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Hydrodynamic modelling of tide-driven currents and their seasonal variability in the north-eastern part of Bangladesh coast

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Abstract

The development of a two-dimensional numerical model of an estuary in the coastal region of the Bay of Bengal on the north-eastern coast of Bangladesh is described. The primary objective of the study is to provide a detailed picture of the tidal characteristics in the study area to enable the simulation of the whole water circulation within the water body. A comprehensive data set is collected from Bangladesh Inland Water Transport Authority (BIWTA) and Chittagong Port Authority (CPA) as part of this study to understand local dynamics and to calibrate and validate the model. Calibration and validation have been achieved through a comparison of computed tidal harmonics against those derived from harmonic analysis of the measured water level variations. The simulation was found to be in good agreement with the collected data. The model simulation clearly show the variation of the surface elevation, their speed and direction separately for summer monsoon and winter season around the model domain area which covers the northern-eastern part of Bay of Bengal. Surface elevation show that tides found mainly semidiurnal in the estuary. Simulation result shows surface elevation is higher in summer monsoon than the winter monsoon. Current speed also higher in summer monsoon than the winter monsoon. Furthermore, this study will be used as base future Ecolab and salinity dispersion study at the same domain.

Keywords: hydrodynamic model, Bay of Bengal, tide current, Surface elevation

1. Introduction

The coastal zone illustrate mainly the area with beach, estuaries, the adjacent lands of coastal water and the offshore water (Brommer and Bochev, 2009). Coastline of Bangladesh is very dynamic & about 710 km long. Here, the Lower Meghna River, one of the world's greatest rivers, finds its way to the Bay of Bengal. The Lower Meghna conveys the combined flows of the Brahmaputra, the Ganges and the Upper Meghna. The hydrodynamic factors such as enormous volume of river water flow, sediment transport, nutrient transport, strong tidal and wind actions, wave, salinity and cyclonic storm surge are playing dominant role in morphological development along coast line of Bangladesh. These hydrodynamic factors and their interactions shape the morphology of the estuary. Continuously Tides, waves and winds action are also responsible for erosion and deposition of sediment on a continuous basis and rates which make dynamic day to day around such zones (Jena et al., 2008). The continental shelf in the head of the bay and along the southern coast of Myanmar is about 200 km wide and the amplitudes of semi-diurnal tides are doubled in these regions while the diurnal tides amplify only marginally, which is consistent with Clarke and Battisti theory. Alam (2003) studied that, tides in

Bangladesh coast enters the Bay of Bengal through the two submarine canyons named 'Swatch of No Ground' and 'Burma Trench' and arrives very near to the 10-fathom contour line at Hiron point and Cox's Bazar respectively at a time. But the massive shallowness of the north-eastern bay gives rise to partial reflections and thereby increases the tidal range and friction distortions concurrently. Hossain (2001) observed that the tides in the coastal and estuarine areas are semidiurnal and have maximum amplitude of 3-4 m at spring tide. In sallow coastal area, tidal activity is an important mechanism for the movement of water and nutrients which is probably a reason for the wide range of biodiversity in the estuarine water. Ali studied the interaction among river discharge, storm surges and tides in the Meghna River estuary in Bangladesh using a two-dimensional vertically integrated numerical model of the northern Bay of Bengal. River discharge and tidal flow across the river mouth act both positively and negate vary depending on the tidal phase, positively during high tide and negatively during low tide (Ali *et al.*, 1998).

