGY

The study of the subsurface geology as recorded from the lithologies around the Sagar Island [1] indicate that the unconsolidated sedimentary correlatable formations (coarse granular and fine sand, silt and clay layers) occur in variable alternating layers upto a depth of 300m. A thick lithomargic (lagoonal) clay blanket occurs at 300m. There is a general increase in the thickness of the sand layers towards south. The details of the information have been given below (Table. 1).

Table 1. Lithological Information

Formation	Location	Log details
Recent(coastal/ estuarine)	GangaSagar	Estuarine clay (0.90m) - 2920 ± 20YBP
Recent (coastal/ estuarine)	Bakkhali	Mangrove woods and estuarine clay(41.0 m) - 6165 ± 100 YBP
Recent (coastal/ estuarine)	Namkhana	Lithomergic clay (1.75m) - 3170 ± 70 YBP

Although numerous works [9] [6] [3] have been carried out to quantify different geomorphological events in the vicinity of Sagar Island, however not much is known on the morphometry and morphodynamics of Sagar Island and its relationship with other Islands. Moreover reports on rate of channel migration in the Hooghly estuary do not exist. The geological evolution of any Island does provide information on ancient coastal dynamics. A comparative study of the past process and the present should help one to bring out a model for predicting the future nature of coastal geomorphological processes and near-shore dynamics.

The geomorphological processes near estuary are influenced by a number of interactive and environmental factors (geological, fluvial, marine, and meteorological). The dynamics of the fluvial processes in the study area (around 1500 sq. km) are very complex and are a function of the alluvial and coastal processes compounded with tidal hydrodynamics. Any attempt to handle the problems, require thorough understanding of tidal and estuarine dynamics.

A. Field Survey

The present work comprises analysis of field data (hydrographic survey data, navigational charts and coastal soundings) of the study area and its processing, satellite image analysis and generation of base models.

B. Satellite Data

In order to analyze the morphological processes and sediment movement in Hooghly Estuary and Sagar Island, satellite images of the last four decades have been used. Landsat MSS image of 17th January, 1973; Landsat TM image of 14th November, 1990; Landsat ETM+ image of 17th November, 2000 and Landsat TM5 image of 8th November, 2011 have been considered for this study. Besides these images, Survey of India (SOI) topographical sheets numbering 79C/1 and 79C/2 (surveyed between 1967 and 1969) have also been used as reference maps to get the accurate results. Moreover, hydrographic survey charts from Kolkata Port Trust have also been used showing sediment transport.

C. Meteorological Inputs

The Sagar Island is exposed to extreme weather condition where the interaction between ocean and land mass is very strong. The climate is tropical to sub-tropical in nature. The various meteorological parameters have been given (Table. 2).

Table 2. Meteorological Parameters

Parameters	July	December
Wind speed (meter/second)	5.55	1.95
Air temperature (^{0}C)	28.9	21.17
Relative Humidity (%RH)	87.4	67.02
Air pressure (hectopascal - hPa)	998	1013.34
Rainfall (mm/month)	100	5
Wind direction (deg)	204	112.89
Wind gust (knots)	74.8	25.41

III. NUMERICAL MODELLING

On the basis of earlier information on the behavior of Hooghly estuary, we attempt to combine the generalized concepts of sediment transport in estuaries with the available data and modelling for Hooghly estuary. The objective is to establish a correlationship among the different hydrodynamic parameters of model results, with reference to the present status of the Hooghly estuary and try to predict future morphological changes in the estuary by long-term simulation.

A. Characteristics of the Hooghly estuary

An estuary may be defined as a semi-enclosed coastal water body which has a free connection with the open sea and within which seawater is measurably diluted with freshwater derived from land drainage [5]. In the Hooghly estuary, the Hooghly (lower part of Ganga-Bhagirathi), Damodar, Rupnarayan and Haldi (lower part of Kangsabati), Rasulpur Rivers are the freshwater sources, eventually draining into the Bay of Bengal.

