Dredging maintenance plan for the Kolkata port, India

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The present study reports on a systematic procedure and maintenance plan for conducting dredging activity at the Kolkata port located in the Head Bay region, east coast of India. It is one of the oldest riverine ports in the country constructed by the British East India Company. The port comprises two docks, viz. Kolkata Dock Complex and the Haldia Dock System under the administrative control of the Kolkata Port Trust. The navigation channel located in the Hooghly River accommodates sea-going vessels with 200 GRT with pilotage assistance cruising upstream almost 145 km from Sagar Islands located in Hooghly estuary. The navigation channel experiences high rates of sedimentation being a riverine port. This study investigates the sedimentation rate throughout the navigation channel, identifying zones of high sedimentation rate. The behavioural pattern of tides and currents is analysed using the state-of-the-art ADCIRC model, and wave conditions are simulated using SWAN model. The hydrodynamic information obtained from ADCIRC and SWAN is input to the SEDTRANS model. Based on the intensity of sedimentation, the maintenance plan is proposed for three dredging seasons. On the basis of this scientific rationale and seasonal dredging maintenance procedure, it is anticipated that huge investments involved in the maintenance dredging of this channel can be minimized.

Keywords: Dredging maintenance, navigation channel, ports and docks, sedimentation rate.

THE past few years have experienced a radical change in the Indian port industry primarily due to the growing importance on physical integration of transport chain. Compared to other developed countries, India has lesser number of ports. The Kolkata Port Trust (KoPT) administers the Kolkata Dock System (KDS) and Haldia Dock Complex (HDC), an important national port located in the Head Bay region of the Hooghly River, east coast of India (Figure 1). This port situated in a strategic location with major cargo-handling facility faces severe problems due to maintenance dredging and other technical issues. The high rate of sediment loads from the Hooghly River creates navigation-related problems for ship traffic. It is anticipated that the future generation vessels would require drafts between 13 and 15.5 m. Due to the current draft restriction, several Indian ports are unable to handle larger vessels typically more than 12.5 m draft and the Kolkata port is one among them. Based on the latest statistics from the Indian Ports Association (IPA), the traffic ($\times 10^3$ tonnes) for the quarter period (Table 1) from April to July during 2012 and 2013 at Kolkata (KDS + HDC) showed a positive variation of ≈5%, signifying its role in the national development. The total contribution of traffic handled from the Kolkata port is about 7.7% of the combined traffic handled by all Indian ports. In the national scenario, the increase is about 0.47%. As seen from Table 1, Paradip is the nearest port to Kolkata. The traffic handling at Paradip showed a quantum jump of 42.83% in 2013 compared to 2012, whereas it was 4.84% at Kolkata. This brings to light that the Kolkata port is losing its position to other ports because of its inefficiency in handling ship traffic. A draft on the consolidated port development plan by IPA and the Port of Rotterdam Authority[1] highlights the vision and strategy for all Indian ports. Based on this report, the throughput per port for KoPT presently stands at 50; the vision is to increase this by 175 during 2025–26. According to this report, the performance indicator for Jawaharlal Nehru Port Trust (JNPT) is the first with an anticipated throughput of 300, followed by Kandla (200) and KoPT in the third place (175) during 2025–26.

Among the major commodities handled by KoPT, projections show that POL (petroleum, oil and lubricants) and crude demands to KoPT will be almost 219% higher by 2025–26 and this demand will be 337% higher in the neighbouring Paradip port[1]. There could be a major loss of iron ore traffic from KoPT in the coming years[1] and 178% gain by the Paradip port (from 12.8 to 22.8 mt). In addition, there could be a substantial increase in coal traffic by 2025–26 (increase of 208% at KoPT and 232% at Paradip). The coming years will have a huge boost in container traffic at KoPT (almost 85.4 mt by 2025–26; marginal at present). Two major ports along the east coast of India benefit by the container traffic, viz. the Chennai port in South India and the Kolkata port in the Head Bay region. Based on these statistics, in the coming years

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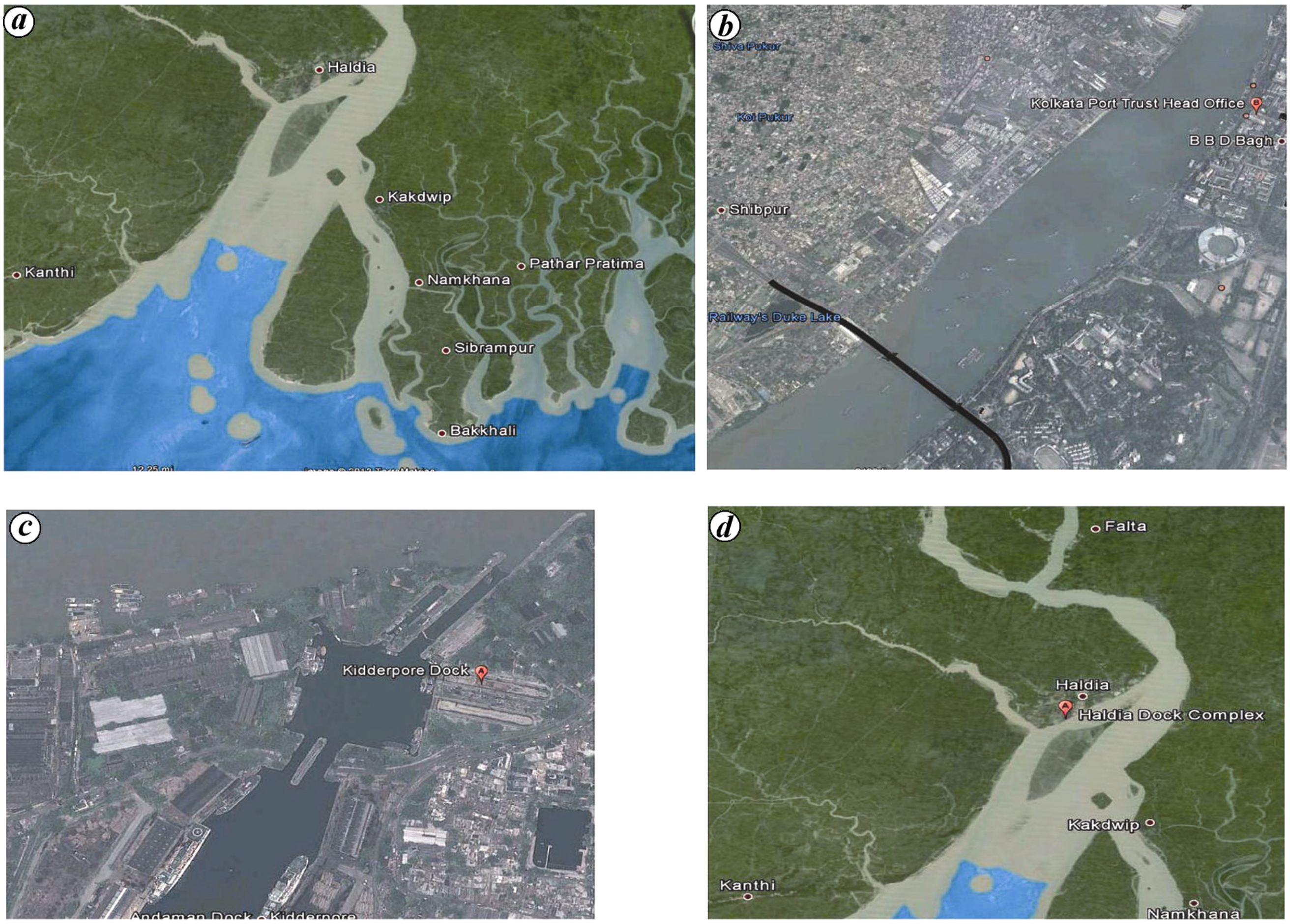

Figure 1. ***a***, The Hooghly River System; ***b***, Kolkata Port Trust; ***c***, Kolkata Dock System; ***d***, Haldia Dock Complex.

