IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)
e-ISSN: 2278-1684,p-ISSN: 2320-334X, Volume 12, Issue 2 Ver. IV (Mar - Apr. 2015), PP 55-62
www.iosrjournals.org

Numerical Modeling for the Propagation of Tsunami Wave and Corresponding Inundation

MD. Mobassarul Hasan[1], S M Mostafizur Rahman[2,] and Upal Mahamud[3].
[1] *Research Associate,Tropical Marine Science Institute,National University of Singapore, Singapore,*
[2] *Assistant Professor, Department of Civil Engineering, Military Institute of Science and Technology, Dhaka, Bangladesh,*
[3] *PhD Student,Graduate school of System and Infomation, Tsukuba University, Tsukuba City, Japan,*

Abstract: *In recent years, the threat of tsunamis has taken an added urgency after a 9.3 magnitude earthquake off Indonesia's Sumatra island in December 2004 which triggered a tsunami and killed more than 230,000 people and left a half million homeless in a dozen countries[3]. Bangladesh experienced relatively minor damage from the tsunami, with 2 people killed. In order to assess the vulnerability of the coastal region of Bangladesh due to tsunami a tsunami model was developed covering the Indian ocean, the Arabian sea, the Bay of Bengal and the coastal region of Bangladesh using MIKE21 modelling system of DHI. The model was calibrated with the tsunami of December 26, 2004, which occurred at the West Coast of Sumatra due to a strong earthquake. In total six scenarios of tsunami were identified based on the potential sources of earthquake in the Bay of Bengal. Initial surface level maps for all the scenarios were generated using QuakeGen, a geological model and MIKE 21 modelling system. Then all the scenarios were simulated with respective initial surface level maps under Mean High Water Spring (MHWS) and Mean Sea Level (MSL). The maximum inundation map for each scenario of tsunami was generated based on the simulated results for MHWS as it is more vulnerable than MSL. Finally inundation risk map was generated using GIS tool and all the maximum inundation map. The inundation risk map for tsunami shows that Sundarban area, Nijhum Dwip, south of Hatia (outside polder) and Cox's Bazaar coast may experience higher flood level during tsunami.*
Keywords - *Tsunami, Propagation, Inundation, Coastal Region, and MIKE21.*

I. Introduction

Tsunami is an oceanic gravity wave generated by submarine earthquake resulting from tectonic processes and other geological processes such as volcanic eruptions and landslides in the sea. The genesis of a tsunami depends on geodynamics (the nature and direction of convergence of the plates), tectonics (geological forces and the nature and types of fault rupture), seismicity (earthquake) pattern and the water depth [7]. The orographic pattern of Bay of Bengal suggests the nature and magnitude of the tsunami wave propagation [2]. Under this study inundation risk map for the coastal region of Bangladesh was prepared based on the simulated results of 6 potential scenarios. In this paper vulnerability of the coastal region of Bangladesh due to tsunami is assessed based on the simulated results.

II. Approach Of The Study

The tsunami model was developed using available data and MIKE 21 modelling tool. The model comprises four (4) nested levels having grid sizes vary from 16200m to 600m. The regional model covers the Indian Ocean, the Arabian Sea, the Bay of Bengal and the coast of Bangladesh whereas the fine grid model covers the coastal region of Bangladesh [4]. In total six scenarios of tsunami have been identified based on the potential sources of earthquake in the Bay of Bengal. Initial surface level maps for all the scenarios were generated using QuakeGen, a geological model and MIKE 21 modelling system. Then all scenarios were simulated with respective initial surface level maps. The maximum inundation map for each scenario of tsunami was generated based on the simulated results. Finally inundation risk map was generated using all the maximum inundation maps and GIS tool.

Decay factors of the propagation of tsunami wave on land were also incorporated in the model using Manning number (M, $m^{1/3}/s$) which is reciprocal of Manning's coefficient of roughness (i.e. M=1/n).