Coastal Embankment Rehabilitation Project, CERP (2000) studied the storm surge modeling study based on the two-dimensional MIKE21 hydrodynamic model adopted. In the hydrodynamic model simulations, meteorological forcing is given by wind and pressure field derived from the analytical cyclone model. The MIKE 21 modelling system includes dynamical simulation of flooding and drying processes, which is very important for a realistic simulation of flooding in the coastal area and inundation. A similar study done at Arabian Sea Gulf of Kacch by M.T. Babu et al. (2004), where the currents of GoK are predominantly tide-driven, they respond significantly to the seasonally changing wind system. Strong southwesterly winds enhance the flood tidal currents by about 20% but reduce the ebb tidal currents by about 20% during June–July. The currents intensify during NE monsoon period as well as SW monsoon period when the winds become stronger. Institute of Water Modelling, IWM (2009) explain that disastrous tropical cyclones form during pre-monsoon (April to May) and post monsoon (October to December) in the Bay of Bengal. Most of the cyclones hit the coasts of Bangladesh with north-eastward approaching angel. Jakobsen et al. (2002) studied the hydrodynamics of the Bay of Bengal in detail using a calibrated and validated two-dimensional numerical hydrodynamic model. The Flood Forecasting and Warning Center (FF&WC) of Bangladesh supported by the Institute of Water Modeling (IWM) in Dhaka and DHI has developed an operational salinity intrusion forecast model enabling both shortterm and long-term forecasting of salinity conditions in the delta. Bay of Bengal model was originally developed by IWM and used in a number of projects where it has been updated, re-calibrated and verified. Jakobsen et al. (2002) performed numerical simulations through the two-dimensional MIKE 21 model during the Meghna Estuary Study (MWR, 1997) and observed a counterclockwise circulation with a northward flow in the Sandwip Channel and a southward flow in the Tetulia River and in the area from Hatia to Sandwip. During the study, it was also observed that the residual circulation, to some extent, traps the river water inside the Meghna Estuary and thus increases the residence time, which is one of the reasons for the relatively low salinity in the estuary even during the dry season.

The main aim of the study is to understand the details tide driven current and water surface level of the domain area. And also understand the physical & hydrological condition of northern area as well as to advance study for this area.

1. Methodology

The two-dimensional MIKE 3 FM model developed by the Danish Hydraulic Institute was used to study the hydrodynamics of the region for 3D free-surface flows with flexible mesh approach. Most suitable technique for irregular boundaries of the water body is flexible mesh. The model is based on the numerical solution of the three-dimensional equations, invoking the Boussinesq assumption and the hypothesisof hydrostatic pressure in the vertical. The turbulence closure is affected using the Smagorinsky in the horizontal and the standard k-ε model in the vertical direction (user manual MIKE 21/3 FMHD, 2014). A continuity equation in ocean is an equation that describes the salt water transport of some quantity. It is particularly simple and particularly powerful when applied to a conserved quantity, but it can be generalized to apply to any extensive quantity. The local continuity equation is written as:

Continuity equation

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=S$$

Where, u, v and w are the velocity components in the x, y and z direction;

Momentum Equation

x momentum

$$\frac{\partial u}{\partial t}+\frac{\partial u^2}{\partial x}+\frac{\partial uv}{\partial y}+\frac{\partial wu}{\partial z}=fv-g\frac{\partial \eta}{\partial x}-\frac{1}{\rho_0}\frac{\partial p_a}{\partial x}-\frac{g}{\rho_0}\int_z^{\eta}\frac{\partial \rho}{\partial x}dz-\frac{1}{\rho_0 h}(\frac{\partial s_{xx}}{\partial x}+\frac{\partial s_{xy}}{\partial y})+F_u+\frac{\partial}{\partial z}(V_t\frac{\partial u}{\partial z})+u_sS$$

y momentum

$$\frac{\partial v}{\partial t}+\frac{\partial v^2}{\partial y}+\frac{\partial uv}{\partial u}+\frac{\partial wv}{\partial z}=-fu-g\frac{\partial \eta}{\partial y}-\frac{1}{\rho_0}\frac{\partial p_a}{\partial y}-\frac{g}{\rho_0}\int_z^{\eta}\frac{\partial \rho}{\partial y}dz-\frac{1}{\rho_0 h}(\frac{\partial s_{yy}}{\partial y}+\frac{\partial s_{yx}}{\partial x})+F_v+\frac{\partial}{\partial z}(V_t\frac{\partial v}{\partial z})+v_sS$$