Table 1. Traffic handled at major ports in India (during the quarter period from April to July for the years 2012 and 2013)*

Port	April to July: Traffic (in '000 tonnes) 2012	2013	Percentage variation against previous year traffic
Kolkata			
Kolkata Dock System	3,785	4,092	8.11
Haldia Dock Complex	9,756	10,104	3.57
Total: Kolkata	13,541	14,196	4.84
Paradip	16,194	23,130	42.83
Visakhapatnam	20,619	19,720	–4.36
Ennore	5,422	8,366	54.30
Chennai	18,382	17,468	–4.97
V.O. Chidambaranar	9,536	9,173	–3.81
Cochin	6,921	6,912	–0.13
New Mangalore	11,227	12,886	14.78
Mormugao	10,637	3,412	–67.92
Mumbai	19,732	17,740	–10.10
JNPT	22,224	20,750	–6.63
Kandla	29,231	30,775	5.28
Total	183,666	184,528	0.47

*Source: Statistics from Indian Ports Association.

there is a need to revitalize KDS and HDC in the stiff competitive economy. Through an efficient maintenance dredging procedure, KoPT can easily regain its position in the performance indicator matrix. At present, a substantial portion of expenditure is incurred on maintenance dredging costs. Hence, there is a need for a maintenance dredging plan that provides required vessel draft for all seasons such that vessels with higher capacity reach KoPT. This requires a maintenance plan that tunes dredging areas along the navigation channel (Figure 2) based on priority. The Dredging Corporation of India (DCI) performs maintenance dredging for the Kolkata port every six months and disposes the dredged sediments at a rate of 350 million m^3/annum dredging season. DCI performs the dredging task to provide draft of 9 m required by the ships, but there is no action plan by DCI for areas experiencing high sedimentation rates even after the maintenance dredging task is completed. Therefore, the dredging work needs to be evaluated based on a sound scientific rationale.

The Central Water and Power Research Station (CWPRS) under the Ministry of Water Resources, Government of India located at Pune, has carried out extensive hydraulic studies on estimating siltation in the navigational channel and berths for KoPT. Some of the studies include salinity distribution and effect of freshwater flows in the Hooghly River[2]. Cole and Vaidyaraman[2] mention the beneficial aspect of freshwater flow in improving navigable depths along the river channel, and its deterioration causes landward movement of sediments. Based on historical records, i.e. 1962 survey, a mathematical model for the lower reach of Rupnarain River was reported[3]. Further studies on tidal computations using mathematical models for improving the navigable conditions were also reported[4]. A recent work[5] utilizes voluminous hydrographic data to understand the relative movement of sediments in the tidal reach of navigable area in the Hooghly River.

Figure 2. The channel considered for the present study.

Amongst the major national ports of India, investment by KoPT is substantial on maintenance dredging and DCI earns approximately 55% from KoPT dredging activities. KoPT is well connected to the East Asian countries and acts as a direct link of exports and imports with the neighbouring countries. A comprehensive scientific study using three state-of-the-art models – the ADCIRC (advanced circulation; SWAN (simulating waves nearshore) and SEDTRANS (sediment transport) is used here to evaluate zones of high sedimentation (Figure 3) in the navigation channel to KDS and HDC. This study will be useful to field practitioners and brings out a maintenance plan that identifies regions of high sedimentation, categorized into zones and their respective priority level.

Methodology

The methodology involved in the preparation of a dredging maintenance plan involves five stages, as shown in Figure 4. The proposed five-phase methodology is as given below:

- Study the patterns of sedimentation in the navigation channel.
- Study the tidal and wind-driven circulation using ADCIRC model.
- Study the wave characteristics utilizing SWAN model.
- Analysis of sedimentation and transport rate using SEDTRANS model.

Figure 3. Identified zones for the maintenance dredging plan.

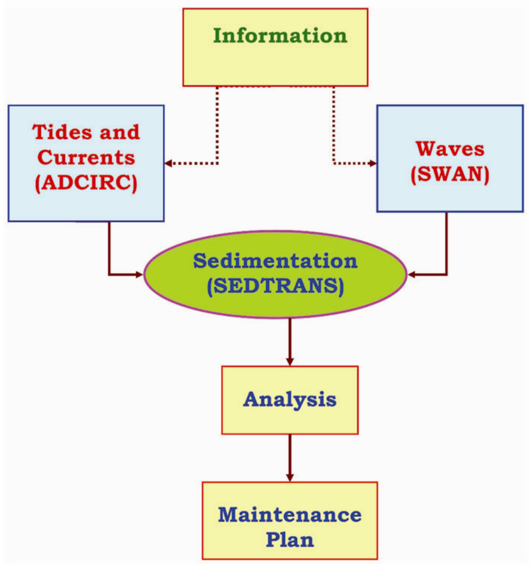

Figure 4. Flowchart for the maintenance dredging plan.

- Final preparation of the maintenance dredging plan based on the above analysis.

Sedimentation pattern in the navigation channel

The Ganges–Brahmaputra perennial river system discharges enormous amount of sediments to the Bengal fan, contributing about 7% of the world flux of sediments (amounting to 1.7×10^{15} g) to the ocean[6]. The tidal effects are noticed upstream nearly 200 km from the estuarine mouth at Sagar Islands. Tides play an important role in the circulation characteristics, causing intense mixing and suspension of bottom sediments. The average freshwater discharge to the Hooghly River is about 3000 $m^3 s^{-1}$ during the southwest monsoon, which reduces to 1000 $m^3 s^{-1}$ during the dry season. The presence of large tidal variation along with presence of islands and navigation channel makes the flow complicated in this estuarine zone. Earlier some studies reported on empirical and physical models to study the sediment transport mechanism in the Hooghly estuary[7]. Thereafter, numerical models were developed to study the circulation and salinity features within the estuary[8,9]. This estuary has a vast expanse of fluvio-tidal and marine coastal sediments comprising sand, silt and clay in a deltaic tropical environment[10].

A recent study shows that coarser grains of nominal diameter (D_{50}) about 0.12 mm are found in the upper reaches of this river, and the particle size gets finer (D_{50} = 0.09 mm) as one approaches towards the estuarine mouth[11]. The tidal pattern prevalent in this estuary is semi-diurnal in nature with neap–spring variations ranging from 2.0 to 5.0 m at the open boundary (mouth of Hooghly estuary). This estuary is shallow in nature with an average depth of about 6 m. Another study highlights the importance of a combined wave–current interaction study to understand the bottom boundary layer characteristics for the Hooghly River[12]. It show that the total bottom stress due to combined effects of wave and current was higher during the ebb phase compared to the flood phase of the tidal cycle, where the velocity in the bottom boundary layer varied in the range between 0.5 and 0.8 m s^{-1}, having implication on the sedimentation patterns. Varying load of sedimentation patterns also alters the bottom friction and thereby the significant wave height[11]. A recent study reported on an upgraded suspended sediment concentration (SSC) model for the Hooghly River[13]. This upgraded SSC model validated with field measurements showed a good match between model and measurements.

