Estuarine Dynamics, Processes and Sediment Transport – A Case Study from the Hooghly Estuary in the Ganges Delta

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Introduction

An estuary is a partly enclosed coastal body of water with one or more rivers or streams flowing into it, and with a free connection to the open sea. The estuarine environment is characterized by a constant mixing of freshwater, saline seawater, and sediment, which is carried into the estuary from the sea and land.

Sediment transport plays a pivotal role in many aspects of coastal engineering. Precise information of sediment transport is vital for port and harbor construction activities, recreational beaches, pipeline safety, and offshore platforms. In this context, an improved understanding of sediment transport is critical for advancement of coastal engineering.

Although many advances have been made in nearshore and coastal hydrodynamic models, the pace in development of sediment transport models still lags. Hydrodynamic processes can be modeled with well-defined governing equations embedded with superior model physics; however, the processes of micro-scale sediment suspension and transport are less well defined. Sediment suspension has been studied separately under the action of surface gravity waves and currents by several researchers. The complexity of the problem arises under the combined action of waves and currents. The present thesis attempts to contribute some observations and inferences based on field and model experiments related to the Hooghly estuarine hydrodynamics and sedimentary processes of the Hooghly estuary in the Ganges delta, India.

The Hooghly estuary, the first deltaic offshoot of the Ganges is a coastal plain estuary and lie approximately between 21°31 –23°20′N and 87°45′–88°45′E. The Hooghly estuary that forms an important link between the Hooghly–Bhagirathi river system and the Bay of Bengal has evolved as a constituent of the world's largest fluvio-marine delta Ganges-Brahmaputra-Meghna (GBM), within the geographical boundary of India. The delta lobes within the alluvial flood plain have been formed by the rivers Bhagirathi-Hooghly, Mayurakshi, Ajoy, Damodar, Silabati, Kangsabati, Rupnarayan, Kaliaghai-Haldi and the Rasulpur. The precipitation dislodges the clastic sediment resulting in sediment-laden river flow that interacts with the salinity and the tidal flow in the Hooghly estuary and enters into the Bay of Bengal.

Exceptionally high sediment movement and water discharge has made the Hooghly estuary a vulnerable zone to land erosion and accretion alongwith dynamic water circulation. During the monsoon, huge quantities of sediment are transported through the rivers and tributaries, a part of which gets deposited in the indentation of terrain and river bed while the remaining part is flushed into the Bay of Bengal. In the dry season, the sediments are re-oriented and mainly deposited within the estuary or near the coast. A net accretion rate of about 50.0 million cubic meters per year has been observed during the last 175 years in the outer Hooghly estuary.

There are three main factors controlling the Hooghly estuary: (1) the regional geology and the structural framework (2) the different physical processes that influences the estuarine system (3) the eco-biology of the living organisms that inhabit it.

The present study focuses on the sedimentation dynamics and morphological processes of the estuary. The study is supported by in-depth hydrological and remote sensing data, followed by GIS analysis. The tidal circulation, salinity processes and climatic parameters which have substantial impact on this estuarine system have been also discussed.

The morphometric changes have significant implications on the estuaries. The Hooghly estuary provides an opportunity to study such morphological changes for better understanding of the coastal and fluvial processes through both long-term records and also a short-term study using satellite imageries. To understand the morphodynamics of the tide controlled estuarine system, the surface water flow and rate of sediment transport have been determined through a mathematical model. A predictive forecast on the morphological evolution that might occur in the Hooghly estuary in future years has been done with the help of this mathematical model.

Review of Literature

The Quaternary geology and the hydraulics of the Hooghly estuary and the river system were studied earlier by various workers (Morgan and McIntire, 1959; Chugh, 1961; Sengupta, 1966; Gole and Vaidyaraman, 1966; Coleman, 1969; Niyogi, 1970; Curry and Moore, 1971; Sengupta, 1972; Bhattacharya, 1973; Biswas, 1974; McDowell and O'Connor, 1977; Mazumder *et al.*, 1984; Chakraborty, 1993; Chakrabarty, 1995; Sanyal, 2000; Paul, 2002; Alam, *et al.*, 2003; Kuehl, *et al.*, 2005; Mukherjee, *et al.*, 2007; Mukherjee, *et al.*, 2009; Prandle, 2009; Purakait, 2009; Jha and Bairagya, 2011; Banerjee *et al.*, 2013; Das *et al.*, 2014; Goswami *et al.*, 2014).

