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Simulation of Storm Surge Level at a Tidal Channel Due To Cyclone along the Bangladesh Coast

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Abstract:*This study was conducted for simulation of storm surge level at a tidal channel due to cyclone along the Bangladesh coast. Bay of Bengal hydrodynamic model (BoB) developed by IWM (Institute of Water Modelling) using MIKE21 was updated with finer mesh resolution at Baleshwar channel. The model was calibrated and validated for water level using the measured data of the year 2017 and 2015 respectively. Moreover, cyclone model of MIKE21 maintained by IWM was calibrated for measured wind speed at several locations for cyclone 1991, cyclone SIDR 2007 and cyclone AILA 2009. These two calibrated models (hydrodynamic and cyclone model) were coupled together and storm surge model was developed for Bangladesh coastline. Finally, this storm surge model was calibrated and validated using the measured storm surge levels for cyclone SIDR 2007 and cyclone AILA 2009. The calibrated and validated storm surge model was further verified with the storm surge levels at several places (Southkhali, Rayenda Bazar and Solombaria) along Baleshwar channel during Cyclone SIDR 2007 measured by Japan Society of Civil Engineers (JSCE) team. Simulated storm surge level of calibrated and validated storm surge model shows a difference of +10.7%, -11.5% and -18.4% at Solombaria, Rayenda Bazar and Southkhali respectively with the measured data of JSCE team for cyclone SIDR 2007. This may happen due to some measurement uncertainties of the JSCE team. Furthermore, the calibrated and validated storm surge model was simulated for five different water level and five different wind speed conditions to see the impacts of water depth and wind speed on storm surge height at Baleshwar estuary. Simulated results were used to establish a relation between cyclone parameters and storm surge height at Baleshwar estuary. An equation was developed for estimating the storm surge height at Baleshwar estuary for a known cyclone, which may help the coastal zone managing authorities for better managing the cyclone challenges.*

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I. Introduction

The Bay of Bengal is one of the hotspots for the generation of tropical cyclones. About one-tenth of the global numbers of cyclones that form in different regions of the tropics occur in the Bay of Bengal[1]. During the period 1960-2009, 19 severe cyclones have hit the coast of Bangladesh[7]. A cyclone in November 1970 hit the southern districts of Bangladesh forcing a 9-m high storm surge and killing approximately 300,000 people. The cyclone of 1991 caused more than 138,000 lives[2]. About 3406 people were reportedly killed in the coastal areas of Bangladesh by the super cyclone SIDR 2007[10]. Cyclone AILA in 25th May 2009 hit the south-western part of Bangladesh (Khulna Division) and West Bengal in India and killing approximately 190 people. Coastal area of Bangladesh is already protected by coastal embankment called polders. There are 139 embanked polders in the coastal area[6] , which were constructed in the late sixties to protect the land from tidal and monsoon flooding and saline water intrusion. Most of the coastal polders were built considering only tide although these are exposed to wind generated waves and cyclone induced storm surges. As a result, coastal embankments are overtopped by cyclonic storm surges. Storm surge simulation inside the river is very important for fixing up the proper embankment crest level. Nowadays, the storm surge simulation is a hot topic for various coastal states and nations because of rapid development of coastal regions. Precise simulation of storm surge level is required for the effective warning system and design of embankment crest level for protection of life and properties of coastal areas. A study by Hasan, 2009 revealed that the required crest level for the embankment of some selected island in Bangladesh coast is higher than the existing crest level during severe cyclone SIDR 2007 for different synthetic track and considering climate change condition. Islam, 2015 carried out a study where storm surge model (coupled hydrodynamic and cyclone model) was calibrated directly using the wind friction factor. The coupled model was used to find out the combined effects of cyclonic wind speed and sea level rise on determining the crest level of the selected polders based on severe cyclone along the Chittagong coast. Over the last two decades several research group made substantial progress in the field of numerical modelling of storm surge in the Bay of Bengal. Most of the study uses the coupled storm surge model (combination of hydrodynamic and cyclone model) for simulation of storm surge level where the model is calibrated with the measured storm surge level at the coast. In this study, the hydrodynamic and cyclone model was calibrated and validated separately and coupled together to develop storm surge model. The model simulated storm surge levels were verified at different locations of Baleshwar channel with the storm surge levels measured by the Japan Society of Civil Engineers after cyclone SIDR 2007.

II. Material and Methods

Study Area: The study mainly focuses on the simulation of storm surge level at Baleshware estuary and inside the river. BaleswarRiver is one of the major tidal river to the south west region of Bangladesh. There are seven coastal polders along the both bank of this river. The river flows through Bagerhat, Barguna and Pirojpur district where 2.15 million population lives according to the Population census 2011. The super cyclone Sidr (2007) passed through Baleswar River which causes serious damage in human lives & properties.

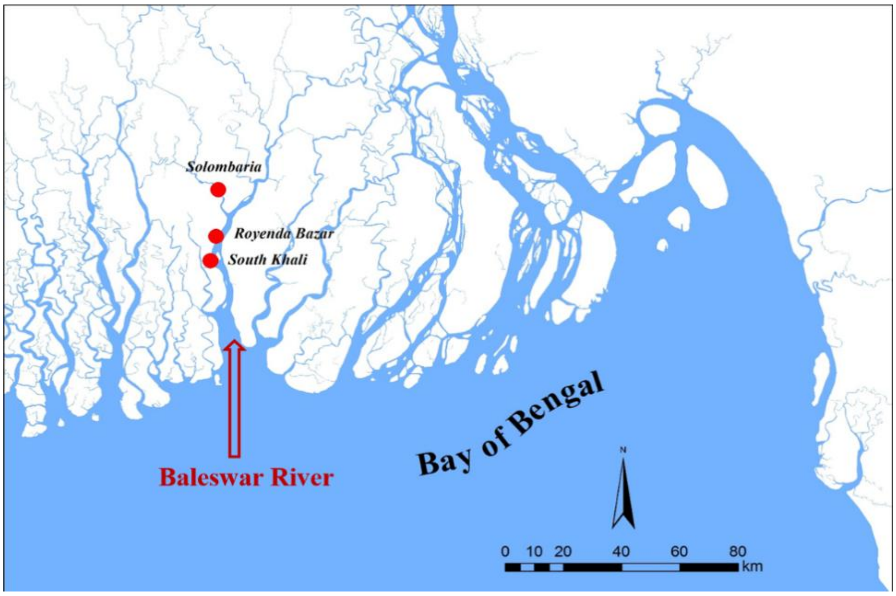

Figure 1: Study area; the coastal zone of Bangladesh and Baleshwar Channel

Methodology and Data Collection: Storm surge model is the combination of hydrodynamic and cyclone model. Different types of data were used for this study including water level data for the normal and cyclone period, historical wind and cyclone data etc. for development of storm surge model. Data was collected from different organizations like IWM, BWDB, BIWTA and BMD. The hydrodynamic model was calibrated and validated with the measured water level data at several locations of coast and inside the river. Again, the cyclone model was calibrated with the measured wind speed for different cyclonic event. Finally, these two separately calibrated models were coupled together and the model was calibrated and validated with the measured storm surge level of cyclone SIDR-2007 and cyclone AILA-2009. The simulated surge level of cyclone SIDR-2007 was further verified with the measured storm surge level along Baleshwar channel by the JSCE team. The storm surge model was further simulated for different water level and wind speed condition to establish a relation between storm surge height and cyclone parameters.

Setup, Calibration and Validation of Hydrodynamic Model: The existing bathymetry of the Bay of Bengal hydrodynamic model of Institute of Water Modelling (IWM) was improved under this study using finer mesh resolution for the study area of Baleshwar channel. The improved bathymetry is shown in Figure 2.