The Hooghly River is highly dynamic in terms of its suspended load. It has an annual run-off of approximately 493 km^3 and carries about 616×10^6 t of suspended solids to the estuarine mouth[14]. In the context of sediment distribution within the Hooghly River, field studies show that bed sediments vary to a large extent. Most of the sediments are non-cohesive, fine sand with increasing friction in the presence of bottom sand ripples. Marine geologists in isolated areas of this estuary conducted extensive sampling studies of bottom sediment characteristics; however, very little information is available on its spatial variability. The spatial variability of bottom sediment texture obtained for the present study is from Indian Remote Sensing Satellite (IRS-1A)[11]. The normal practice is that maintenance dredging is performed at regions experiencing both low and high sedimentation rates. This suggested the need for a technical plan, and thus 22 zones were identified in the navigation channel (Figure 3) for which a detailed study of sediment transport mechanism has been attempted. For all the 22 zones, analysis of sedimentation rate was performed for one year based on environmental forcing from waves and hydrodynamic conditions.

The ADCIRC hydrodynamic model

The tide generating forces result from gravitational attraction between the Earth, Sun and Moon. In contrast, the response of the oceans to these forces is subject to modification by non-astronomical factors such as configuration of the coastline, local depth of the water, ocean floor topography and other hydrographic and meteorological influences. These may play an important role in altering the tidal height range, the interval between high and low water, and time of arrival of the tides at a particular location. The depth-averaged version of ADCIRC (2DDI) model was used in the present study and it solves the vertically integrated continuity equation for water surface elevation (ζ) and vertically integrated momentum equations for the currents[15]. The vertically integrated continuity equation is

$$\frac{\partial H}{\partial t} + \frac{\partial}{\partial x}(UH) + \frac{\partial}{\partial y}(VH) = 0, \qquad (1)$$

where

$$U,V = \frac{1}{H}\int_{-h}^{\zeta} u,v \, dz$$

is the depth-averaged velocities along the X- and Y-directions, u, v are the vertically varying velocities in the X- and Y-directions, $H = \zeta + h$ total water depth, ζ the elevation of water surface from the geoid and h is the water depth. The discretization procedure for time is different in the continuity and momentum equations. The time derivatives are discretized over three levels, which means the prognostic water level depends on the present and past water level information. In the momentum equations, the time derivatives are explicit, excluding the Coriolis term, where the averages of present and predicted values of velocities are considered. At each grid point, the

ADCIRC model solves for water level and depth-averaged currents for the user-defined time-step. The water level information is obtained by solving the generalized wave continuity equation (GWCE), a combined form of the continuity and momentum equations[16] expressed in the form

$$\frac{\partial^2 \zeta}{\partial t^2} + \tau_0 \frac{\partial \zeta}{\partial t} + S_p \frac{\partial \tilde{J}_\lambda}{\partial \lambda} + \frac{\partial \tilde{J}_\phi}{\partial \varphi} - S_p UH \frac{\partial \tau_0}{\partial \lambda} - VH \frac{\partial \tau_0}{\partial \varphi} = 0, \quad (2)$$

where

$$\tilde{J}_\lambda = -S_p Q_\lambda \frac{\partial U}{\partial \lambda} - Q_\varphi \frac{\partial U}{\partial \varphi} + fQ_\varphi - \frac{g}{2} S_p \frac{\partial \zeta^2}{\partial \lambda} - gS_p H \frac{\partial}{\partial \lambda}\left[\frac{P_s}{g\rho_0} - \alpha\eta\right] + \frac{\tau_{s\lambda,\text{winds}} + \tau_{s\lambda,\text{waves}} - \tau_{b\lambda}}{\rho_0} + (M_\lambda - D_\lambda) + U\frac{\partial \zeta}{\partial t} + \tau_0 Q_\lambda - gS_p H \frac{\partial \zeta}{\partial \lambda},$$

and

$$\tilde{J}_\varphi = -S_p Q_\lambda \frac{\partial V}{\partial \lambda} - Q_\varphi \frac{\partial V}{\partial \varphi} - fQ_\lambda - \frac{g}{2} \frac{\partial \zeta^2}{\partial \varphi} - gH \frac{\partial}{\partial \varphi}\left[\frac{P_s}{g\rho_0} - \alpha\eta\right] + \frac{\tau_{s\varphi,\text{winds}} + \tau_{s\varphi,\text{waves}} - \tau_{b\varphi}}{\rho_0} + (M_\varphi - D_\varphi) + V\frac{\partial \zeta}{\partial t} + \tau_0 Q_\varphi - gH \frac{\partial \zeta}{\partial \varphi}. \quad (3)$$

The currents obtained from the vertically integrated momentum equations are expressed in the form[16]

$$\frac{\partial U}{\partial t} + S_p U \frac{\partial U}{\partial \lambda} + V \frac{\partial V}{\partial \varphi} - fV = -gS_p \frac{\partial}{\partial \lambda}\left[\zeta + \frac{P_s}{g\rho_0} - \alpha\eta\right] + \frac{\tau_{s\lambda,\text{winds}} + \tau_{s\lambda,\text{waves}} - \tau_{b\lambda}}{\rho_0 H} + \frac{(M_\lambda - D_\lambda)}{H},$$

$$\frac{\partial V}{\partial t} + S_p U \frac{\partial U}{\partial \lambda} + V \frac{\partial V}{\partial \varphi} + fV = -g \frac{\partial}{\partial \varphi}\left[\zeta + \frac{P_s}{g\rho_0} - \alpha\eta\right] + \frac{\tau_{s\varphi,\text{winds}} + \tau_{s\varphi,\text{waves}} - \tau_{b\varphi}}{\rho_0 H} + \frac{(M_\varphi - D_\varphi)}{H}. \quad (4)$$

In eq. (4), the term $S_p = \cos \varphi_0 / \cos \varphi$ is the conversion factor for spherical coordinates. φ_0 is the reference latitude, U and V are the depth integrated currents along X- and Y-directions, $Q_\lambda = UH$ and $Q_\varphi = VH$ are the fluxes per unit width; f the Coriolis parameter; g the acceleration due to gravity; P_s the atmospheric pressure at water surface; ρ_0 the reference water density; η the Newtonian equilibrium tidal potential and α is the effective earth elasticity factor; $\tau_{s,\text{winds}}$ and $\tau_{s,\text{waves}}$ are the surface stresses due to winds and waves; τ_b the bottom stress; M_λ and M_φ are the lateral stress gradient; D_λ and D_φ are the momentum dispersion terms and τ_0 is the numerical parameter which optimizes phase propagation properties.