Kuehl *et al.* (2005) observed that the Ganges and Brahmaputra rivers coalesce in the Bengal basin in Bangladesh. Sedimentation patterns in the subaerial delta have been strongly influenced by tectonics, which has compartmentalized the landscape into a mosaic of subsiding basins, and uplifted the Holocene and Pleistocene terraces. The Holocene evolution of the delta also has been mediated by changing river discharge, basin filling, and delta-lobe migration. Offshore, a large subaqueous delta has prograded seaward across the shelf, and is intersected in the west by a major submarine canyon that acted both as a barrier for the farther westward transport of the sediment of the rivers and also as a sink for about a third of the fluvial sediment discharge. Subaerial and subaqueous progradation during the Holocene period has produced a compound clinoform, a feature which appears to be common for large rivers discharging onto an energetic continental shelf.

However, Jha *et al.* (2011) remarked that the Ganga-Brahmaputra delta is situated in the southern part of Bengal basin in eastern India. The Bengal basin as well as the Ganga-Brahmaputra delta, is a significant low flat terrain which has an elevation of 10-30m above the mean sea level. While the delta building processes have been active in the southern part, the northern portion shows the development of a mature landscape.

The hydrodynamics and the hydraulic behavior of the Hooghly estuary have been also studied by many researchers (Chugh, 1961; Gole, 1966; McDowell, 1977; Mazumder, 1984; Chakraborty, 1993; Sanyal, 2000). Bhattacharya (1973) described the deltaic activities of the

Bhagirathi-Hooghly river system. The patterns of the sediment transport have been also discussed by few researchers (Bhattacharya, 1973; Biswas, 1974). The general hydraulics and estuarine dynamics in terms of energy dissipation rate have been also discussed by few researchers (Dube, 2003; Das, *et. al.,* 2005; Chaudhuri and Das, 2008; Prandle, 2009; Banerjee, 2013). *However a detailed quantitative analyses of the upland surface water flow, sediment erosion, sediment transport and deposition in the Hooghly estuarine system, are lacking. The current work addresses these issues through mathematical modeling*.

Objectives and Scope

The objectives of this work are as follows:

a. To understand the Hooghly estuarine system and to reconstruct the paleosedimentary processes in the Hooghly estuary

b. To understand the hydrodynamics and the sediment transport mechanics in the Hooghly estuary

c. To identify the vulnerable area of erosion and deposition and model the trend of estuarine transformation using numerical techniques

d. To quantify the total sediment load transported through the Hooghly estuary using numerical methods, satellite imageries, and GIS studies

e. To develop a feasible methodology for the 3d-bathymetry mapping of the Hooghly estuary using archive data, space technology and prediction analysis

f. To setup a hydrodynamic and sediment transport model for real time estuary and river management using computational techniques (MIKE11 and MIKE21)

The details of a-f have been appended below in the flow chart (Fig. 1)