The River Ganges is one of the biggest Rivers in the world, discharging into the Bay of Bengal through one of the world's largest deltas. The Hooghly / Bhagirathi River is a distributary of the Ganges delta, separating from the main Ganges River at Farakka, 560kms upstream of Sagar Island. The Bhagirathi River is the freshwater section, while the tidally influenced lower section is called the Hooghly River. Some of the distributaries of Ganges upstream of Farakka also join the Hooghly / Bhagirathi River. The other major discharges into the Hooghly River are from the Damodar valley, which joins the Hooghly through the Damodar River and the Rupnarayan. The Damodar valley has a number of reservoirs that reduce peak runoff discharges. The Rupnarayan joins the Hooghly near Hooghly point. Tide propagates 300 km upstream of Sagar Island, increasing in amplitude from Sagar towards Hooghly point, and subsequently decreasing to negligible tide near Swarupganj.

Downstream (or seaward) of Hooghly point, the estuary begins to broaden exponentially - a feature typical of most estuaries. The portion between Haldia and Sagar with the Jellingham Bar and the Auckland Bar forms the inner estuary while the portion south of Sagar forms the outer estuary. The estuary has a number of islands and shoals, splitting flows through channels and resulting in a complex hydrodynamic flow field. These bars exist from the outer harbour to the upper reaches of the tidally influenced section of the River. The stability of the bars is critical for operation of the port. The bars upstream of Diamond Harbor have stabilized since the commissioning of the Farakka barrage in early 1970's. The barrage ensures perennial flow from the Ganges into the Hooghly River.

B. Sediment Movement in Estuaries

It must be recognized that estuarine sediment transport and morphology remains one of the most complex problems in coastal engineering. After decades of engineering projects in estuaries, with some success and some failures, there remains no consensus on the most appropriate technique, other than concluding that River training projects in estuaries require long-term geomorphological studies, accompanied by continuous monitoring during and after a project on River training. Estimates of sedimentation rates, if not calibrated, can differ from field sedimentation rates by a factor of 2 to 5 [8].

Sediment transport in estuaries primarily results from currents due to freshwater inflows and tidal behavior. The higher the currents, the greater the shear stress and turbulence generated at the bed, and greater the movement of sediment by bed load and suspended load transport. In theory, an estuarine system attempts to reach a state of dynamic equilibrium for a given set of hydraulic conditions (freshwater, tides, geometry). While this does not imply a steady state condition, where sedimentation patterns remain constant, it implies that fluctuations will occur within certain limits over a longer period (in the order of decades). One method of determining the stability of an estuary is by plotting the change in estuary volume over a period of time.

The "stable condition", in reality however, is an elusive state, as the inputs to the system rarely remain stable. For instance, increased erosion and sedimentation and erosion in the channels can result in ever changing bathymetry, increased sediment carried from the catchment area can result from changing land use, increased runoff due to a "good" monsoon and cyclones are all natural causes for changes. These uncertainties of the inputs together with the continuing evolution of the theory related to estuarine sedimentation results in high uncertainties in predicting the behavior of an estuary accurately. Long-term modelling and continuous monitoring can help reduce this uncertainty.

C. Sediment transport modes

Sediment particles are transported by water in three distinct modes

- rolling and/or sliding motion
- saltating or hopping motion, and
- suspended particle motion

Shear stress on the bed of an estuary, results from variation of velocities of water near the bed. In other words, the moving water imposes a force on the bed material in the direction of flow. As water velocity increases, the variation increases and thus greater the shear stress. When the shear stress at the bed just exceeds the critical value required for initiation of motion, sediment particles begin rolling and/or sliding while remaining in continuous contact with the bed. The rate of sediment movement along the bed will be driven by friction and gravity in the case of sloping beds. The direction of the sediment movement is defined by the direction of water flow and the slope of the bed.

As water velocity and shear stress further increase, the particles are suspended momentarily, moving along the bed in more or less regular jumps, called saltations. With increasing bed shear stress levels, the upward turbulent forces lift the sediment particles from the bed into the water column. If these forces are greater than the submerged weight of particles, the particles will remain in suspension. Deposition occurs when the grains come to rest in bed load transport or by settling out of suspension. Erosion and deposition can occur simultaneously depending on the grain size of the particles. In the Hooghly River, the high range of grain sizes and velocities is likely to result in all of the above modes of transport.