The solution to GWCE is based on implicit or explicit procedure. The implicit solution requires the application of Jacobi conjugate gradient method that iterates to converge. The explicit solution utilizes the lumped diagonal mass matrix method that is faster per time-step compared to the implicit solution, requiring smaller time-steps for stability. The latest version of ADCIRC model is parallel[17] and in a parallel computing environment, the ADCIRC solution algorithm requires local and global communication between computational cores.

The SWAN wave model

The SWAN is a third-generation wave prediction model formulated based on the wave-action balance equation, mathematically expressed in the form[18]

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial x}(c_x N) + \frac{\partial}{\partial y} + (c_y N) + \frac{\partial}{\partial \sigma}(c_\sigma N) + \frac{\partial}{\partial \theta}(c_\theta N) = \frac{S_{\text{total}}}{\rho} \equiv \frac{S_{\text{in}} + S_{\text{nl}} + S_{\text{ds}} + S_{\text{bot}}}{\rho}, \quad (5)$$

where $N(\sigma, \theta)$ is the wave action density, equivalent to the wave energy density $E(\sigma, \theta)$ divided by the intrinsic frequency (σ). The other terms in eq. (5) denote the time (t), relative frequency (σ), wave direction (θ), propagation velocities in the x- and y-spaces (c_x and c_y) respectively; the terms c_σ and c_θ are the propagation velocities in spectral space and direction. In other words, the first term in eq. (5) represents the local rate of change of action density in time. The second and third terms denote the propagation of action density in geographical space. The fourth term represents the shifting of action density in frequency space due to variations in depth and current. The fifth term takes care of the depth and current-induced refraction processes. The terms on the right hand side of the action density balance equation (S_{total}) account for the resultant action density attributed from wave generation (S_{in}); nonlinear wave–wave interactions (S_{nl}) and dissipation mechanisms (S_{ds}) and (S_{bot}). These terms refer to the source and sink mechanisms in the wave-energy balance equation. The wave generation term S_{in} deals with the momentum transfer from atmosphere to ocean and is responsible for wave evolution and growth during the initial stage of wave growth. The weak resonant nonlinear wave–wave interaction responsible for the redistribution of wave energy is denoted by the S_{nl} term. The dissipative effects due to white-capping, bottom effects and depth-induced breaking are represented by the terms S_{ds} and S_{bot}

respectively. A detailed description on the physical parameterization of these sources and sink mechanisms is available in the literature[18–20].

The SEDTRANS model

The SEDTRANS is a sediment transport model to understand the transport mechanism in continental shelves and estuaries. It simulates location-specific sediment transport as a function of water depth, sediment type, currents and waves. The latest version, SEDTRANS05 (ref. 21) is used in the present study to understand the sedimentation rate of the navigation channel in the Hooghly River. SEDTRANS05 computes the bottom boundary layer parameters for specified currents, or combined wave–current conditions. The threshold bed-load movement is computed as a function of grain size, sediment density, water salinity and temperature. The evolution of bed forms can also be predicted taking into consideration the prevailing hydrodynamic conditions. The activation of cohesive sediment algorithm in SEDTRANS can model the full cycle of bed erosion and suspension transport including flocculation and deposition. The computed time-varying hydrodynamic information from ADCIRC and wave characteristics from SWAN are provided as input to SEDTRANS05 to estimate the sedimentation patterns in the navigation channel.

Dredging maintenance plan

The present study considers the maintenance plan only for those high rated sedimentation zones on the navigation channel that require dredging on priority basis, but not on the disposal mechanism of dredged sediments. The study also does not consider dredging activities on river-bank side slopes, its stability and the pipeline transport of dredged sediments. The potential environmental impact of dredged sediments and their disposal, and cost–benefit analysis are also not the scope of the present study. Taking into consideration high sedimentation rates and annual dredged amount of sediments in entire zones of the navigation channel, the threshold value of 400 million cubic metres (mcm) is prescribed for developing the dredging maintenance plan. Therefore, it is expected that this information compiled and supplemented in a common platform can help the planners and field practitioners to access the same, identify dredging requirement thereby developing a regional dredging strategy.

Results and discussion

In a hydrodynamic perspective, the Ganges is the fifth largest river in the world that bifurcates from the Farakka barrage and discharge as the Hooghly River into the West Bengal delta. The tides have an important role in the estuarine part of the Hooghly River that joins the Bay of Bengal. The high range of tidal variation at the river mouth influences the estuarine environment categorizing the Hooghly downstream as a well-mixed estuary. Intense mixing by tides leads to vertical homogeneity most of the year with the exception of slight stratification existing for a short period during the southwest monsoon season attributed from freshwater discharge. The maximum surface discharge from Hooghly River occurs during the northeast monsoon period, amounting to about 4000 $m^3 s^{-1}$, which reduces to almost 1000 $m^3 s^{-1}$ during the summer months of May and June. The estimated report of surface run-off varies from 0.88, 4.02, 18.7, 8.47, 20.47 to 1.93 km^3 $month^{-1}$ respectively, during May to October[22]. The flow pattern inside the riverine environment is complicated due to large tidal variation, irregular estuarine geometry, presence of small islands, and navigation channels, all these separated by shallow zones. Therefore, selection of a suitable hydrodynamic, wave and sediment transport model is crucial to understand the near-shore and river hydrodynamics required for realistic estimation of sedimentation patterns. This justifies the use of state-of-the-art numerical models such as ADCIRC, SWAN and SEDTRANS as done in the present study.

There exists a morphological disequilibrium in the duration of flood and ebb tidal cycles in the Hooghly River[12]. The duration of semi-diurnal flood tide is almost 3 h with tidal speeds varying from 2 to 3 $m s^{-1}$ for flood phase, and speed less than 1 $m s^{-1}$ during the ebb phase[11]. This asymmetry in time–velocity scales of tidal propagation can lead to varying amounts of sediment load during the peak flood and ebb discharges. The estimated loads vary in the order between 2.6×10^5 and 1.09×10^5 $m^3 s^{-1}$ during peak flood and ebb cycles[23] at the estuarine mouth. This leads to conclusion that net sediment movement in the Hooghly channel is landward. On a long timescale, this time–velocity asymmetry in tides leads to major sediment sink necessitating maintenance dredging for optimum draft for sea-going vessels entering KDS and HDC. The other requirement for dredging is ventilation of the navigation channels from clogging.