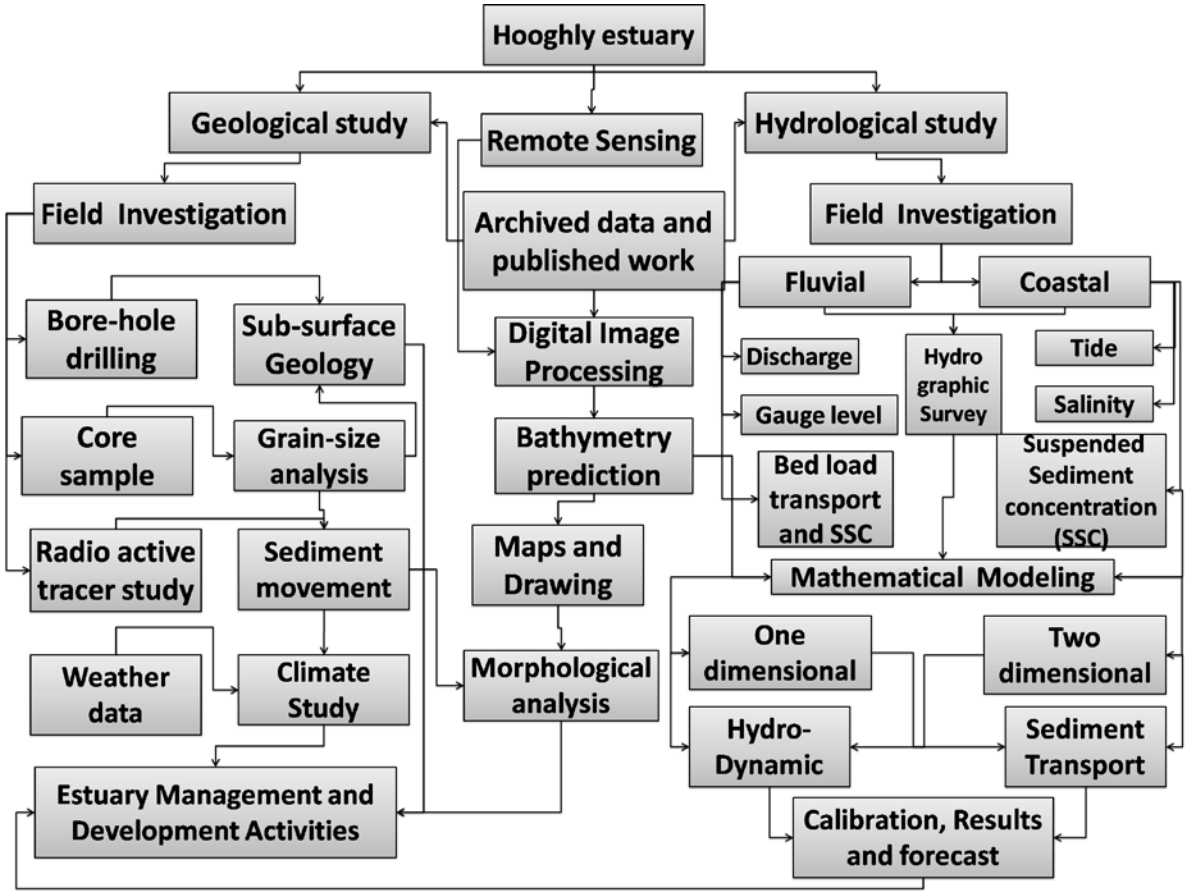

Fig. 1. Flow chart depicting the various steps used to carry out the present work

Results and Discussions

A comprehensive endeavor through hydro-geological introspection and mathematical calculations for studying the hydrodynamics and sedimentary processes in the Hooghly estuary has been presented.

The geology of the Hooghly estuary has been understood in the perspective of its evolutionary history. The hydrological characteristics, surface sedimentary processes, sub-surface characteristics of the estuarine system have been discussed.

In the context of different mechanisms and forcing factors, the evolutionary trends and variability in morphodynamic behavior of the Hooghly estuary have been studied in two steps (i) qualitative and quantitative analyses of the generated data of the Hooghly estuary for a long-term assessment of geomorphological transformations (ii) a short-term quantitative

investigation based on the available hydrographic survey data alongwith the satellite imageries.

Special attention has been given on the application of a numerical model to explore the morphological evolution of the Hooghly estuary. This was done with the help of one-dimensional and two-dimensional hydrodynamic and sediment transport model. As a model tool, MIKE 11 HD, MIKE 11 NST, MIKE 21 HD, MIKE 21 MT modules of Danish Hydraulic Institute, Denmark have been used (MIKE-11: module for one-dimensional (1D) analysis, MIKE-21: module for two-dimensional (2D) analysis, HD: hydrodynamic calculations; NST: non-cohesive sediment transports, MT: mud transport calculations).