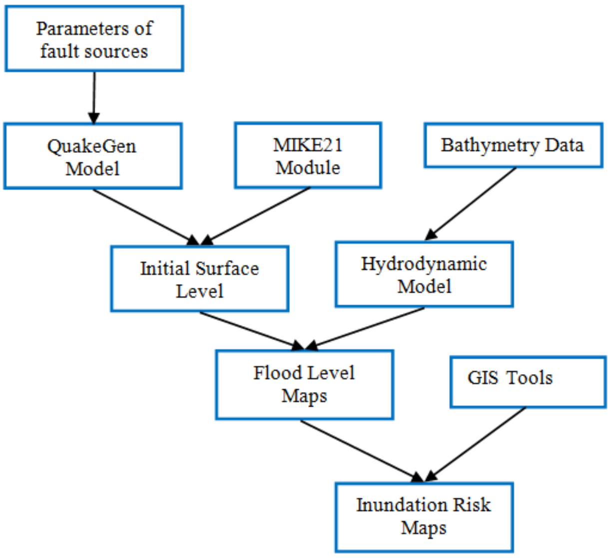


Figure 1: Flow diagram of study methodology

III. Numerical Modelling Of Tsunami

Tsunami (pronounced tsoo-nah-mee) is an oceanic gravity wave generated by submarine earthquake resulting from tectonic processes and other geological processes such as volcanic eruptions and landslides in the sea. Tsunami is a Japanese word meaning harbor wave. Its amplitudes are typically small in the open sea but can reach to damaging amplitudes near the shore or in shallow or confined waters [1]. They are also called oceanic seismic waves.

When two ocean plates move towards each other and one of the plates form uplift during Earth Quake causes tsunami. Figure 2 shows the subduction of one plate under another continental plate during earthquake.

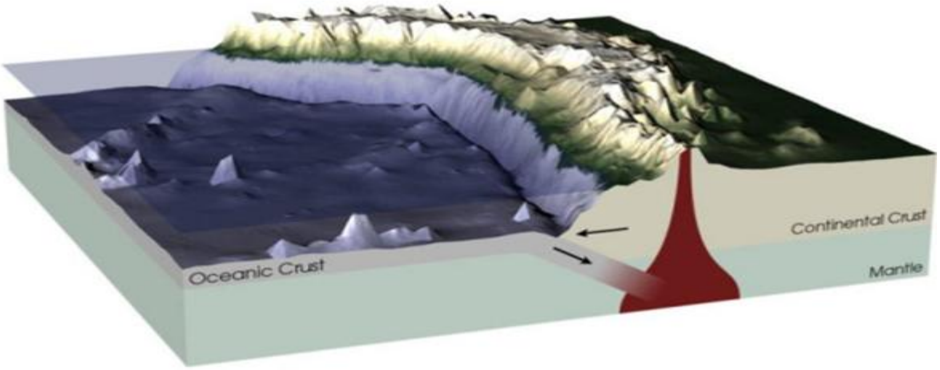


Figure 2: Subduction of one plate under another continental plate

During earthquake three different types of slip occur between two ocean plates along the fault line: normal dip-slip, reverse dip-slip and strike-slip (shown in Figure-3). But the reverse (forming uplift) and the normal dip-slip (forming subsidence) are tsunamigenic.

Figure 3: Normal Dip-Slip (left one), Reverse Dip-Slip (middle one) and Strike-Slip

The numerical modelling of the tsunami waves from the source to the coastal inland can be considered in three stages:

1. Source Modelling: simulation of initiation of tsunami generated by sea floor displacement;
2. Tsunami Wave Propagation Modelling: simulation of tsunami wave propagation from the source to the coast; and
3. Tsunami Inundation Modelling: simulation of tsunami waves propagation from the coast to the inland over dry land

3.1 Source Modelling

Based on the aforesaid geophysical and geological data, the potential fault source map of the Bay of Bengal was prepared (Figure 4). The parameters of the fault sources such as rupture length, slip offset, dip angle, slip angle, strike angle, and the moment magnitude are required to generate tsunami simulations [1]. All of them were calculated accordingly from geophysical and seismological data. Finally six (6) potential tsunamigenic fault-sources were identified for model simulation. The positions of the potential sources of tsunami with earthquake parameters are presented in Table 1.