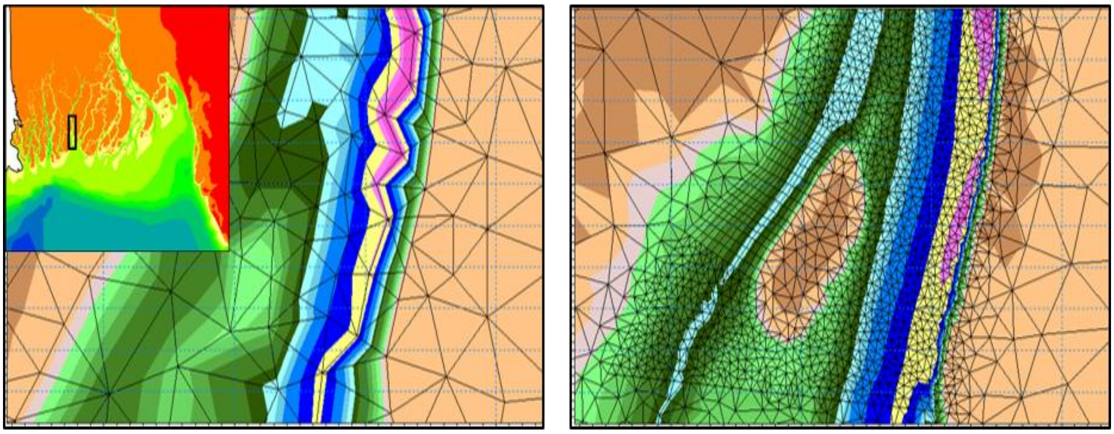

Figure 2: Existing bathymetry of IWM (left) and improved bathymetry under this study (right)

There are three open boundaries in the model. Rated discharge was used as the upstream boundary which was collected from Bangladesh Water Development Board (BWDB). South boundary was generated from Global tide model. A spatially varying map of bed resistance was used for calibration of hydrodynamic model in this research work. The main model parameter used for the calibration and validation of the hydrodynamic model is shown in the Table 1.

Table 1: The model parameters used for hydrodynamic calibration

Model Parameter	Value
Numerical Scheme	Low
Eddy Viscosity	Smagorinsky formulation constant 0.28
Bed Resistance	Constant in time, varying in domain
Coriolis force	Varying in domain

The hydrodynamic model was simulated for a 15 days period of March 2017 and May 2015. Model was calibrated and validated with the water level data at several locations of the sea and inside the river. Figure 3 shows the model calibration and validation locations.

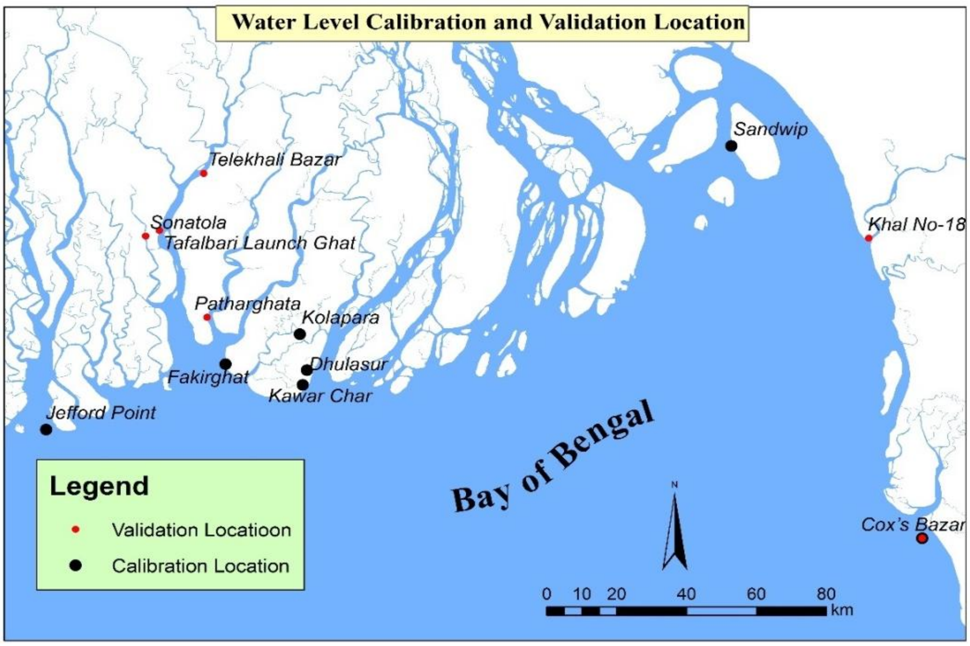

Figure 3: Hydrodynamic model calibration and validation locations

Calibration and validation results of water level at different locations are shown in Figure 4 & 5.