The two-dimensional (2D) models (hydrodynamic-HD / sediment transport-MT) have been employed for the outer Hooghly estuary. For the rivers and channel networks, one-dimensional (1D) models (HD / ST) have been used for the calculation of sediment flow and flux.

From the results of different flow models, the sediment budget has been prepared for the Hooghly estuary and its riverine system. A mathematical model has been proposed for the future bathymetric conditions of the Hooghly estuary. The results show that the outer Hooghly estuary has a net sediment loss of 48.57 million m^3 while the incoming sediment deposit gains to 52.49 million m^3 per year.

Attention has been given to establish a comprehensive investigation of the geomorphic sequence of the Hooghly estuary and its river system, and based upon which local planning and management decisions may be taken. It is believed, that the Hooghly estuarine system is exceptionally complex and any inferences evolving from this study should be seen as a preliminary attempt in the process of understanding of the estuary.

Conclusions

The hydrogeological behavior and mathematical models for estuarine hydrodynamics and sediment transport in the Hooghly estuary have been documented.

From the results of different model studies, a sediment budget has been prepared for Hooghly estuary and its river system. The proposed mathematical model predicts a morphological forecast on the optimistic bathymetric condition of the Hooghly estuary in the ensuing 22nd century.

Attention has been given to establish a coherent geomorphological sequence of Hooghly estuary and its river system upon which local planning and management decisions may be taken. The Hooghly estuarine system is exceptionally complex and that the inferences ensuing from this study should be seen as only the first stage in the process of understanding of this complex estuarine system.

The Hooghly estuary has experienced rhythmic changes with respect to deposition or erosion during the last 175 years. A periodic pattern was followed by each event of successive growth (phase of deposition) or consecutive decay (phase of erosion). Each phase lasted for about 35 years and this tendency had been prevailing upon since nineteenth century. The short-term study suggests that the estuary depth has changed in a rhythmic pattern since the year 2000 and the trend analysis depicts that, for next couple of years, the estuary volume (below high bank level) will be maintained at somewhere near to 25000 million m^3.

The mathematical model on the net sediment transport shows that the outer estuary is undergoing a net sediment loss of 48.57 million m^3 and draining out of the system towards the sea, and there is a surplus of the incoming sediments amounting to 52.49 million m^3 per year. A net accretion rate of about 50.0 million cubic meters per year has been observed during the last 175 years in the outer Hooghly estuary.

Limitations

During the course of study, utmost attention has been paid to understand the sedimentation pattern and primary functioning of the Hooghly estuary. However, there are certain areas where the work remains questionable.

(a) Morphological analysis - the earlier survey charts have been prepared manually and the accuracy of the datasets is questioned. In the morphological study the net changes between

successive datasets have been considered, but the intermediate information on anthropogenic intervention which *is often not well documented* have been overlooked. The past trends have been used to predict the future behavior though the same may not always be a good indicator.

(b) Mathematical modeling - in the mathematical model, the computational domain is constructed through nodes and elements which are discrete points. The model does not have any information in between the points which are the major departure from the reality and therefore does not completely represent the complex estuarine bed. Again, it is obvious that each of the estuarine survey took over six months to one year. In this period, the surveyed data would have been subject to error as the morphology changed on each tidal cycle. The conversion from the chart to a digital image poses some limitations.

Future scope of work

Some relevant incorporation that may be helpful to the future researchers

- Bathymetric prediction in the estuaries is very prospective and challenging job for any water resource investigations. Development of more efficient method using latest high resolution satellite data is a good scope for future study.
- Modeling of fine sediment transport with different fraction of bed layer is also a potential study area.
- A comprehensive sediment budget considering all the contributing reservoirs with measured data for a longer period need to be prepared for a better understanding of the Hooghly estuarine system.

Disclaimer

All scientific or analytical inferences drawn in the present work are only meant for academic purpose, and have no consequences on the views of the Kolkata Port Trust. All observations, inferences, errors of observations (if any) lie solely with the author.

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