where t is the time; x, y and z are the Cartesian co-ordinates; η is the surface elevation; d is the still water depth; $dh += \eta$ is the total water depth; u, v and w are the velocity components in the x, y and z direction; $f=2\Omega\sin\varphi$ is the Coriolis parameter (Ω is the angular rate of revolution and ϕ the geographic latitude); g is the gravitational acceleration; ρ is the density of water; s_{xx} , s_{xy} , s_{yx} *and* s_{yy} are components of the radiation stress tensor; V_t is the vertical turbulent(or eddy) viscosity; p_a is the atmospheric pressure; ρ_0 is the reference density of water. S is the magnitude of the discharge due to point sources and (u_s , v_s) is the velocity by which the water is discharged into the ambient water.

The total water depth, h, can be obtained from the kinematic boundary condition at the surface, once the velocity field is known from the momentum and continuity equations. However, a more robust equation is obtained by vertical integration of the local continuity equation

$$\frac{\partial h}{\partial t}+\frac{\partial hu}{\partial x}+\frac{\partial h\bar{v}}{\partial y}=hS+\hat{P}-\hat{E}$$

Where $\hat{P}$ and $\hat{E}$ are precipitation and evaporation rates, respectively, and u and v are the depth-averaged velocities

The fluid is assumed to be incompressible. Hence, the density, ρ , does not depend on the pressure, but only on the temperature, T, and the salinity, s, via the equation of state

$$\rho = \rho(T,s)$$

The continuity equation expresses the mass conservation, while the momentum equation is actually the fundamental law of dynamics, written for fluids. The only assumption in these equations is that the fluid should be Newtonian and this is indeed an excellent approximation for water.

2. Data Used for Model Development

The modelling study has been devised in combining with accumulation data analysis and numerical modelling. Data on recent bathymetry, tidal data of the estuary have been collected from BITWA recent survey. For model simulation, four seasons were identified based on previous studies (e.g. Chowdhury *et al.*, 1997) on climatic conditions of Bangladesh, namely pre-monsoon (March - May), summer monsoon (June - September), post-monsoon (October - November) and winter monsoon (December - February). Meteorological and hydrological data have been analyzed for mainly two periods (summer monsoon and winter monsoon) to set-up a three dimensional numerical model. Data used for a time of 07/01/2015 to 07/17/2015 for summer monsoon and 01/01/2016 to 01/17/2016 for winter monsoon used in model simulation. Hourly tidal condition has considered. Therefore, 670 time steps have counted with CFL condition 0.82 for each monsoon. Grid spacing consider 200 m & 10 sigma (s) coordinate layer considered. Another important parameter are flooding and drying condition for model stability, which considered 0.5 m for flooding depth & 0.05 m for drying depth.

2.1 Tidal Data & bathymetric Data

Tidal data of Chittagong and Cox's bazaar estuary has collected from Bangladesh Inland Water Transport Authority (BIWTA). BIWTA also published tide table with updated tidal condition. BIWTA, established Chart Datum (CD) values by using the extended harmonic analysis by Admiralty method along the different river systems and off-shore islands which is internationally accepted. The modified chart datum formula is:

$$CD = Z_0 - (M_2 + S_2 + K_1 + O_1) - S * SSF$$

CD is the Chart Datum, Z_0 is the Mean Sea Level above CD, M_2 is the principal lunar semidiurnal constituent, S_2 is the principal solar semidiurnal constituent, K_1 is luni solar diurnal constituent, O_1 is the lunar diurnal constituent.