The ADCIRC grid used in this study comprises of 41,580 nodes and 80,800 elements, and the model runs with a time-step of 5 sec for all the months during 2011. The model output obtained at time-step of 30 min interval from the starting date of simulation is used in this analysis. Both ADCIRC and SWAN use similar finite element grid structure. Along the open ocean boundary six tidal constituents are prescribed, viz. K1, M2, N2, O1, P1 and S2 in the ADCIRC model. The combination of these six tidal constituents depicts the true tidal field that exists in the Bay of Bengal[24]. The amplitude and phase of these six tidal constituents at the open boundary is synchronizes with the model simulation start time. The tidal field propagates thereafter marching forward with time to the coastal areas along the navigational channel and complex

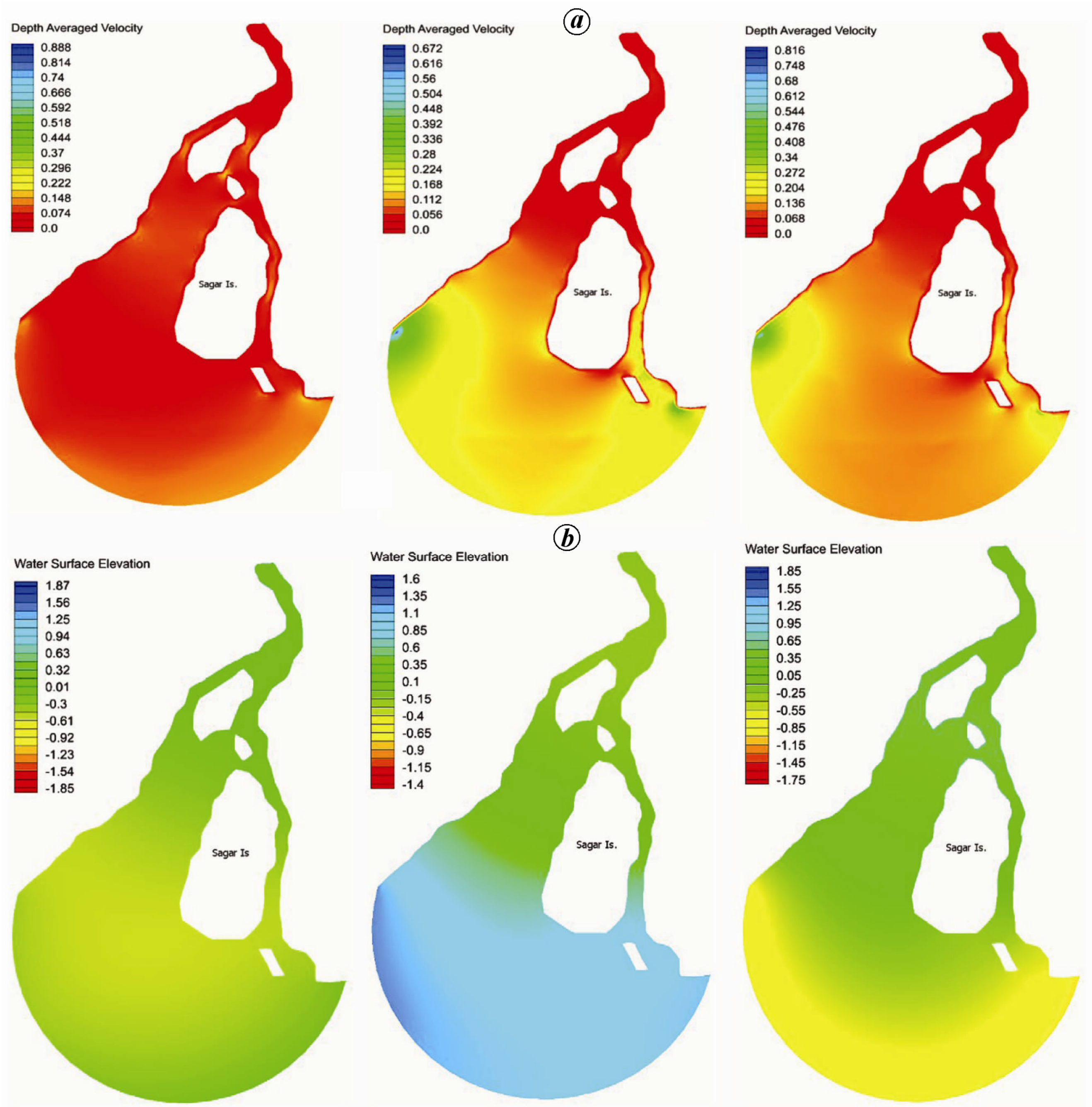

Figure 5. ***a***, Depth averaged velocity (m s^{-1}); ***b***, water-level elevation (m) during February, June and December computed by the ADCIRC model.

geometry. Figure 5 *a* shows the model-computed depth-averaged velocity and associated water-level elevations for three typical dredging seasons (February, June and October). The depth-averaged velocity in general is higher along the navigation channel route during all three dredging seasons, including areas covering the immediate vicinity of KDS and HDC. As expected, this velocity tends to decrease along the upstream reach of the Hooghly River. The surrounding regions south of Sagar Islands from where vessels approach the navigation channel have relatively higher velocity close to 0.3 m s^{-1}.

The water surface elevation computed from ADCIRC follows the tidal cycle and is shown in Figure 5 *b*. The occurrence of phase reversals in water elevations is clearly observed along the up- and downstream sectors of the Hooghly River. This is attributed to the local depth variation and influence of bottom friction for a tidal wave that progresses from deep to very shallow waters. The average depth of the Hooghly River is about 6 m along the upstream tributary, and this increases to about 10–12 m in the open boundary surrounding Dadanpara and Sagar Islands.

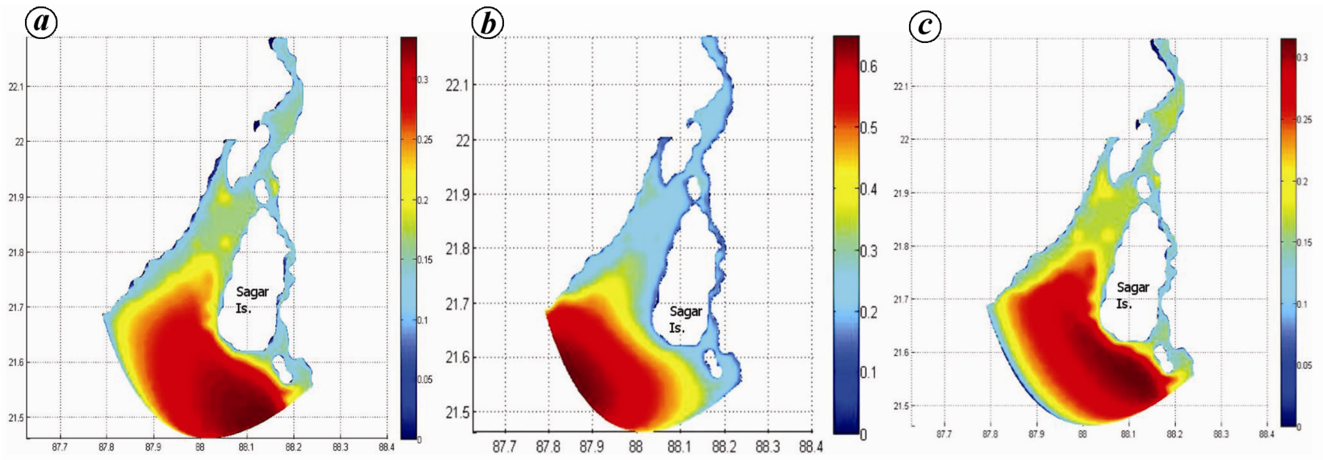

Figure 6. Significant wave height (m) for (***a***) February, (***b***) June and (***c***) December computed using the SWAN model.