Table 1: Potential earthquake sources with parameters

Potential Sources of Tsunami	*Fault Location*	*Fault Segment's Length*	*Max Fault Slip (Δ)*	*Initial Rupture Time*	*Fault dip angle, (δ)*	*Fault slip angle , (λ)*	*Fault strike angle, (φ)*	*Focal depth (d)*	*Moment magnitude (Mw)*
		(km)	*(m)*		*(deg)*	*(deg)*	*(deg)*	*(km)*	
FS-1	22N, 91.7E	70	5m (Observed) 7m (Potential)	0	30	65	340	10	**6** **7.5** (Potential)
FS-2	21N, 92E	90	5m (Observed) 7m (Potential)	0	30	65	340	10	**6** **7.5** (Potential)
FS-3	18.5N, 93.5E	250	3 -7 m (Observed)	0	40	45	340	10	**8** (Potential)
FS-5	17N, 92E	250	5	0	50	40	20	10	**8**
FS-4	12N. 92E	350	5	0	50	45	30	10	**8** (Potential)
FS-6	07N, 92E	300	9	0	40	50	320	10	**9**

The most important part of tsunami modelling is to create initial water level displacement due to the impact of the Earthquake. A geological model named QuakeGen model was used for calculation of deformation in bed level based on the geophysical and seismological data.

The model is based on the theory of Manshinha and Smylie 1971[2]. It calculates a displacement of the seabed that results from seismic fault movements in the earth's crust, assuming that the crust consists of an elastic body and fault shape is rectangular. The model describes the deformation of the bed level due to a double coupled model developed by Yoshimitsu Okada in 1985 [6] (Figure-5 and Figure-6).