Admiralty charts no 0084 Karnaphuli river bathymetry also used to create bathymetry. Interpolation technique used base on sparse linear algebra and PDE discretization's in python3.0. After interpolation bathymetry, flexible mesh has been created. In the open boundary, the DTU10 (Technical University of Denmark) global ocean tide model is an update of the AG95 Ocean tide. Resolution is 0.125° x 0.125°, including the 12 major tidal constituents. A new global ocean tide model DTU10 is developed based on FES2004 (Finite Element Solutions) and the 'response method' (Munk and Cartwright, 1966).

2.2 Domain area

The selected of domain area was north-eastern part of Bay of Bengal along the coast of Bangladesh, Chittagong to Cox's bazaar area, have a latitude of 21°25' north latitude to 22°20' north latitude (about 77748.5 m) and have a longitude of 91°30' west longitude to 92°15' west longitude (about 99622.3m). Length and height is calculated by UTM-46 (The Universal Transverse Mercator) conformal projection uses a 2-dimensional Cartesian coordinate system to give locations on the surface of the Earth.

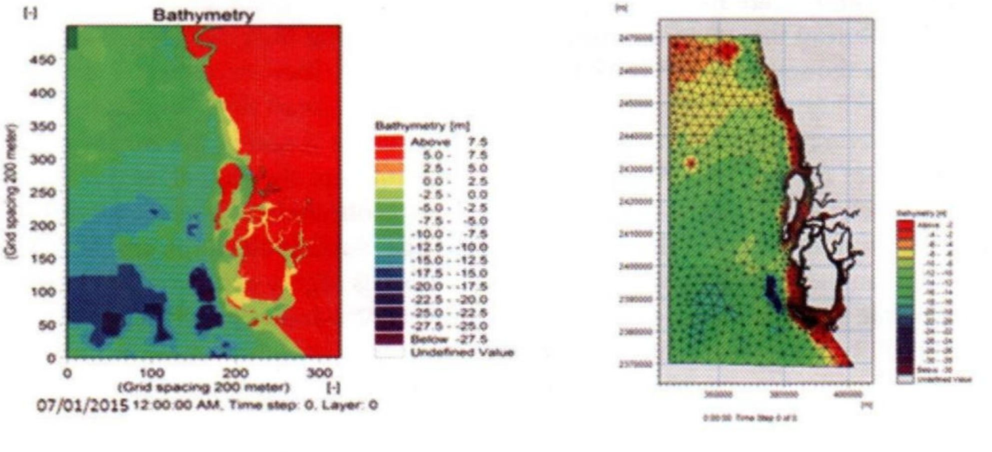

Fig. 1: Bathymetry and Flexible mesh for domain area

3. Result and Discussion

The three-dimensional hydrodynamic model of the Bay of Bengal have been calibrated against tidal level comparing the model results surface elevation. Model shows a very good agreement on the summer monsoon (0.92) rather than the winter monsoon (0.82). So, field measurement to make the model performance to a satisfactory level. The validation has been made only with the available data for the year 2015 at Kutubdia Island. Hydrodynamic simulation has been made for 17 days for both the summer and winter monsoon in order to establish the hydrodynamic characteristics for surface elevation and tidal current. Locations of calibration areas have been presented in Fig. 02.