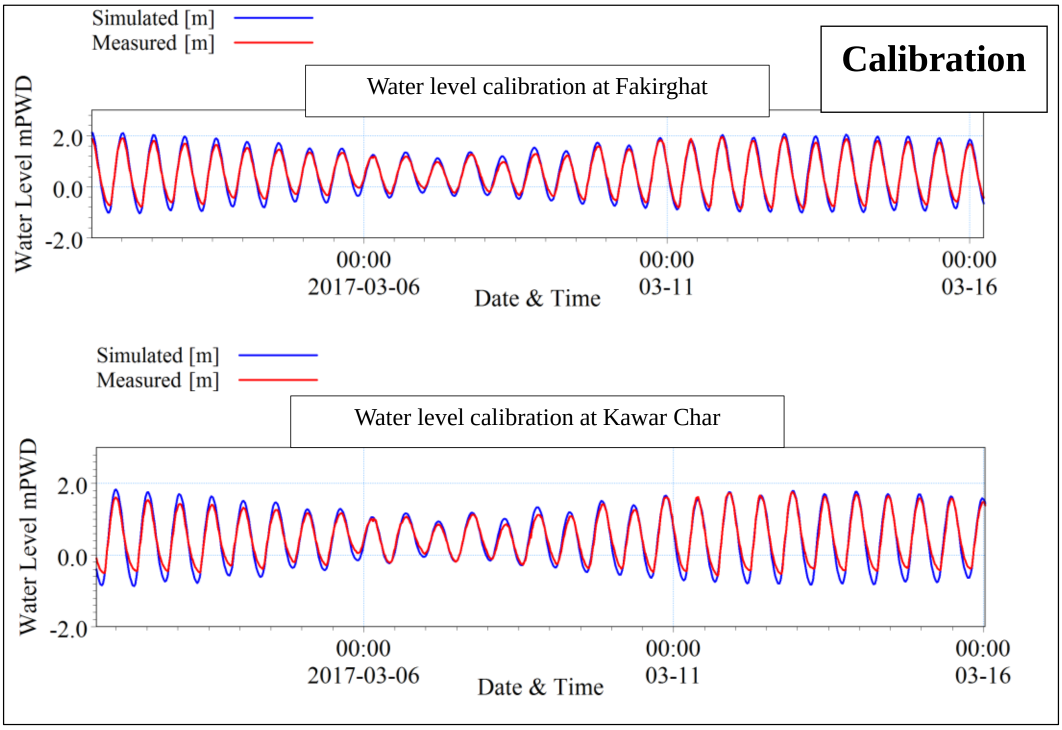

Figure 4: Calibration and validation of hydrodynamic model

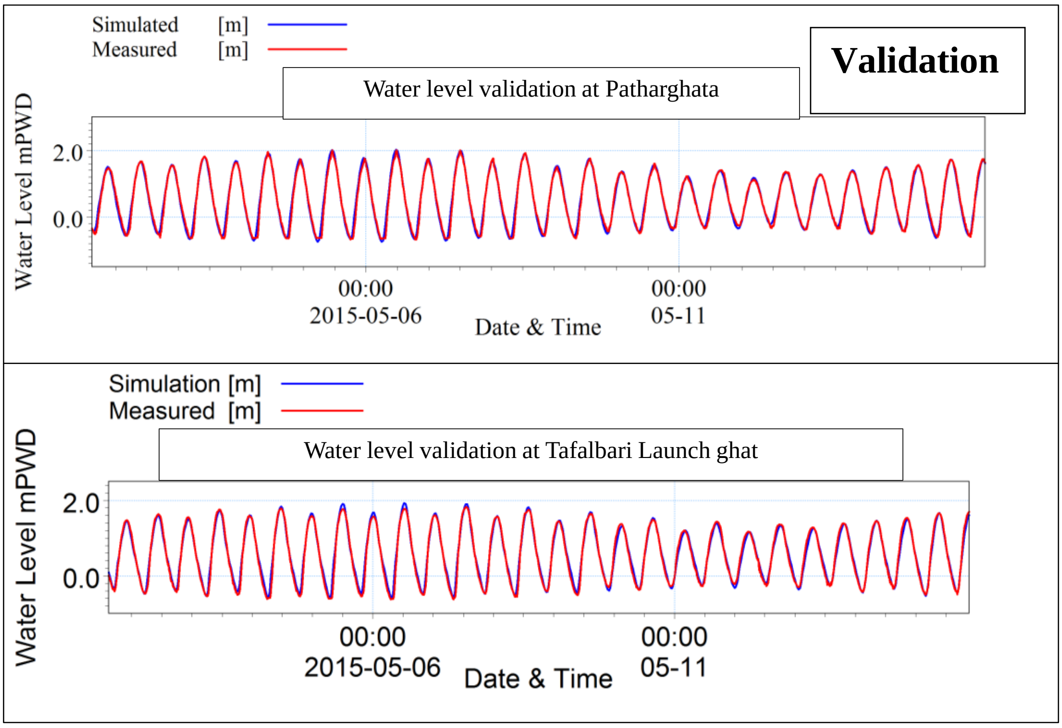

Figure 5: Validation of hydrodynamic model

Setup, Calibration and Validation of Cyclone Model: The description of a cyclone is based on few parameters related to the pressure field, which is imposed to the water surface and a wind field which is acting as a drag force on the water body through a wind shear stress description. To generate the wind field, Holland Single Vortex theory was applied. The cyclone model needs following data for the description of wind field and pressure field; Radius of maximum winds, Maximum wind speed, Cyclone track forward speed and direction, Central pressure and Neutral pressure.

Geostrophic Correction: In order to obtain surface winds, a boundary layer wind speed correction was applied to the gradient wind. The near-surface wind is usually obtained by the following relation (Harper et al., 2001) is shown in Equation (1)

$$V_{10r} = K_m * V_{g(r)} \quad (1)$$

Where$V_{g(r)}$ is the rotational wind gradient speed at a distance r from the center of the cyclone. As mentioned by Harper et al, (2001) different values for the parameter K_m are available in the literature. In this research work 0.75 was used as geostrophic correction factor.

Forward Motion Asymmetry: Cyclonic wind circulate anti clockwise in the norther hemisphere. The wind field is asymmetric so that winds are typically stronger to the right of cyclone track and lower to the left due to the contribution of cyclone movement. Following Harper et al. (2001) the forward motion asymmetry was taken in to account in the cyclone wind generation tool at surface level by the following general relationship;

$$V_{10}(r, \theta) = K_m . V_g (r) + □_{fm} .V_{fm} .\cos (\theta_{max} – \theta) \quad (2)$$

The proportion of the added forward cyclone speed V_{fm} can be adjusted using the correction factor □$_{fm}$(0.5 for this study). The maximum intensity is added along an assumed line of maximum winds defined by the angel θ_{max} measured relative to the cyclone movement direction. In this study, $\theta_{max}$was used as 115

Wind Inflow Angel: All the parametric wind models introduced previously assume a circular wind flow pattern which does not represent the observed surface wind directions. Frictional effects cause the inflow of winds towards the center of the storm. The inflow angel β is typically of the order of 25 but decreases towards the storm center. Empirical formula proposed by Sobey et al. (1977) was used in the cyclone wind generation tool. The parameters used for the calibration of Cyclone model is given in Table 2

Table 2: Cyclone model parameter

Model Parameters	Value	
Parametric Model	Holland Single Vortex Theory	
Geostrophic Correction K_m	0.75	
Forward Motion Asymmetry	Harper et al.	
	Delta_f$_m$	0.5
	Theta_max	115 deg
Inflow Angel	Sobey et al.	

Cyclone module of MIKE is capable of generating wind speed and pressure field over the whole domain. Bangladesh Metrological Department (BMD) usually collects wind data at different locations. Historical wind speed data of BMD was compared with the model simulated wind speed. Figure 6 shows the wind calibration location. Figure 7 shows some calibration plot of wind speed during cyclone 1991 and 2007.

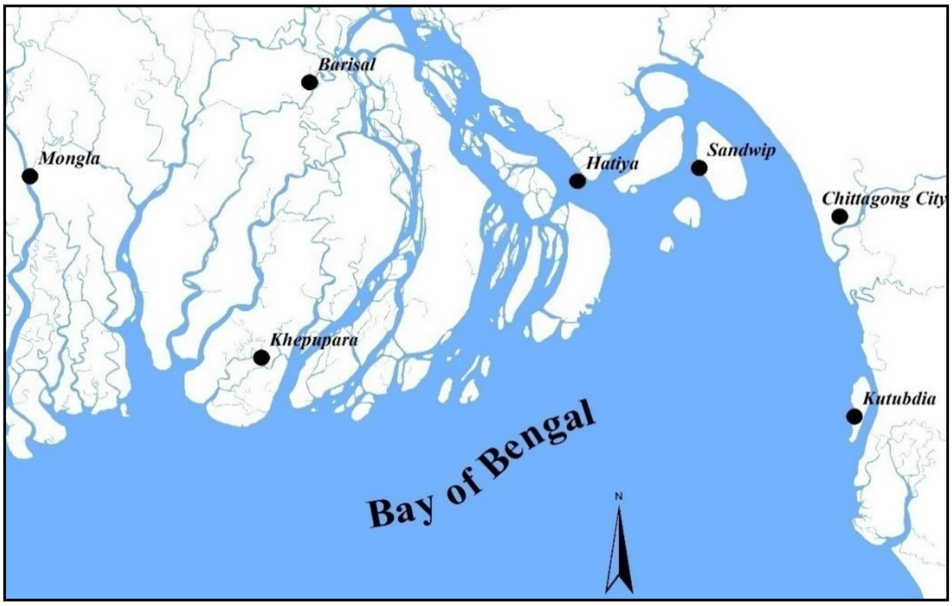

Figure 6: Map showing the wind calibration location

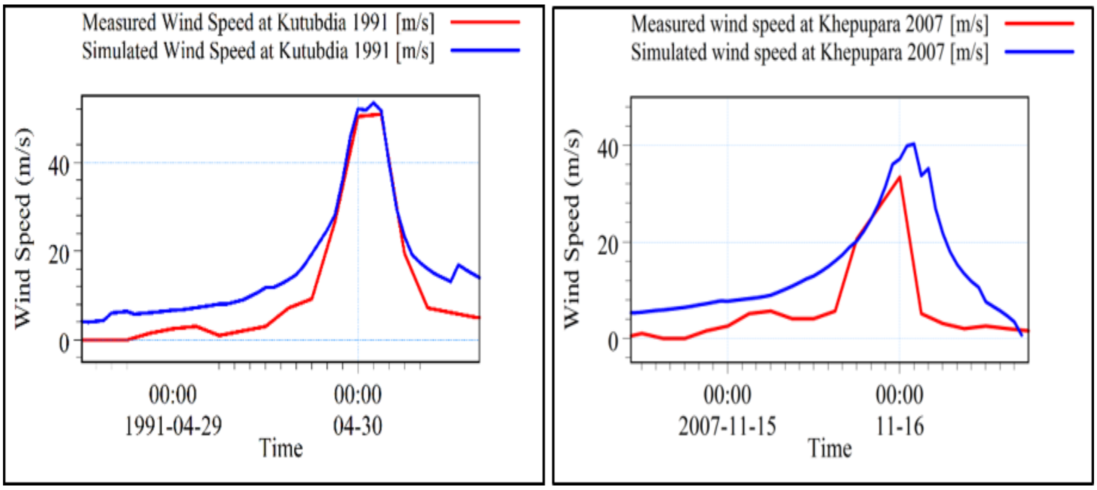

Figure 7: Calibration of cyclone model for wind speed during cyclone 1991 at Kutubdia and cyclone SIDR 2007 at Khepupara

Development, Calibration and Validation of Storm Surge Model: The calibrated and validated hydrodynamic model and cyclone model was coupled together to develop storm surge model for simulation of surge levels along the Bangladesh coastline. Wind friction coefficient was used as the calibration parameter for storm surge level. The wind friction can be specified either as a constant or varying with the wind speed. In the latter case, the friction is linearly interpolated between two values based on the wind speed and if the wind speed is below the lower limit or above the upper limit the friction is given the value corresponding to that limit. In this study, a speed dependent wind friction factor was used (0.0016-0.0026 for 0-24 m/s wind speed) for the calibration of storm surge level. Storm Surge level was calibrated and validated at Hironpoint for cyclone SIDR (2007) and cyclone AILA (2009) respectively. The calibration and validation plots are presented in Figure 8.