D. Bed load and suspended load transport

Bed load transport means the transport of particles by rolling, sliding and saltating while suspended load transport is the transport of suspended particles. In addition to material from the bed of the estuary, suspended load may also include fine silt and clay particles from upstream catchment areas (wash load). Bed load and suspended load transport often occur simultaneously.

Bed load transport is highly dependent upon water velocity, the rate of transport varying with about the cube of water velocity. The general form of the relationship is

$$Q_t \alpha U^n \quad ....(1)$$

Where Q_t is bed load sediment transport rate and U is velocity. The coefficient can vary from 2.5 to 5 depending on the empirical relationship determined by various researchers. In general, n=3, while for Hooghly estimates are n=5. Thus, bed load transport is sensitive to small changes in velocity.

E. Sources of sediment

There are number of sediment sources (Fig. 2) in an estuary [4]. Each of the sources contributes different types of sediment. For example, Riverbank erosion and catchment runoff provide large quantities of sand, silt and clay. Catchment runoff can also contribute organic matter to the River/estuary. Littoral processes (i.e. processes in coastal waters) can supply sand to an estuary. Wind action on dunes and inter tidal sand banks carries fine sand into an estuary.

Table 3: Sources of Sediment

S_{LB}	littoral drift and/or bank erosion
S_D	return of dredged spoil
S_O	Entrance marine shoals and tidal delta sands
S_P	Disposal of domestic and industrial effluents and solid wastes
S_W	wind erosion of coastal dunes and drying inter tidal shoals
S_A	decomposition and excretions of marine and River plants and animals
S_R	erosion of upper catchment and transport by Rivers and streams

F. Upstream Sources

The catchment area for the River Ganges is 1.6 million km^2. At Farakka, the annual measured suspended sediment load is 729 M t/yr, of which 328 M t/yr is transported to Hooghly River. In addition, sediment flows can occur from the Damodar River Valley, Haldi River and distributaries of Ganges entering downstream of Farakka. Kolkata Port Trust estimated that 100 Mm^3 of suspended sediment is transported per year into the Hooghly estuary downstream of Kukrahatti near the Hooghly point. Even if one considers a deposition of 1 mm in the study area between Kukrahatti and Sagar roads, the siltation is equivalent to 1.28 Mm^3.

Freshwater flows during large runoff events can be greater than peak tidal flows. Thus, freshwater runoff can transport sediment downstream at very high rates, as evidenced by the unstable shallow sand shoals in Rangafalla channel. The sand transported downstream by freshwater flows may be deposited on the seaward face of the entrance bar. After the flood dissipates, the sand is reworked by the tidal currents and waves and is returned to the estuary over a period of several months.

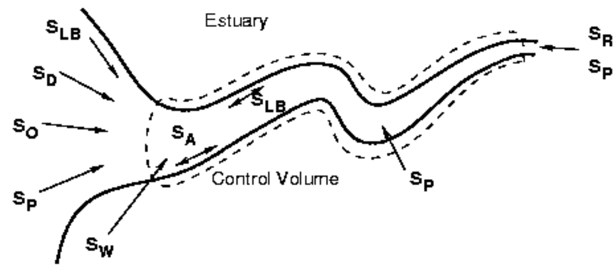


Fig. 2: Sources of Sediment Transport [4]

In addition, the presence of salt in an estuary produces a longitudinal density gradient, with water densities around the mouth of the estuary being greater (because of higher salt concentrations) than densities around the head of the estuary. This results in the enhancement of flood tide velocities near the bed and ebb tide velocities near the surface (Fig. 3). When averaged over a tidal cycle, this behavior leads to residual currents, in which saline water flows upstream along the bottom of the estuary and less Fig. 3: salinity Circulation in Estuaries salty, even fresh water, flows seawards near the surface. This pattern of residual flows is referred to as gravitational circulation (it is driven by the gravitational forces resulting from density differences).