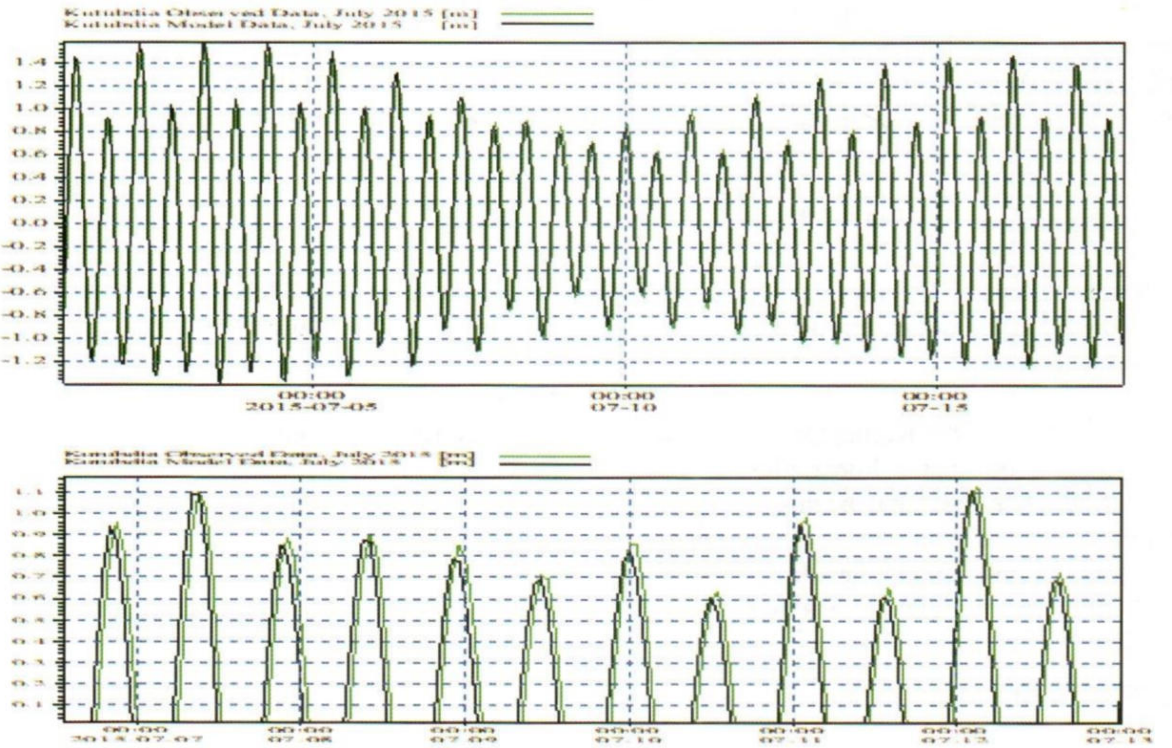

Fig. 02: Comparison between model data and observed data at summer monsoon

3.1 Surface Elevation

Model simulation shows that the surface elevation of the domain area affected much with the tidal condition. Some seasonal variation in are found in Fig. 3 (Two tidal phase condition discussed winter & summer season consecutively). During the winter monsoon first hour of spring high tide (Fig. 3 a), height surface height found about 1m at the southern part of domain and it gradually increases towards north. Due to tidal condition, the bottom topology and geography setting, surface elevation of tidal height gradually increased toward the north-eastern direction and a anticyclonic flow pattern is found at the Northeastern part (near Sandwip island) of Bay of Bengal (Jakobsen et al., 2002). Simulation shows that, at the 4th hour of high tide maximum surface elevation found 1.5 m at the west of Moheshkhali island and surface elevation continuously increase with time. At the final hour of spring tide, surface elevation reaches almost 1.82 m at northern part of domain near the Sandwip Island. This pattern is highly active on all phases of tide. On the other hand, during the summer monsoon surface elevation shows similar pattern with tide, but the maximum surface elevation 2.15m is higher than the winter. From the simulation about 0.3 m higher surface elevation found in summer monsoon spring tide than the winter monsoon spring tide, which may be caused by huge amount of fresh water influx from Ganges-Brahmaputra estuary and the south-easterly monsoon wind during the summer monsoon. In the both season, at the spring tide, highest surface elevation found at the northern part of domain (Kutubdia Island) near the Sandwip Island area.