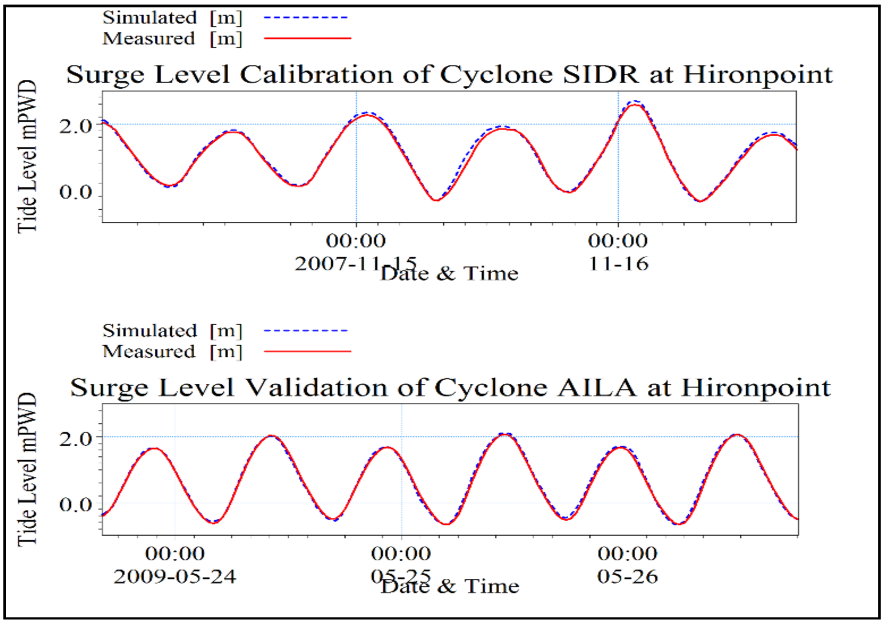

Figure 8: Surge level calibration and validation at Hironpoint during cyclone SIDR (15.11.2007) and AILA (25.05.2009)

III. Result

Calibrated and validated storm surge model was used to simulate the storm surge level for cyclone SIDR, 2007 at different locations of the model domain. Simulated maximum storm surge level during SIDR along Baleshwar channel is shown in Figure 9 (a). The storm surge level at three locations of Baleshwar and Ghasiakhali Channel namely Solombaria, Rayeda bazar and Southkhali are shown in Figure 9 (b).

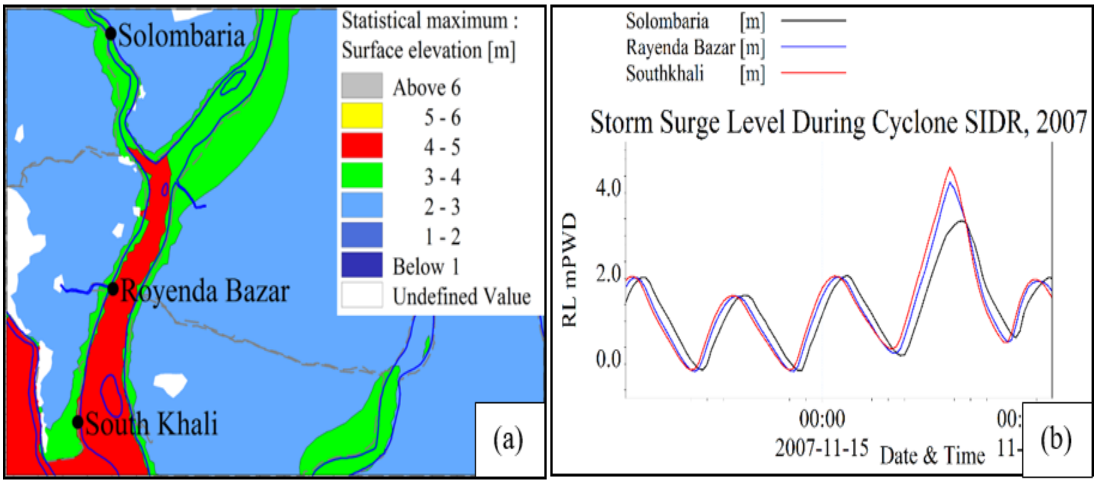

Figure 9: Figure shows maximum storm surge level along Baleshwar channel (a) and time series of storm surge level at Solombaria, Rayenda Bazar and Southkhali (b)during cyclone SIDR-2007

Table 3: Maximum storm surge level at Solombaria, Rayenda Bazar and South Khali during Cyclone SIDR-2007

Location Name	River Name	Maximum Storm Surge Level (mPWD)
Solombaria	Ghasiakhali Channel	3.15
Rayenda Bazar	Baleshwar River	4.05
South Khali	Baleshwar River	4.40

Simulation of Wave Model for Cyclone SIDR: Existing wave model of IWM was updated including the small channels of the study area in the model domain. Wave model was simulated for cyclone SIDR using the storm surge model simulated result as shown in Figure 10. Maximum wave height is shown in Figure 10 (a). Maximum wave height at three locations of Baleshwar and Ghasiakhali Channel namely Solombaria, Rayeda bazar and Southkhali are shown in Figure 10 (b).

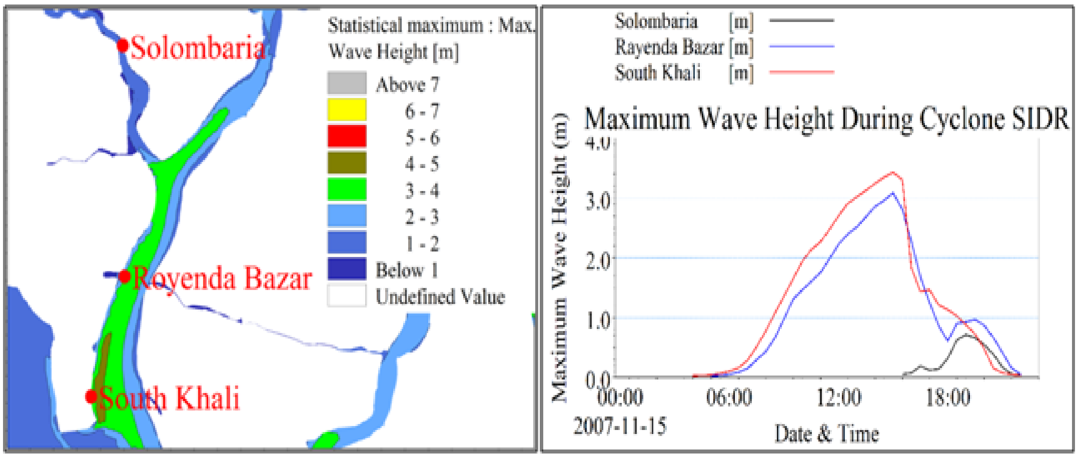

Figure 10: (a) Maximum wave height along Baleshwar Channel and (b) Maximum wave height during cyclone SIDR at Solombaria, Rayenda Bazar and Southkhali

Table 4: Maximum wave height at Solombaria, Rayenda Bazar and South Khali during Cyclone SIDR-2007

Location Name	River Name	Maximum Wave Height (m)
Solombaria	Ghasiakhali	0.71
Rayenda Bazar	Baleshwar River	3.07
South Khali	Baleshwar River	3.43

Verification of Simulated Surge Level at Baleshwar channel with measured storm surge level by JSCE during Cyclone SIDR-2007: Cyclone SIDR attacked south coast of Bangladesh in November 15, 2007. Japan Society of Civil Engineers (JSCE) team visited affected area during December 26-28, 2007. They visited three locations along Baleshwar River namely Slombaria, Rayenda Bazar and South Khali. The measurement locations are shown in Figure 10.