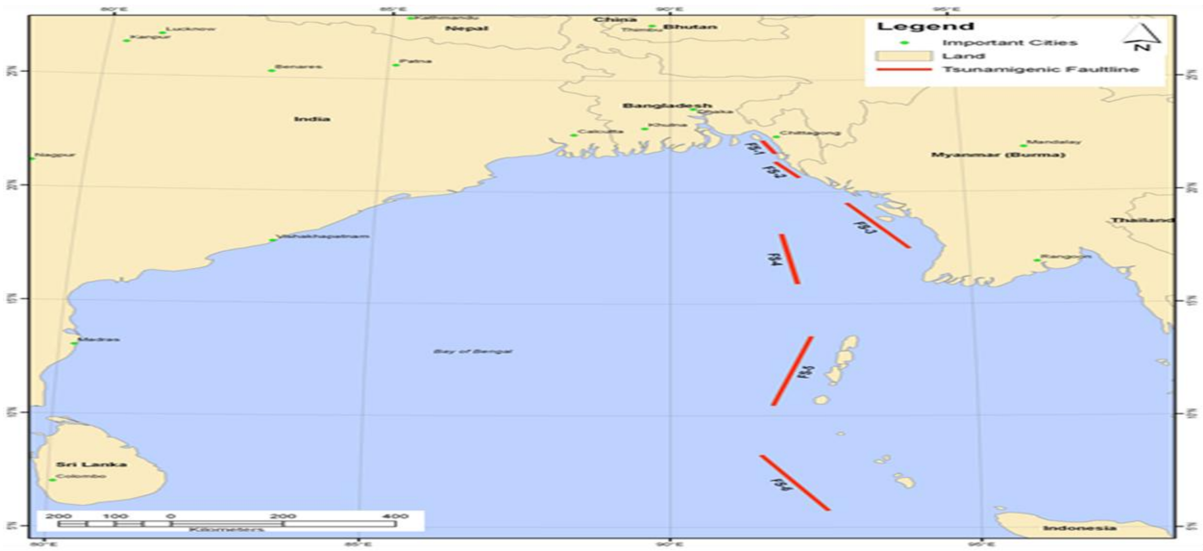


Figure 4: Potential fault-source map of the Bay of Bengal

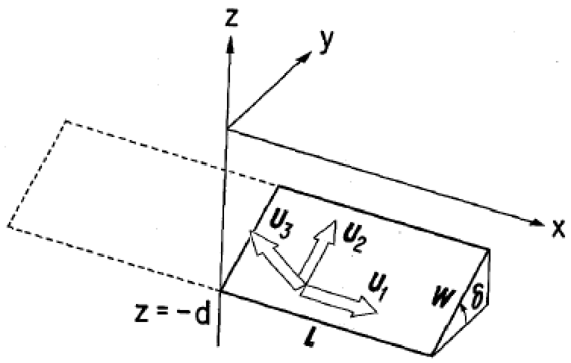


Figure 5: Geometry of the Okada model

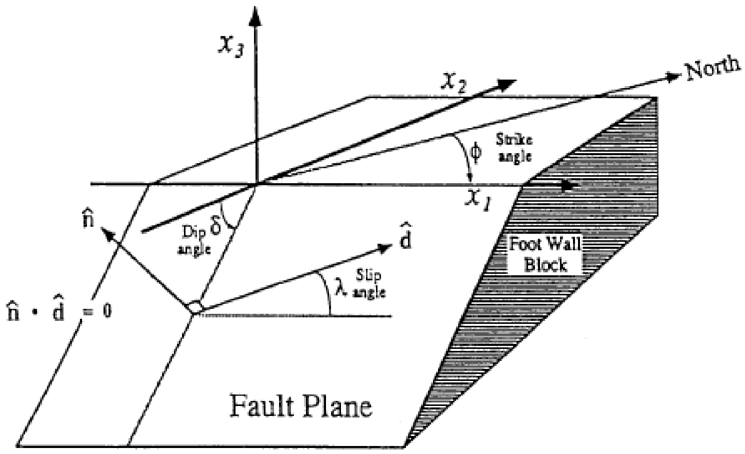


Figure 6: Parameter descriptions in the Okada model

(Curray, 1971) Strike is the azimuth of the fault plane (fault strike line) measured from North, and dip is the azimuth of the fault plane measured from the horizontal line. Slip is the angle of the fault slip direction measured from the horizontal line. The result from QuakeGen is the Initial displacement of the bed level.

Based on the output from QuakeGen the initial surface level was calculated using hydrodynamic module of MIKE 21 modelling system [7]. In this way initial surface level maps for six (6) potential sources were generated based on the geological parameters. A sample plot of initial surface level of tsunami (FS-5) is presented in Figure-7.

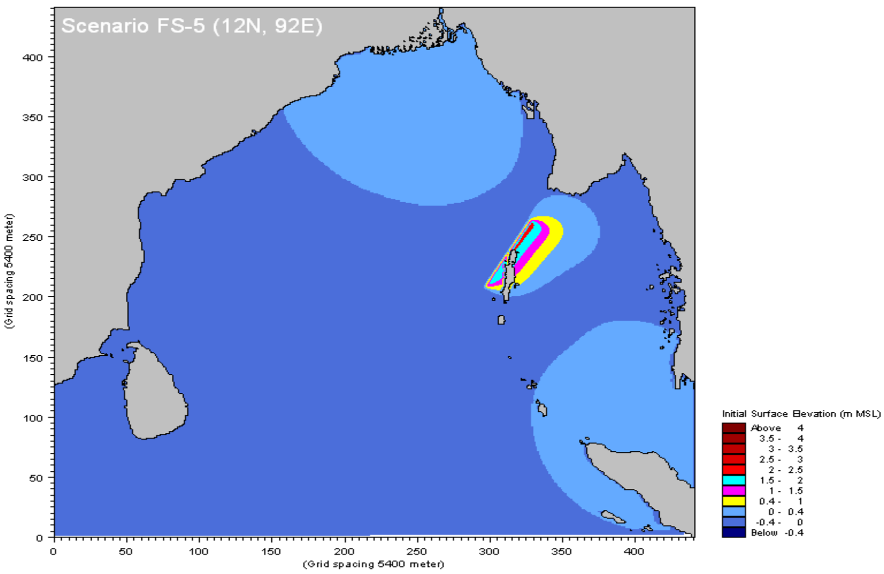


Figure 7: Initial Surface level of tsunami scenario FS-5

3.2 Tsunami Wave Propagation and Inundation Modelling

Tsunami wave propagation and inundation modelling from its sources to the Bangladeshi coast were carried out using hydrodynamic module or flow module of MIKE21 modelling system. The scientific background of these two modules is described below.