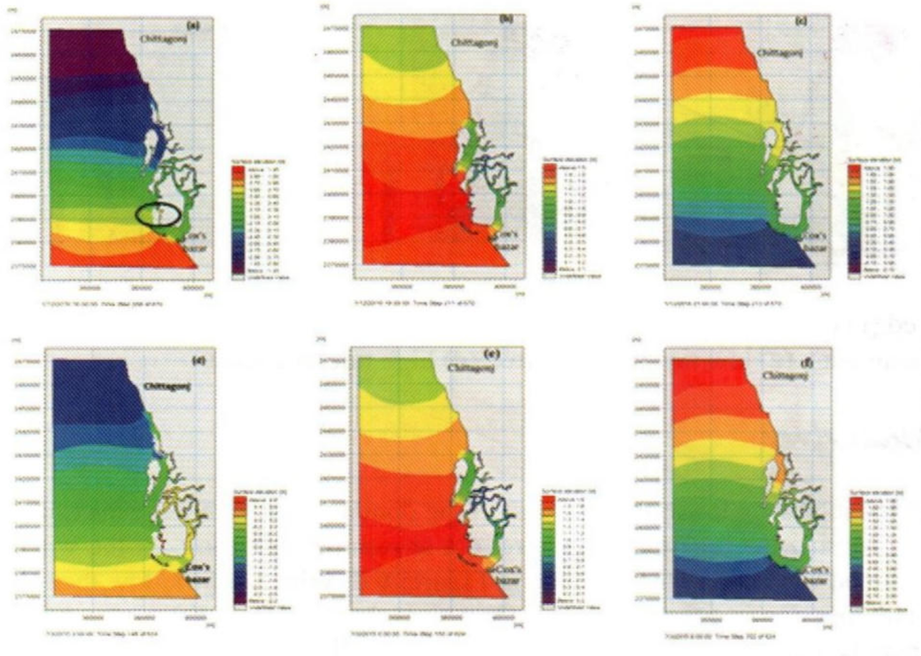

Fig. 3: tidal condition of study area low tide to high tide 2 hour interval (a) 1st hour of a winter high tide (b) 4th hour of a winter high tide (c) final hour of a winter high tide; (d) 1st hour of summer high tide (e) 4th hour of summer high tide and (f) final hour of high tide (summer). In both season, surface elevation found higher at the northern part of Domain area.

3.2 Surface elevation at Bakkhali River

Bakkhali River have a different surface elevation pattern relative to the open ocean. Narrow outlet and bottom topology are the major cause of these surface elevation pattern. The simulation reveal that, during spring tide of summer monsoon height surface elevation found 1.18 m in Bakkhali River, where as 2.15 m at the open ocean. On the other hand, lowest elevation found at neap high tide about 0.38m but during the low tide Bakkhali River experiences surface elevation very close to zero. Kutubdia channel & the Moheshkhali channel show almost similar characteristic, but hardly negative surface elevation found at 2nd or 3rd hour of high tide that means elevation is below mean sea-level.

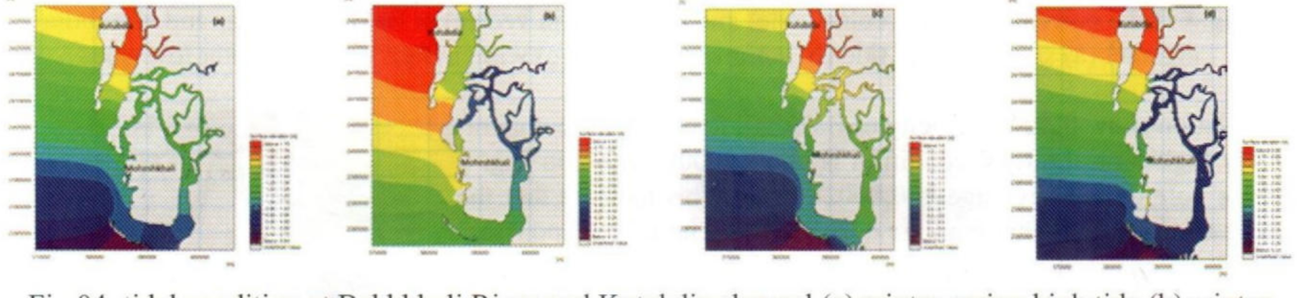

Fig 04: tidal condition at Bakhkhali River and Kutubdia channel (a) winter spring high tide (b) winter neap high tide (c) Summer Spring High tide (d) Summer Neap high tide. Simulation found a similarities of surface elevation in both season, but summer has little higher surface elevation then the winter.