Table 5: Storm surge level measured by JSCE team

Location Name	River name	Date & Time of Measurement	Tide Level during Measurement Time (mPWD)	Surge Height (m)	Storm Surge Level (mPWD)
Solombaria	Ghasikhali	26/12/2007 9:18	(-) 0.30	3.47	3.17
Rayenda Bazar	Baleshwar	26/12/2007 11:30	0.32	5.99	6.32
South Khali	Baleshwar	26/12/2007 14:15	1.03	6.47	7.50

Verification of the model simulated surge Level with JSCE Measurement: JSCE team measured the surge height in consultation with the local community. In practical situation, it is not possible by the local people to separate the contribution of storm surge level and wave height on highest tide level during storm surge. So, their measurement (JSCE) should be verified with the cumulative of simulated storm surge level and maximum wave amplitude (half of wave height). In this regard, both the storm surge and wave model was simulated under this present study for cyclone SIDR-2007. A comparative picture is shown in Table 6.

Table 6: Verification of simulated surge level with JSCE team

Location Name	River Name	Measured by JSCE Team	Model Simulation			% of Error
		Surge Level (mPWD)	Simulated Level (mPWD)	Wave Amplitude (m)	Surge Level (mPWD)	
Solombaria	Ghasiakhali	3.17	3.15	0.36	3.51	+10.7
Rayenda Bazar	Baleshwar	6.32	4.05	1.54	5.59	-11.5
South Khali	Baleshwar	7.50	4.40	1.72	6.12	-18.4

It is clear from the above figure that simulation result not completely matched with the JSCE measurement. There is an error of (+) 10.7%, (-) 11.5% and (-) 18.4% at Solombaria, Rayenda Bazar and Southkhali respectively. In reality, it is very difficult to match the surge level completely with each other. Lot of uncertainties is there. JSCE team measured the highest surge level in consultation with the local community and investigating some physical sign. Again, they measured the surge height with reference to the river water level of their measurement time but they did not measure the tide level of river simultaneously. Tide level was assessed from a hydrodynamic model (south west regional model of IWM). Despite of above limitations, the simulation result shows a decent agreement with the JSCE measurement.

Comparison of Simulated Surge Level with IWM Existing Model: Institute of Water Modelling simulated storm surge level at different locations of the coast and inside the river for nineteen severe cyclones under Coastal Embankment Improvement Project (CEIP). Their surge simulation location is shown in Figure 11

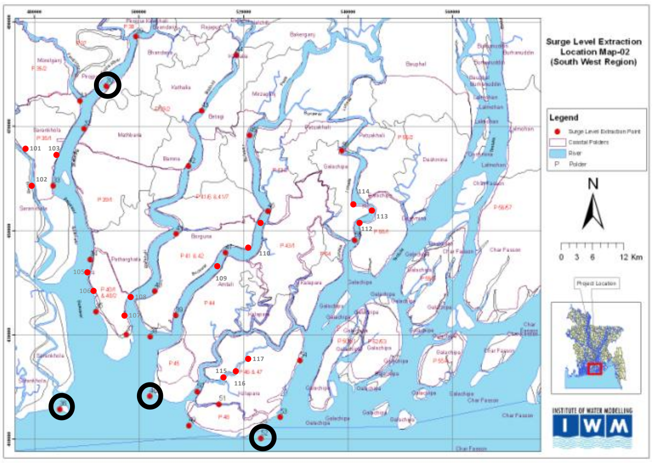

Figure 11: Storm surge simulation location of IWM

The separately calibrated storm surge model (under this study) was simulated for cyclone SIDR-2007 and the storm surge level was extracted for the above locations. Storm surge level from both the simulation is compared and given in the Table 7

Table 7: Comparison of storm surge level with IWM existing model

Location ID	Location Name	Simulated storm surge level under CEIP project (mPWD), IWM	Storm surge level simulated under this research work (mPWD)	Decrease in surge level (m)
i	ii	iii	iv	v = (iii – iv)
30	Near confluence of Ghasiakhali and Baleshwar channel	3.57	3.33	0.24
36	Baleshwar estuary	4.77	4.64	0.13
48	Bishkhali estuary	4.44	4.28	0.16
52	Near Kuakata	5.10	4.88	0.22

Separately calibrated model shows decrease of storm surge level compared to the coupled model results. It is seen that storm surge level decreased by a range of 13 to 24 cm at different locations of Baleshwar river and estuary.

Changes of Surge Height with wind speed and water depth

Storm Surge Simulation for Different Wind Speed: Synthetic model of cyclone SIDR-2007 considering different wind speed was used for this simulation. To see the sensitivity of wind speed over the surge height, other parameters like water level, cyclone track kept constant for all simulations. But it is not possible to change the wind speed without changing the central pressure. To see the effect of wind speed on storm surge height, the contribution of pressure difference on surge height can be eliminate from the total surge height using the following formula.

$S_a = (1013-P_c) * 0.033$ (3)

(Source: R. SILVESTER, COASTAL ENGINEERING,2 1974)

Where $S_a$is the surge height in feet and Pc is the central pressure in millibar.

The model was simulated for zero water level condition in the south boundary to keep the same water level condition for all simulations. Thus, five simulations were carried out considering original wind speed, +5% increased wind speed, +10% increased wind speed, (-) 5% decreased wind speed and (-) 10% decreased wind speed. The surge height was extracted from the simulation results at the mouth of Baleshwar estuary. The surge extraction location is shown in Figure 12.

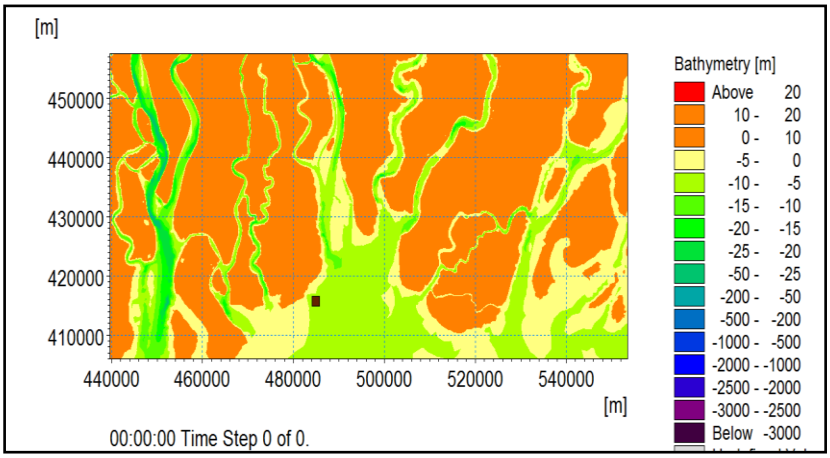

Figure 12: Surge extraction location at the mouth of Baleshwar channel

It can be seen from the above figure that elevation of sea bed at this point is (-) 8.00 mPWD. Storm surge level for different wind speed is shown in Figure 13.