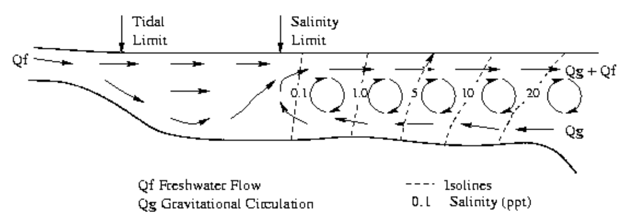


Fig. 3: Salinity Circulation in Estuaries

Both tidal distortion and gravitational circulation facilitate a net upstream movement of suspended solids, i.e. a residual suspended load flux. Because of tidal distortion, the duration of high water slack is different from low water slack, thereby generating differences in the slack water settling opportunity for suspended particles. This, coupled with differences in current behavior around the two slacks, can impart a net displacement to suspended sediment each tide cycle. While gravitational circulation may be low in the well mixed Hooghly estuary relative to more stratified estuaries, the salinity limit may serve as an indicator of direction of net movement of sediment. For the September 2002 survey conducted by National Institute of Ocean Technology, the salinity front of 1-2 ppt was found in the Jellingham and Gangra region. For the March 2003 survey, the salinity front had moved upstream towards Balari and Kulpi. Thus, as expected, the null point or salinity limit shifts depending on the freshwater flow results in increased dredging when the salinity limit is in the vicinity of Jellingham.

G. *Mathematical Modelling*

Short term mathematical modelling for hydrodynamics and sediment transport were carried out to assess the baseline condition and future morphological changes. A two dimensional depth averaged model was used to simulate hydrodynamics, ignoring effects of wind, wave, salinity etc. Analysis of sediment samples shows some areas are predominantly sandy and some clayey. In addition, seasonal salinity variations near the mouth of the estuary that can affect the cohesive properties of sediments. Fine sand can behave like cohesive sediment in saline waters and silt may exhibit non-cohesive properties in fresh water. Thus both cohesive and non-cohesive sediment transport models were used for the study.

1. Hydrodynamic Simulation

Hydrodynamic simulations has been done through the Mathematical model (CCHE-GUI 3.0, source: National Center for Computational Hydroscience and Engineering, School of Engineering, The University of Mississippi University, USA). This is a depth averaged two-dimensional finite difference model based on the mass and momentum conservation equations. Since this is a two-dimensional model, it assumes the estuary to be well mixed, which was established from various literatures. The basic inputs required for model are bathymetry of the area, boundary conditions, bed friction and eddy viscosity. Wave and wind effects were not considered in this study, primarily because of the lack of data. The governing equations are provided below.

2. Governing Equations

The depth integrated two-dimensional equations are solved in CCHE2D model.

Continuity Equation:

$$\frac{\partial z}{\partial t}+\frac{\partial (hu)}{\partial x}+\frac{\partial (hv)}{\partial y}=0 \quad \text{.......(2)}$$

Momentum Equations:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-g\frac{\partial Z}{\partial x}+\frac{1}{h}[\frac{\partial (h\tau_{xx})}{\partial x}+\frac{\partial (h\tau_{xy})}{\partial y}]-\frac{\tau_{bx}}{\rho h}+f_{Cor}v \quad \text{...(3)}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-g\frac{\partial Z}{\partial y}+\frac{1}{h}[\frac{\partial (h\tau_{yx})}{\partial x}+\frac{\partial (h\tau_{yy})}{\partial y}]-\frac{\tau_{by}}{\rho h}+f_{Cor}u \quad \text{...(4)}$$

where *u* and *v* are the depth-integrated velocity components in the *x* and *y* directions respectively; *g* is the gravitational acceleration; *Z* is the water surface elevation; ρ is water density; *h* is the local water depth; f_{Cor} is the Coriolis parameter; $\tau_{xx}, \tau_{xy}, \tau_{yx}$ and τ_{yy} are the depth integrated Reynolds stresses; and τ_{bx} and τ_{by} are shear stresses on the bed surface.

CONCLUSION

It is an area of constant dynamic mophological activities. Erosion and deposition take place together as coastal geomorphological process. In order to estimate the movement of sediment and other hydrographic elements detail field investigation is essential. Preparation of facies map for stratal correlation is also needed. Detailed granulometric analysis of the sediment samples following standard methods (sieve and particle size analyzer) is also necessary. Analysis of water samples for bulk chemistry and estimation of bulk density of bed load samples will also be very much helpful to draw a concrete conclusion regarding the study area in the near future. Various numerical modelling and simulation for detecting sediment transport rate helps a lot in this complex analysis.

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