3.3 Tidal current speed and direction

There are an anti-clock wise tide-driven circulation found in the domain area, that may cause of eastern boundary of the domain is surrounded by the landmass. This feature make more complex hydrodynamics of Bakkhali river (position of Sonadia Island also responsible for that flow pattern). Simulation reveal that the tide driven current are maximum found 1.6 ms-1 at the 4th and 5th hour of high tide and also maximum found 1.4 ms-1 at the 3rd and 4th hour of low tide. Both the winter and summer monsoon maximum current speed found at the west of Moheshkhali Island and the east of Sonadia Island at Figure: 5b and 5d. During the winter monsoon maximum current speed found 1.42 ms-1 and during the summer it increase with the wind, but may little decrease with fresh water mixing and maximum current speed found 1.67 ms^{-1}.

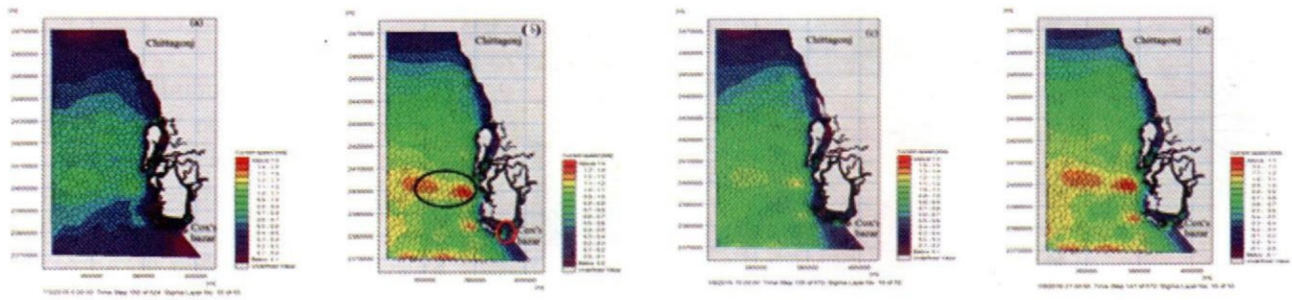

Fig 05: tide driven current speed (in color code) and direction (with arrow vector) (a) low tide (summer), (b) high tide (summer); (c) low tide in winter and (d) high tide in winter.

3.4 Current at the Bakkhali river

At the Bakkhali river current speed relatively lower than the rest of the domain area, where the maximum current speed found the 1.0 ms-1 during the high tide in Figure: 6 a at summer monsoon. At the winter monsoon current speed highest found 0.9 ms-1 at the low tide in Figure: 6 d. Which is little low then the summer monsoon, but the current direction is opposite to each other's, as their tidal condition also different. Shallow bottom topology may be one of the cause of this situation. This situation also indicate that in the summer monsoon have a strong tidal current at the high tide. On the other hand, winter monsoon have a stronger current in the low tide.