Figure 13: Storm surge level for different wind speed (upper), a zoomed view of surge level (lower)

It is evident from the figure that storm surge height increases with the increase of wind speed. Storm surge height due to pressure difference depends on corresponding central pressure. Storm surge height for all the scenario and corresponding wind speed and central pressure and given in Table 8

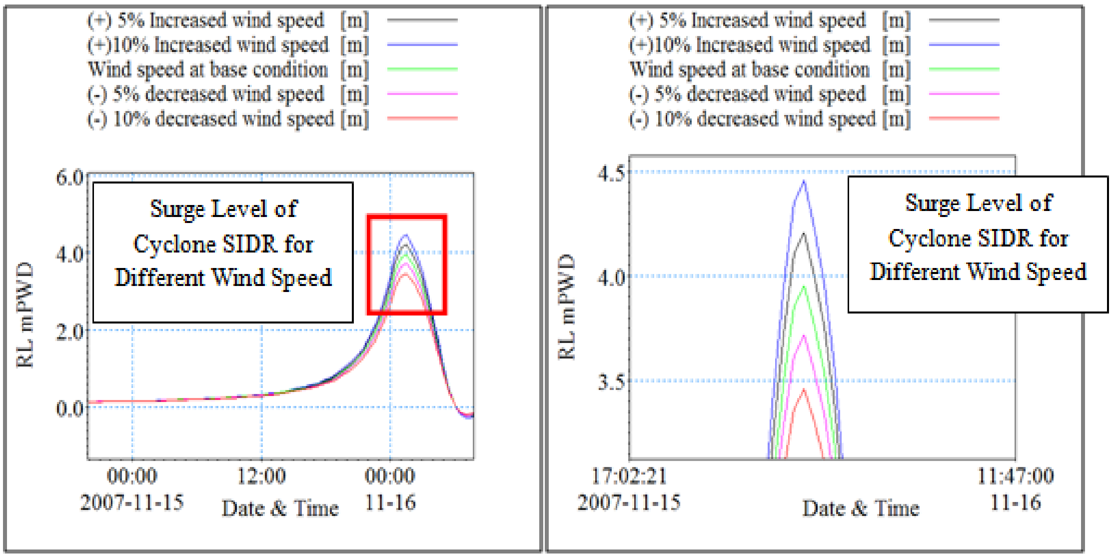

Figure 13: Storm surge level for different wind speed (upper), a zoomed view of surge level (lower)

Table 8: Storm surge height, pressure field and wind speed for different options

Scenario	Wind Speed(m/s) at the Extraction Point	Surge Height (m) at the Extraction Point	Pressure (HPa) at the Extraction Point	Contribution of Pressure (m) (Equation 4.1)	Contribution of Wind Speed (m) (Surge Height-Contribution of Pressure)
i	ii	iii	iv	v	vi = (iii-v)
Base	37.26	3.95	962.37	0.51	3.44
(+) 5% Wind Speed	39.04	4.2	955.25	0.58	3.62
(+) 10% Wind Speed	40.76	4.45	954.32	0.59	3.86
(-) 5% Wind Speed	35.59	3.71	966.01	0.47	3.24
(-) 10% Wind Speed	33.69	3.45	969.99	0.43	3.02

Wind speed is plotted against surge height and shown in Figure 14

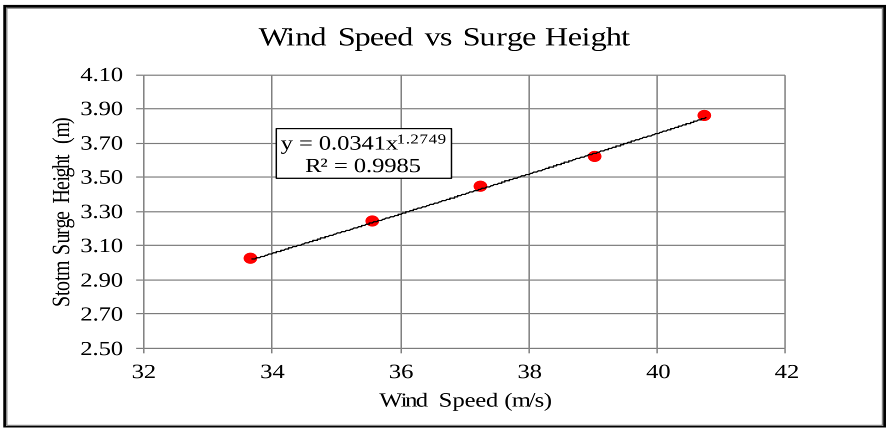

Figure 14: Wind speed vs storm surge height

The relationship between wind speed and the surge height can be expressed by the following expression

$$Y = 0.0341*X^{1.2749} \quad (4)$$

Where X is wind speed in m/s and Y is the surge height in meter. The above expression was developed for cyclone SIDR-2007 kept the water depth constant for the particular location (only for the mouth of Baleshwar River). It is evident that storm surge height is a power function of wind speed with increasing trend.

During maximum surge height, the wind direction was 294 degrees with respect to north. Above equation is true only when the cyclonic wind hit that location from 294 degrees. To make the equation direction independent, a component of wind speed was considered in the above equation. Then the above equation became like following expression

$S_w=0.0341*(V_w Cos\Delta\Theta)^{1.275}$(5)

Where S_w is the surge height in meter due to wind speed, V_w is the wind speed in m/s and $\Delta\Theta$ is the angle between reference wind direction (294) and actual wind direction i.e. ($\Delta\Theta = \Theta$-294)

Storm Surge Simulation for Different Water Depth: The model was further simulated for the same cyclonic event (SIDR) keeping the same wind speed and track but different water level for all the simulations. Instead of using tidal water level in the south boundary, a constant water level was used. Simulation was carried out for zero water level, (+) 1 mPWD, (+) 2 mPWD, (-) 1 mPWD and (-) 2 mPWD water level condition. Storm surge height was extracted at the same location of Baleshwar estuary (Figure 12). Extracted surge height is shown in Figure 15.

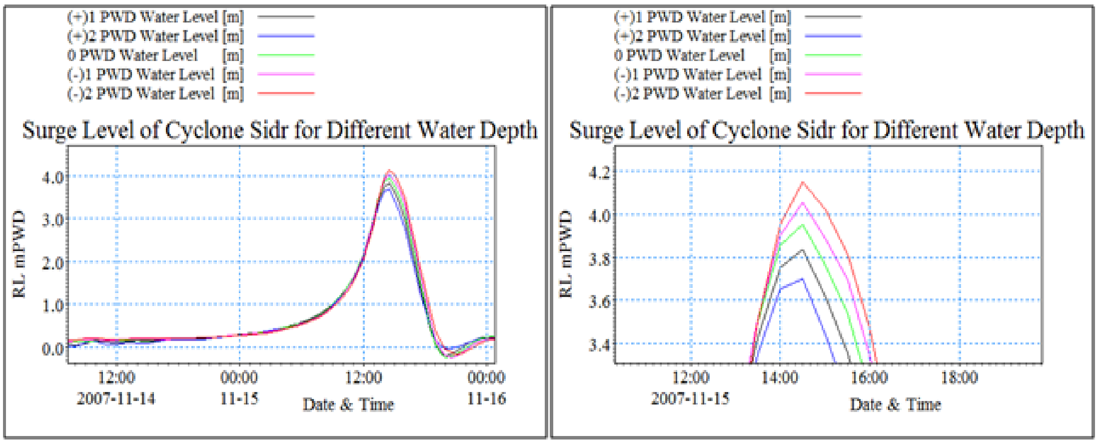

Figure 15: Storm surge height for different water level

It can be seen from the above figure that storm surge height changes with the change of water depth although the wind and the cyclone track is same for all the simulation. Maximum surge height occurred when the water depth is Minimum. Storm surge height of different options is given in Table 9.