Surface gravity waves play an important role in the sediment transport mechanism. The oscillatory nature of water motion leads to wave transport due to the deformation of short waves also referred to as 'wave asymmetry' caused by the decreasing water depth. The net sediment transport occurs due to the combined effect of currents and short waves in a riverine environment. The wave activity in the study domain is shown in Figure 6 for the three dredging seasons. In general, the significant wave height in the Hooghly estuary for all the months in a year is <0.5 m, having mean wave period $1 < 4$ s. The wave activity is higher in the estuarine environment where local water depths can vary between 10 and 12 m. In the upstream reach of the Hooghly River, the wave activity is relatively weak with significant wave heights less than 0.35 m. It is attributed to limited fetch along with complex coastal geometry and depth-limited nature of the river channel resulting in lower wave heights. Along the navigation channel, the significant wave heights are less during the winter months (<0.2 m), and relatively higher (<0.35 m) during the southwest monsoon period.

Especially in a riverine environment, the gravity-induced flow can be either steady or quasi-steady leading to generation of bed-forms resulting in bed load and suspended load. The varying bed forms can produce spatially varying ripple geometry, as reported by an earlier study for the Hooghly River[11]. The sediment motion initiates through shear stress at the channel bed. The movement of grains for a given size begins when the shear stress at the bed reaches a critical value. When the shear stress at the sediment bed is lower than the critical shear stress, the sediment particles begin to deposit on the channel bed. This critical shear stress can be evaluated from the Shield's curve that provides the critical shear stress for erosion as a function of particle size. The bottom boundary layer is important to understand the mechanics of sediment transport, and the work by Chitra *et al.*[12] highlights its importance for the Hooghly estuary under combined wave–current action. In this study, SEDTRANS05 was used to study the complex sedimentation process for different zones in the navigation channel of the Hooghly River. In addition to bottom boundary layer parameters, the flexibility in SEDTRANS05 also includes the prediction of bed-form development, bed-load and suspended load transport rates for both cohesive and non-cohesive sediments. To handle the variability of sedimentation and erosion processes over large spatial scales, there is a requirement for multi-dimensional models. In the present study, the spatial area under consideration confines only to the shipping route navigation channel, for which a one-dimensional model like SEDTRANS05 would suffice. The latest version of SEDTRANS05 used in this study is superior in hydrodynamics leading to realistic estimates of sediment transport rate. It incorporates a new cohesive sediment algorithm[21], providing a detailed variation of sediment properties with water depth. In addition, a better representation of suspended sediments for a wide range of settling velocities and particle flocculation processes is inherent in the physical parameterization of SEDTRANS05.

This model can simulate the transport of sand or cohesive sediments under the combined effect of waves and current. The mean bed shear stress and combined velocity profile is predicted using the formulation by Grant and Madsen[25]. Five methods are available in SEDTRANS05 to predict the sediment transport for non-cohesive sediments[26–28]. Two methods[29,30] are used to predict the total load transport that includes the bed-load and suspended load. The effects of suspended sediment stratification are neglected in the suspended load transport calculation by SEDTRANS05. The cohesive sediment algorithm has a limitation in modelling the sand–mud mixture, the resuspension of fluid mud by waves and instabilities in the water–sediment interface. The intrusion of intense flood tides into the navigation channel measurably dilutes the freshwater, and the water quality is similar to brackish water with lower salinity. Hence, the flocculation

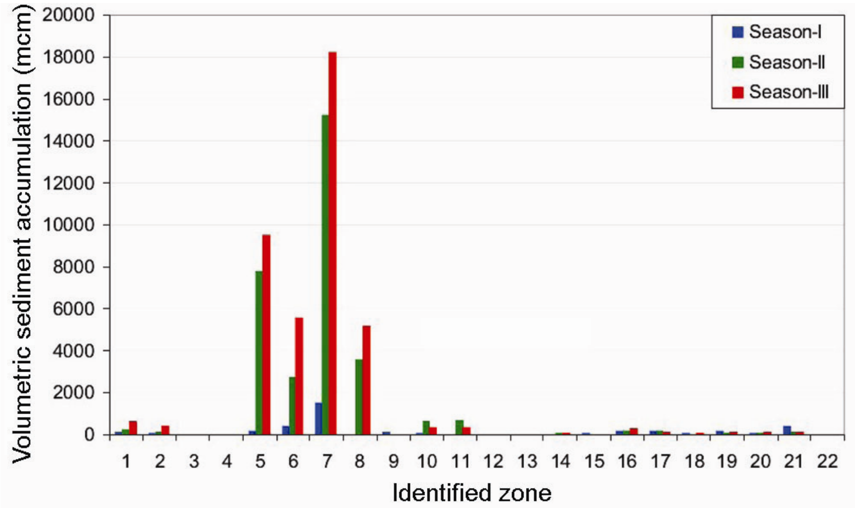

Figure 7. Volumetric accumulation of sediments (mcm) along various zones of the navigation channel.

Table 2. Total sediment transport for three dredging seasons (in million cubic metres; mcm)

Zone number	Season-I	Season-II	Season-III
1	113.79	222.12	589.43
2	53.98	137.32	364.82
3	0.00	0.00	0.00
4	0.00	0.00	0.00
5	179.16	7,752.38	9,475.02
6	385.54	2,739.74	5,538.81
7	1,524.08	15,237.93	18,171.51
8	27.11	3,547.33	5,150.14
9	108.70	0.00	0.00
10	58.06	635.56	344.74
11	5.86	653.07	359.91
12	0.00	0.00	0.00
13	5.24	0.00	0.00
14	21.06	33.06	38.47
15	41.91	0.00	0.00
16	179.00	184.33	270.52
17	140.52	153.00	129.07
18	45.70	16.58	62.41
19	140.81	71.60	85.28
20	67.51	71.73	92.84
21	374.51	92.17	110.53
22	0.00	0.00	0.00

equation used by SEDTRANS05 for the Hooghly River is valid. The formulation by van Rijn[28] was used to estimate the critical shear velocity for sediment suspension. Considering the grain size texture in the navigation channel for the Hooghly River, the formulation of van Rijn[28] justifies its use in the present study.

The output of hydrodynamic and wave parameters computed from ADCIRC and SWAN models for the entire year of 2011 is integrated with the SEDTRANS05 model using bed-load equation[28]. Table 2 and Figure 7 show the model-computed accumulated sediment volume in mcm during each dredging season considering the wave–current transport mechanism for all the 22 zones. Zone-7 located far west of Namkhana and in the eastern boundary of Sagar Islands has the highest sediment transport accumulation for all dredging seasons. Season-I has the lowest accumulation rates compared to the other two seasons for zones located at the entrance of the navigation channel into the Hooghly River and south of Sagar Islands. High sedimentation rates for Season-I occur along zone-21 near the outer harbour area of HDC and along the eastern part of Nayachara Islands, the navigational route to KDS. In zone-7, the sedimentation rates are about 4.35%, 43.55% and 52.08% of the total accumulated volume of sediments for all three dredging seasons. As seen from Figure 7, there is a high rate of sedimentation at the entrance of the navigation channel (zones 5–7) in close vicinity off Sagar Islands. The Haldia Dock that handles vessels with larger draft is located in zones-21 and 22, with zone-21 at its closest proximity. The highest sedimentation rate occurs during the dredging Season-I that amounts to 64.88% of the total accumulated sediments. The remaining dredging seasons (II and III) contribute to 16.06% and 19.14% of the total respectively.