The flow model is two-dimensional hydrodynamic simulation program which calculates non-steady flow resulting from tidal and meteorological forcing on rectilinear grid. The model solves the non-linear shallow water equations on a dynamically coupled system of nested grid using finite difference numerical scheme. It simulates unsteady two-dimensional flows taking into account density variations, bathymetry and external forcing such as metrology, tidal elevations, currents and other hydrographical conditions. The basic partial differential equations are the depth integrated continuity and momentum equations (shallow water equations):

$$\frac{\delta\xi}{\delta t}+\frac{\delta p}{\delta x}+\frac{\delta q}{\delta y}=0$$

$$\frac{\delta p}{\delta t}+\frac{\delta}{\delta x}\left(\frac{p^2}{h}\right)+\frac{\delta}{\delta y}\left(\frac{pq}{h}\right)+gh\frac{\delta\xi}{\delta x}+\frac{gp\sqrt{p^2+q^2}}{C^2h^2}-fq-C_w\frac{\rho_A}{\rho_W}WW_x+h\frac{\delta}{\delta x}\left(\frac{p_a}{\rho_w}\right)=0$$

$$\frac{\delta q}{\delta t}+\frac{\delta}{\delta y}\left(\frac{q^2}{h}\right)+\frac{\delta}{\delta x}\left(\frac{pq}{h}\right)+gh\frac{\delta\xi}{\delta y}+\frac{gq\sqrt{p^2+q^2}}{C^2h^2}+fp-C_w\frac{\rho_A}{\rho_W}WW_y+h\frac{\delta}{\delta y}\left(\frac{p_a}{\rho_w}\right)=0$$

Where, xy is the horizontal coordinates [m], t is time [s], h is the water depth [m], ζ is the Surface elevation [m], p and q is the flux densities in x and y directions [m3/s/m], g is acceleration due to gravity [m/s^2], C is Chezy's bed resistance coefficient [$m^{1/2}/s$], f is Coriolis parameter [s^{-1}], Cw is the wind friction factor [-], W (Wx, Wy) is the wind speed and its components in x and y directions [m/s], P_a is the atmospheric pressure [$kg/m/s^2$], ρ_A is the density of air [kg/m^3], ρ_w is density of water [kg/m^3].

MIKE21 allows the use of nested grids, which is especially important for the simulation in coastal areas with complex geometries of land-water boundaries. The model uses dynamically consistent two-way nesting technique. The detailed resolution near land and large gradients in the water depth are necessary to describe the local shoaling effect of the tsunami. The correct propagation of tsunami waves depends primarily on the initial conditions of the wave and secondly on the bathymetry of the area. After the calculation of water surface deformation from source model or from empirical equations, the tsunami propagation model will then be initialized with the deformed sea surface, after which it simulates the spreading and propagation of the wave in different directions and finally produces inundation at the land area.

3.3 Tsunami Wave Propagation and Inundation

A tsunami model was developed for the Indian ocean, the Arabian sea, the Bay of Bengal and the coastal region of Bangladesh using MIKE21 modelling system of $\text{DHI}_{\text{Water.Environment.Health}}$. The model was then applied to simulate the tsunami propagation and inundation from its sources to the coast of Bangladeshi. The tsunami model comprises four (4) nested levels with the following grid sizes:

- Regional model having grid size of 16200m
- Coarse model having grid size of 5400m;
- Intermediate model having grid size of 1800m and
- Fine model having grid size of 600m.