Table 9: Storm surge height for different water depth

Boundary Water Level (mPWD)	Bed level at the Extraction Point (mPWD)	Water Depth (m)	Simulated Surge Level (mPWD)	Surge Height (m)	Change in Water Depth (m)	Change in Surge Height from base condition due to change in water depth (m)
i	ii	iii =i - ii	iv	v = iv - i	vi = iii - 8	vii = v – 3.95
(+)1	(-) 8	9	4.84	3.84	1	-0.11
(+)2		10	5.7	3.7	2	-0.25
0		8	3.95	3.95	0	0.00
(-)1		7	3.05	4.05	-1	0.10
(-)2		6	2.15	4.15	-2	0.20

To assess the net effect of water depth on storm surge height, change in surge height and water depth from the base condition (zero water level condition) was calculated in the above table and plotted in Figure 16

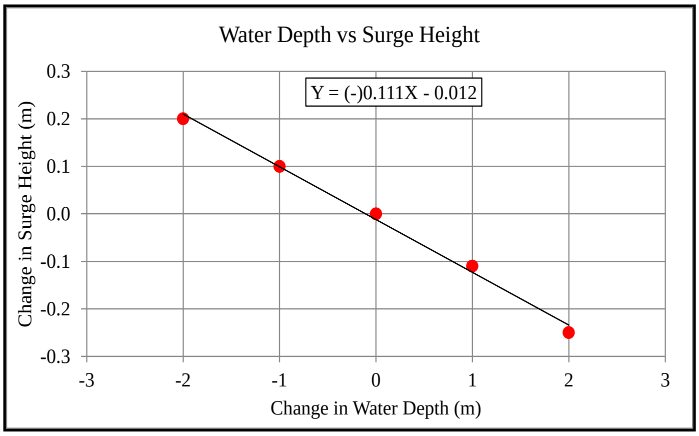

Figure 15: Change in surge height due to change in water depth

The relation between water depth and surge height can be defined by the following expression.

$$Y = (-)\ 0.111X - 0.012 \qquad (6)$$

Where Y is the change in surge height in meter and X is the change in water depth in meter. In this case, the reference water depth is 8 meters. So, the equation can be re-written as

$$S_h = (-)\ 0.111*(d-8) - 0.012 \qquad (7)$$

Where S_h is the surge height due to change in water depth, d is the water depth.

It can be seen from the above figure and expression that storm surge height is inversely proportional to water depth. The physical process involved during storm surge can be explained such a way; the surface slope (surge) is balancing the wind stress. This balance is a function of the water depth. The higher depth (e.g. at high water) the smaller slope/surge, again at smaller water depth the higher slope/surge.Increase in one meter water depth can decrease surge height by 11 cm and vice versa at Baleshwar estuary if wind speed and cyclone track remain constant.

Effect of wind speed and water depth on storm surge height has already described in this section. Thus, the total surge height at that location (Baleshwar Estuary) is the summation of Equation 3, 5 and 7.

Storm surge height at Baleshwar Estuary, S_{be} = Sa + Sw + Sh

$$S_{be} = [(-)\ 0.111*(d-8) - 0.012] + [0.0341*(V_w Cos\Delta\Theta)^{1.275}] + [0.01006*(1013-P_c)] \qquad (8)$$

Where,
S_{be} = Surge height at Baleshwar estuary
d = Water depth in meter
V_w = Wind Speed in m/s at 10-meter height
$\Delta\Theta$ = (Wind direction – 294) in degree
P_c = Central Pressure in millibar

Verification of the Storm Surge Calculation Equation: Storm surge height calculation equation was verified with the model simulation result of IWM. IWM simulated surge level at Baleshwar estuary for different cyclonic event (Under CEIP project). Astronomical tide level at that location was generated from the global tide model. Storm surge height was calculated deducting the astronomical tide level from the storm surge level. Again, storm surge height was calculated using equation 8. These two results were compared for verification of the equation. Surge height for cyclone 1970 is shown in Figure 17.

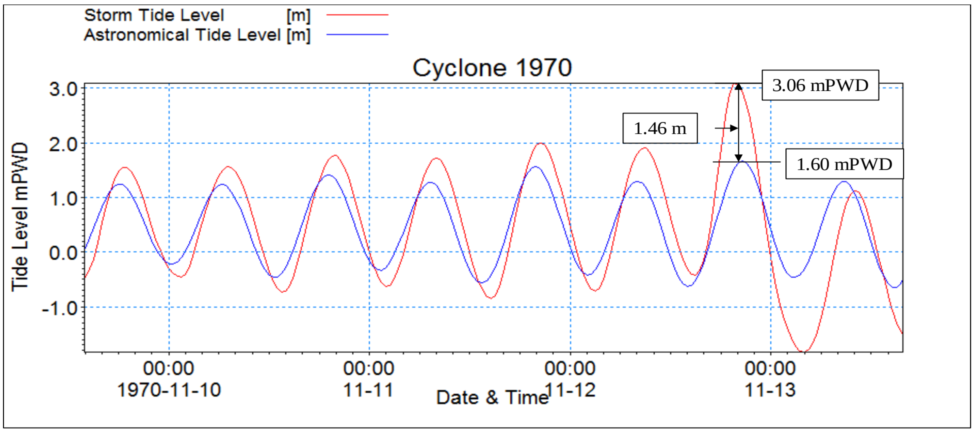

Figure 16: *Surge height during cyclone 1970*(Source: IWM model and global tide model)

Surge level, astronomical tide level and surge height for different cyclonic event is given in Table 10

Table 10: Surge level, astronomical tide level and surge height by IWM

Cyclonic Event	Storm Surge Level (mPWD)	Astronomical Tide Level (mPWD) During Cyclone	Storm Surge Height (m)
1961	1.61	1.03	0.58
1965-May	1.76	1.36	0.40
1970	3.06	1.60	1.46
1974	1.96	1.21	0.75
1985	1.81	1.52	0.29
1988	1.93	0.28	1.65
1991	2.09	1.70	0.39
1997-May	1.53	1.01	0.52
1997-Sep	1.80	0.90	0.90
2007	4.77	0.80	3.97
2009	2.56	1.85	0.71

(Source: IWM 2013)

Generation of wind parameter for severe cyclones: Cyclone module of MIKE was used to generate the wind and pressure field for the severe cyclone. Generated wind and pressure data for cyclone 1970 is shown in Figure 18.

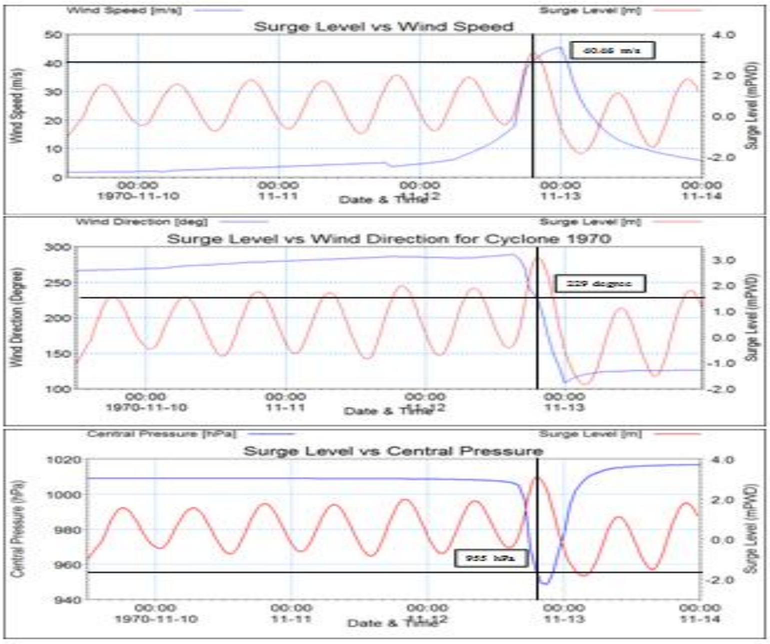

Figure 17: *Generated wind and pressure field during cyclone 1970 at Baleshwar estuary*

Wind speed direction and central pressure for severe cyclone at Baleshwar estuary is given in Table 11

Table 11: Wind speed, direction and central pressure of different cyclonic event at Baleshwar estuary