A comprehensive study was done on the various issues involved in estimating sediment transport and methodology involved in the assessment of relative sediment movement with special reference to navigation in the Hooghly River[5]. This study based on field observation and survey records indicates that total sediment transport is proportional to the fifth power of velocity field[5]. Based on field measurements in the Hooghly River, calculations of both suspended and bed-load sediment transport were also reported[5]. The suspended load was estimated by integrating the velocity and concentration profile for the full tidal cycle and bed-load using the Einstein–Brown relationship. The calculations for the bed-load were based on grain size D_{50} for fine sand equivalent to 0.125 mm, and total load was estimated using the Engelund–Hansen

Table 3. Validation of total sediment transport for the Hooghly River during spring tide*

Distance from sea at Sagar (km)	Average width (km)	Maximum discharge ($m^3 s^{-1}$)		Maximum cross-sectional mean speed ($m s^{-1}$)		Reported bed-load transport factor (per unit width, $\propto V^5$)		Calculated bed-load transport from the present study	
		Flood	Ebb	Flood	Ebb	Flood	Ebb	Flood	Ebb
0	21	2.6E5	1.1E5	1.5	1.3	1.0	0.5	0.9495	0.3934
30	6.8	1.4E5	0.7E5	2.3	1.4	8.4	0.7	10.395	0.9913
51	5.0	6.7E4	3.7E4	1.6	1.2	1.3	0.3	0.9492	0.3814
77	1.6	3.8E4	1.4E4	2.0	1.5	4.2	1.0	5.4454	0.7170
108	1.0	2.1E4	1.1E4	2.4	1.5	10.5	1.0	13.020	1.0125
129	0.7	1.2E4	0.8E4	1.4	0.8	0.7	0.04	0.4950	0.1333
134	0.5	7.7E3	7.4E3	1.3	1.1	0.5	0.13	0.7170	0.2147

*Source: Sediment relative movement in Hooghly River (Ghosh[5]).

Table 4. Criteria for sedimentation and choice of dredging seasons

Criteria for sediment volume (V_s) during seasons I, II and III (V_{s1}, V_{s2} and V_{s3}; in mcm)	Remarks
$V_{s1} < 200$, $V_{s2} < 200$ and $V_{s3} < 200$	Perform dredging activity during season-III
$V_{s1} < 200$, $V_{s2} < 200$ and $V_{s3} > 200$	Perform dredging activity during season-III
$V_{s1} < 200$, $V_{s2} > 200$ and $V_{s3} < 200$	Perform dredging activity during season-II
$V_{s1} < 200$, $V_{s2} > 200$ and $V_{s3} > 200$	Perform dredging activity during seasons-III and II
$V_{s1} > 200$, $V_{s2} > 200$ and $V_{s3} < 200$	Perform dredging activity during seasons-I and II
$V_{s1} > 200$, $V_{s2} < 200$ and $V_{s3} > 200$	Perform dredging activity during seasons-I and III
$V_{s1} > 200$, $V_{s2} < 200$ and $V_{s3} < 200$	Perform dredging activity during season-I
$V_{s1} > 200$, $V_{s2} > 200$ and $V_{s3} > 200$	Perform dredging activity during seasons-I–III

Table 5. Maintenance dredging plan for the three dredging seasons

Zone number	Season-I	Season-II	Season-III
1	1	0	1
2	0	0	1
3	0	0	0
4	0	0	0
5	1	0	1
6	1	0	1
7	1	1	1
8	1	0	1
9	1	0	0
10	1	0	1
11	1	0	1
12	0	0	0
13	0	0	1
14	0	0	1
15	0	0	1
16	0	0	1
17	0	0	1
18	0	0	1
19	0	0	1
20	0	0	1
21	1	0	1
22	0	0	0

formula. The total load transport based on measured suspended sediment flux and bed-load was about 6.65 m^3/m width, while the estimate for total load transport using Engelund–Hansen formula was about 10.65 m^3/m. There is only one study that covers several years of compiled hydrographic data records on the total sediment transport for the Hooghly River[5]. The calculation of sediment transport considered in this study[5] was based on the fifth power of velocity (Table 3). The net bed-load sediment transport estimated for the long stretch of the Hooghly River upstream is purely based on field measurements (Table 3). In the present study, calculations were performed both for the flood and ebb phases of tidal cycle for a stretch of 134 km upstream (at seven locations), and the validation with the work of Ghosh[5] is provided. As seen from Table 3, the results show a close match between the reported value of bed-load transport from field measurements and the proposed methodology. The maximum difference between the calculated and reported bed-load sediment is about 24%. This is reasonable and well within the proposed range[31], and it varies with the exact power of velocity from 5 to 6 (ref. 5). At many locations on the Hooghly River, calculations from the present study are very close to the published results[31], where the sediment transport is proportional to the fifth power of velocity field.

The criteria for maintenance dredging plan in this study are based on a threshold value of 200 mcm according to the guidelines of the DCI. Table 4 shows the various combinations based on this criterion and choice of dredging seasons. The dredging activity for a particular season is based on the threshold criteria chosen from these combinations. Table 5 shows the recommended maintenance plan for dredging activity based on the criteria (Table 4) for all three dredging seasons and at all 22 zones of the navigation channel. In Table 5 '1' denotes the need for dredging and '0' represent no dredging requirement for that respective dredging season. The study also provides details of zone preference (Table 6) used in the case of exigency to provide the required vessel draft. The zone preference pattern provides information to identify the target areas on priority basis to maintain the required channel depth for safe vessel movement.

Summary and conclusion

The present study reports on the development of a maintenance plan for dredging activity based on scientific rationale for the navigation channel in the Hooghly River. KoPT has two docks under its administrative control that can accommodate deep draft vessels in this riverine environment, KDC and HDS. It is one of the oldest ports in India, located in a region of strategic interest. The Hooghly River carries along with it a large amount of sediments, both cohesive and non-cohesive in nature, that discharge into the Bay of Bengal. The tides dominate the mixing process in the Hooghly estuary and as a result, it is classified as a well-mixed estuary. The navigation channel experiences a high rate of sedimentation and by virtue of asymmetric nature in tide-velocity component between the flood and ebb phases of a tidal cycle, the net sediment load occurs on the landward side of the estuarine environment. The excessive amount of sedimentation results in clogging of the navigation channel and demands the need of periodic maintenance dredging. The investment by KoPT is substantial to maintain sufficient under-keel clearance for sea-going vessels. DCI is actively involved in the periodic maintenance dredging activity along this navigation channel. Previous studies for the Hooghly River focused mainly on the chemical, biological and geological aspects. Very few studies can be found in the literature on the Hooghly River dynamics and its associated physical oceanographic characteristics, in spite of two major ports in the region. This motivated the need for development of an action plan for maintenance dredging taking into account the annual spatio-temporal variability of physical oceanographic parameters leading to a deterministic level of sedimentation patterns in the navigation channel. The present study identifies 22 zones that cover the entire navigational channel from Sagar Island (downstream of Hooghly River) in the estuarine region until KDC and HDS (river upstream). The resultant sedimentation patterns on monthly scales are obtained through integration of three state-of-the-art numerical models that represent the hydrodynamics, waves and sediment transport patterns in the Hooghly River. These three numerical models are integrated to obtain the volumetric sediment distribution along various zones in the navigation channel. The study takes into account three dredging seasons (I–III), and based on various combinations of sedimentation with reference to the threshold limit specified by DCI, a seasonal maintenance dredging plan has been drafted for the navigation channel. This study shows that the estuarine environment near Sagar Islands, the navigation channel entrance experiences the highest rate of sedimentation, which requires priority and action for maintenance dredging during all seasons. The maintenance plan also reveals that the region near the entry to Haldia Dock also requires dredging during all seasons. The overall sedimentation rates are higher during Season-III for most of the zones in the navigation channel. We believe that this work can benefit the port authorities to help plan the priority areas for maintenance dredging.