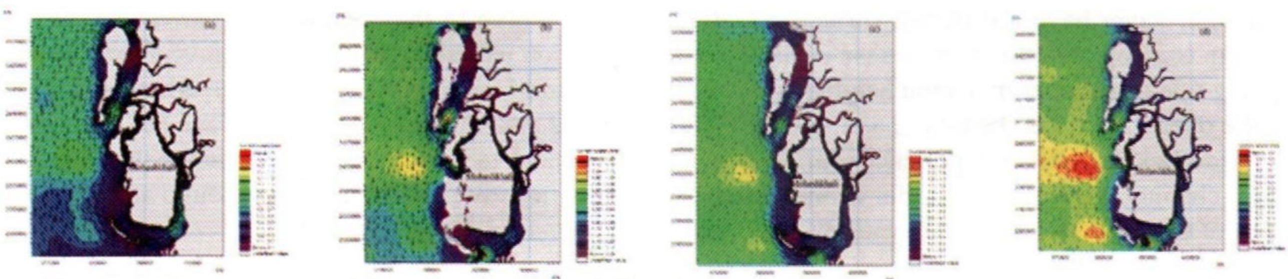

Fig. 6: tidal current speed (in color-code) and direction (in vector) at Bakhkhali river and Kutubdia channel (a) summer high tide (b) summer low tide; (c) winter High tide (d) winter low tide

Simulation show that, W velocity of Bakkhali River is also comparatively higher on the tidal condition is about 0.0009 ms-1 in Fig. 7 where hole domain average is 0.00028 ms-1. This indicate that the vertical mixing is higher than the domain area. The sallow and irregular shape of bottom topology is one of the cause of high W valocity.

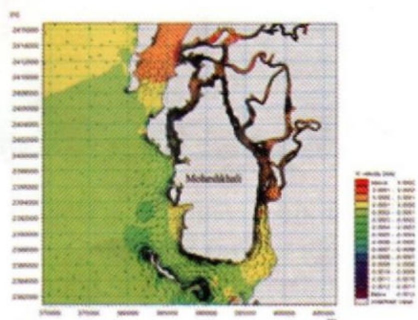

Fig. 7: W velocity of surrounding area of Moheshkhali Island

3.5 Discussion

An anti-clockwise circulation structure is found around in the northern part of the domain area, which is mainly forced by tide. In the east of Kutubdia channel, the residual anti-clockwise circulation pattern found during the summer monsoon is similar to the circulation pattern found during winter season, which implies the area is dominated by tide both in winter and summer monsoon. Model simulation shows during the high tide and low tide a week opposite current found from the Bakkhali River. One of the possible reason of this, is during the high tide surface elevation of Bakkhali River is higher in surrounding area. So water move from high pressure zone to low pressure zone. This situation remain stable almost first hour of high tide. And during the low tide just opposite case work.

We faced some problems on model calibration and validation. The bathymetry was created by combining old and new data and in the overlapping areas quite big differences were found. Furthermore, it was not possible to collect discharge measurement from Bakkali river and also Meghna river at model simulation period. We instigated the performance of the eastern boundary on the basis of constituents from one global ocean model (DTU-2010) and we found model results agree with local data. Lack of knowledge on the water discharge conditions and fresh water influx along the northern boundary is presently considered the biggest hamper in improving the quality of the model results. One of the reason to choose northern boundary equivalent to Chittagong and our main focus on Bakkhali river. One of purpose of our study is to understand the hydrodynamic condition of Bakkhali river and further study could be nutrients dynamic of this area as hydrodynamic model is prerequisite of any others dynamics model such as mud transport, sediment transport, nutrients dynamic.

4. Conclusion

A hydrodynamic numerical model has been set up which covering the north-eastern part of the Bay of Bengal. The model has been calibrated and validated successfully. The surface elevation and details of tide driven current in the Chittagong and Cox's Bazar Estuary was determined on the basis of the model results. It shows a counter-clockwise circulation with a northward flow in the Chittagong near the Sandwip Island. Surface Elevation Highest found 2.15 m at Northern Part of Domain at the spring tide in the summer and 1.82 m spring tide in the winter season. Current speed 1.65 m/s found at the summer season and 1.42 m/s found at winter season. Surface Elevation higher at Bakkhali River during the low tide relatively the open ocean and tidal current also differ with rest of the domain area. The circulation influences the ecological, morphological and salinity conditions in the area, but the influences are not quantified at this study. Nutrients source of adjacent area could be understands through study of Bakkhali River.

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