Cyclonic Event	Maximum Wind Speed (m/s)	Wind Direction (degree)	Central Pressure (hPa)
1961	26.50	214.00	985.00
1965-May	11.50	289.00	1002.70
1970	40.46	229.00	955.00
1974	29.82	221.00	994.00
1985	16.36	225.00	1000.37
1988	26.80	344.15	1003.38
1991	10.33	260.29	1006.84
1997-May	18.24	234.83	1000.95
1997-Sep	12.15	293.16	1002.86
2007	37.26	294.00	962.37
2009	16.01	285.40	1006.35

Verification of the Surge Calculation Equation with IWM Result: Storm surge height calculated in Table 10 can be verified with the storm surge height calculated by the equation 8. Surge height calculated using the above information (Table 11) is compared with IWM surge height and given in Table 12

Table 12: Storm surge height (from developed equation) verification with IWM simulation result

Cyclonic Event	Maximum Wind Speed (m/s)	Wind Direction (degree)	ΔΘ (degree)	ΔΘ (radian)	Central Pressure (hPa)	Water Depth (m)	Surge Height (m) from the Equation	Surge Height (m) IWM
1961	26.5	214	80	1.396825397	985	9.03	0.39	0.58
1965-May	11.5	289	5	0.087301587	1002.7	9.36	0.70	0.4
1970	40.46	229	65	1.134920635	955	9.50	1.68	1.46
1974	29.82	221	73	1.274603175	994	9.21	0.58	0.75
1985	16.36	225	69	1.204761905	1000.37	9.52	0.27	0.29
1988	26.8	344.15	50.15	0.875634921	1003.38	8.28	1.33	1.65
1991	10.33	260.29	33.71	0.588587302	1006.84	9.70	0.39	0.39
1997-May	18.24	234.83	59.17	1.033126984	1000.95	9.01	0.59	0.52
1997-Sep	12.15	293.16	0.84	0.014666667	1002.86	8.90	0.81	0.9
2007	37.26	294	0	0	962.37	8.80	3.84	3.97
2009	16.01	285.4	8.6	0.15015873	1006.35	9.85	1.00	0.71

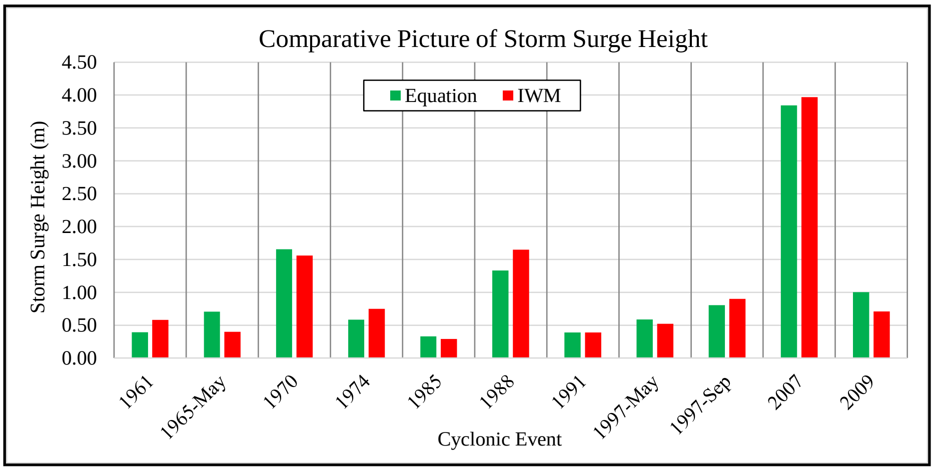

Figure 18: Storm surge height verification

It can be seen from the above figure that there is fare agreement between the IWM simulated result and storm surge height calculated by the equation. A correlation graph can be shown between the surge height of IWM and surge height estimated by the equation.

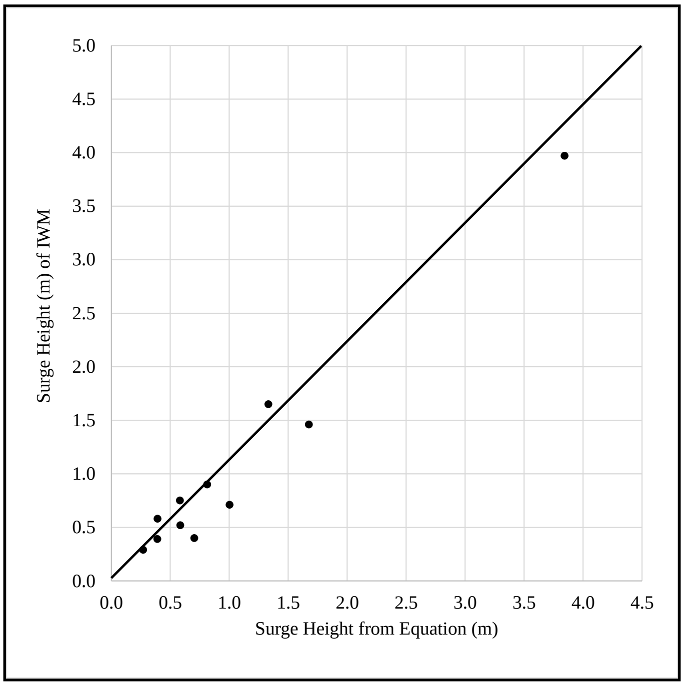

Figure 19: Correlation graph for storm surge height of IWM and estimated by the equation

A good correlation can be seen from the above figure between the storm surge height of IWM and the storm surge height estimated by the equation.

IV. Discussion

The bathymetry of Bay of Bengal hydrodynamic model (BoB) of IWM was improved with finer mesh resolution at Baleshwar channel and the hydrodynamic model was calibrated and validated for water level using the measured data of the year 2017 and 2015 respectively. Moreover, cyclone model was calibrated for measured wind speed at several locations for cyclone 1991, cyclone SIDR (2007) and cyclone AILA (2009).
These two calibrated models (hydrodynamic and cyclone model) were coupled together and storm surge model was developed for Bangladesh coast. Finally, this storm surge model was calibrated and validated using the measured storm surge levels for cyclone SIDR (2007) and cyclone AILA (2009).

Simulation result of separately calibrated storm surge model (under this research work) shows a difference of (+) 10.7%, (-) 11.5% and (-) 18.4% at Solombaria, Rayenda Bazar and Southkhali respectively with the field investigation of JSCE team for cyclone SIDR-2007 due to some measurement uncertainty.

The model also shows a little change in the surge level compared to the existing model of IWM. It was seen that storm surge level decreased by a range of 13 to 24 cm at different location of Baleshwar channel and estuary.

Total ten simulations were carried out to see the effect of wind speed and water depth on storm surge height at Baleshwar estuary. Five simulations were carried out for base condition of cyclone SIDR and (+) 5%, (+) 10%, (-) 5% and (-) 10% changed wind speed condition. It can be seen from the simulation result that storm surge height is a power function of wind speed.

Another five simulations were carried out for cyclone SIDR considering (+) 2mPWD, (+) 1mPWD, 0mPWD, (-) 1mPWD and (-) 2mPWD water level condition. It can be seen from the result analysis that storm surge height is inversely proportional to the water depth.

These analysis results have been used to establish a relation between cyclone parameter and storm surge height. An equation was developed for estimating the storm surge height at Baleshwar estuary is given below.

$$S_{be} = [(-)\ 0.111*(d-8) - 0.012] + [0.0341*(V_w \text{Cos}\Delta\Theta)^{1.275}] + [0.01006*(1013-P_c)]$$

Storm surge height was simulated using this equation at Baleshwar estuary for different cyclonic event and verified with the simulated surge height of IWM at that point. It can be seen by comparing the simulated storm surge height (from equation) and IWM model simulation that this equation can give us a quick estimation of storm surge height for Baleshwar estuary for a given cyclone.

V. Conclusion

Separately calibrated storm surge model (under this study) can be used as a useful and effective tool for the simulation of cyclone at a tidal channel along Bangladesh coast.Storm Surge Simulation result shows that storm surge height is a power function of wind speed andinversely proportional to the water depth.It can be seen by comparing the estimated storm surge height with IWM model simulation that the equation developed under this study can give us a quick estimation of storm surge height for Baleswar estuary.

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