Table 6. Zone preference for dredging activity

Preference	Zone number	Preference	Zone number
1	7	12	2
2	6	13	18
3	21	14	15
4	5	15	8
5	16	16	14
6	19	17	11
7	17	18	13
8	1	19	3
9	9	20	4
10	20	21	12
11	10	22	22

1. Indian Port Development Plan, Indian Ports Association, Coordination of business plans for major ports in India, Port of Rotterdam Authority, 2007, p. 135.
2. Cole, C. P. and Vaidyaraman, P. P., Salinity distribution and effect of fresh water flows in the Hooghly River. In Proceedings of Tenth Conference on Coastal Engineering, Tokyo, Japan, September, 1966, pp. 1312–1434.
3. Chatterjee, A., Mathematical model of the lower reach of Rupnarain River on the basis of 1962 survey. In Proceedings of 42nd Annual Research Session, vol. II(A), Technical Papers on Hydraulics, Madras, 20–29 June 1972, p. 109.
4. Sinha, G., Basu, A. N., Chakraborty, D. N. and Bhandari, P. C., Mathematical model for the River Rupnarain. In Proceedings of 42nd Annual Research Session, vol. II(A), Technical Papers on Hydraulics, Madras, 20–29 June 1972, p. 109.
5. Ghosh, S. N., Assessment of relative movement of sediment in a tidal reach with special reference to navigation in river Hooghly. *ISH J. Hydraul. Eng.*, 2000, **6**(1), 1–11.
6. Milliman, J. D. and Meade, R. H., World-wide delivery of river sediment to the oceans. *J. Geol.*, 1983, **91**, 1–21.
7. Biswas, A. N. and Chakrabarti, A. K., Sediment transport in tidal river. *J. Hydraul. Div.*, *ASCE*, 1974, **100**, 1677–1683.
8. Sinha, P. C., Dube, S. K., Rao, Y. R. and Chatterjee, A. K., A mathematical model for tidal circulation in estuaries. *Nonlinear World*, 1995, **2**, 257–273.
9. Sinha, P. C., Rao, Y. R., Dube, S. K., Rao, A. D. and Chatterjee, A. K., Numerical modeling of circulation and salinity in Hooghly estuary. *Mar. Geodesy*, 1996, **19**, 197–213.

10. Biswas, A. N., Geohydro-morphometry of Hooghly estuary. *J. Inst. Eng.* (*India*), 1985, **66**, 61–73.
11. Chitra, A. and Bhaskaran, P. K., Parameterization of bottom friction under combined wave-tide action in the Hooghly estuary, India. *Ocean Eng.*, 2012, **43**, 43–55.
12. Chitra, A., Bhaskaran, P. K., Jain, I., Bhar, A. and Narayana, A. C., Bottom boundary layer characteristics in the Hooghly estuary under combined wave–current action. *Mar. Geodesy*, 2010, **33**, 261–281.
13. Chitra, A. and Bhaskaran, P. K., Numerical modeling of suspended sediment concentration and its validation for the Hooghly estuary, India. *Coastal Eng. J.*, 2013, **55**(2), 23.
14. Qasim, S. Z., Sengupta, R. and Kureishy, T. W., Pollution of the seas around India. *Proc. Indian Acad. Sci.* (*Anim. Sci.*), 1988, **97**(2), 117–131.
15. Luettich, R. and Westerink, J., Formulation and numerical implementation of the 2D/3D ADCIRC finite element model version 44.xx, Report, 2004, p. 74.
16. Dietrich, J. C. *et al.*, Modeling hurricane waves and storm surge using integrally-coupled, scalable computations. *Coastal Eng.*, 2011, **58**, 45–65.
17. Bhaskaran, P. K., Nayak, S., Subba Reddy, B., Murty, P. L. N. and Sen, D., Performance and validation of a coupled parallel ADCIRC-SWAN model for THANE cyclone in the Bay of Bengal. *Environ. Fluid Mech.*, 2013; DOI:10.1007/s10652-013-9284-5.
18. Booij, N., Ris, R. C. and Holthuijsen, L. H., A third generation wave model for coastal regions. Part I: model description and validation. *J. Geophys. Res.*, 1999, **104**, 7649–7666.
19. Ris, R. C., Spectral modelling of wind waves in coastal areas. Ph D thesis, Delft University of Technology, 1997.
20. Ris, R. C., Holthuijsen, L. H. and Booij, N., A third-generation wave model for coastal regions – verification. *J. Geophys. Res. C*, 1999, **104**, 7667–7681.
21. Neumeier, U., Ferrarin, C., Amos, C. L., Umgiesser, Georg, L. and Michael, Z., SEDTRANS05: an improved sediment-transport model for continental shelves and coastal waters with a new algorithm for cohesive sediments. *Comput. Geosci.*, 2008, **34**(10), 1223–1242.
22. Biswas, H., Mukhopadhyay, S. K., De, T. K., Sen, S. and Jana, T., Biogenic controls on the air–water carbon dioxide exchange in the Sundarban mangrove environment, northeast coast of Bay of Bengal, India. *Limnol. Oceanogr*, 2004, **49**(1), 95–101.
23. Nandy, S. and Bandyopadhyay, S., Trend of sea level change in the Hugli estuary, India. *Indian J. Geo-Mar. Sci*., 2011, **40**(6), 802–812.
24. Murty, T. S. and Henry, R. F., Tides in the Bay of Bengal. *J. Geophys. Res. C*, 1983, **88**, 6069–6076.
25. Grant, W. D. and Madsen, O. S., The continental shelf bottom boundary layer. *Annu. Rev. Fluid Mech*., 1986, **18**, 265–305.
26. Brown, C. B., Sediment transportation. In *Engineering Hydraulics* (ed. Rouse, H.), Wiley, New York, 1950, pp. 769–857.
27. Yalin, M. S., An expression for bed-load transportation. *J. Hydraul. Div., Proc. ASCE 89*, 1963, 221–250.
28. van Rijn, L. C., *Principles of Sediment Transport in Rivers, Estuaries, and Coastal Seas*, Aqua Publications, The Netherlands, 1993.
29. Engelund, F. and Hansen, E., *A Monograph on Sediment Transport in Alluvial Streams*, Teknisk Vorlag, Copenhagen, 1967, p. 62.
30. Bagnold, R. A., Mechanics of marine sedimentation. In *The Sea* (ed. Hill, M. N.), Wiley-Interscience, New York, 1963, vol. 3, pp. 507–527.
31. McDowell, D. M. and O'Connor, B. A., *Hydraulic Behavior of Estuaries*, McMillan Publishing Company, London, 1977.

Received 13 April 2014; revised accepted 7 July 2014