The model is four-way nested and it is driven though the release of the applied initial surface elevation only. The Meghna Estuary is resolved on a 600m grid resolution. The fine grid model domain covers the coastal region up to Cox's Bazar. The Regional model was used to absorb energy at the boundary and to avoid reflection from internal boundaries. All the boundary conditions at the regional model were set to zero. The Coarse grid model which covers the Bay of Bengal, is the actual domain where initial surface deformation due to sub-sea earth quakes was applied. The intermediate grid model serves only as a transition to the local fine grid model. The fine grid Model was used for detailed study of the inundation and flood risk due to the Tsunami wave. Figure 8 shows the regional model domain.

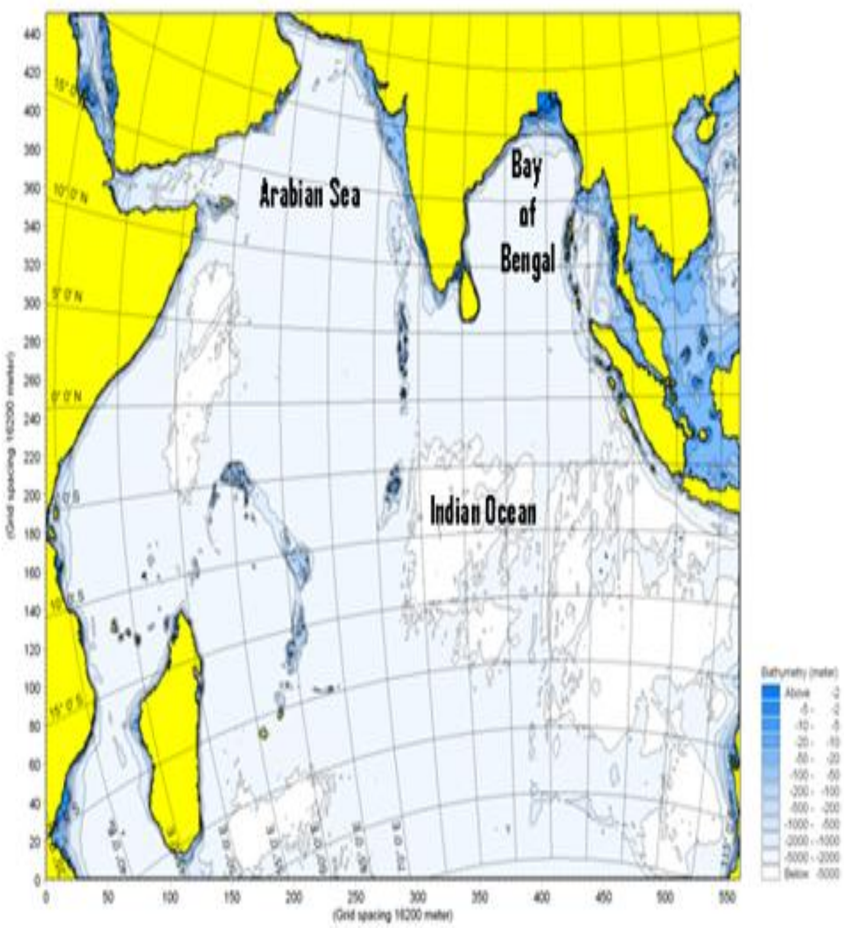


Figure 8: Regional model domain

The simulation parameters of the tsunami model are shown in Table 2.

Table 2: Tsunami Simulation Parameters

Period Start	01-01-2008	00:00
Period End	01-01-2008	12:00
Time Step	30 seconds	
No of Time Steps	1440	
Manning	64 $m^{1/3}$ /s	
Constant Eddy	1 m^2/s	
Wind	0 m/s	
Flood depth	0.3 m	
Dry depth	0.2 m	

The regional grid model of tsunami was calibrated with the tsunami of December 26, 2004, which occurred at the West Coast of Sumatra due to a strong earthquake.

3.3.1 Incorporation of Decay Factor in the Model

Decay factors of the propagation of tsunami and storm surge waves on land were incorporated in the model using Manning number (M, $m^{1/3}/s$) which is reciprocal of Manning's coefficient of roughness (i.e. M=1/n).

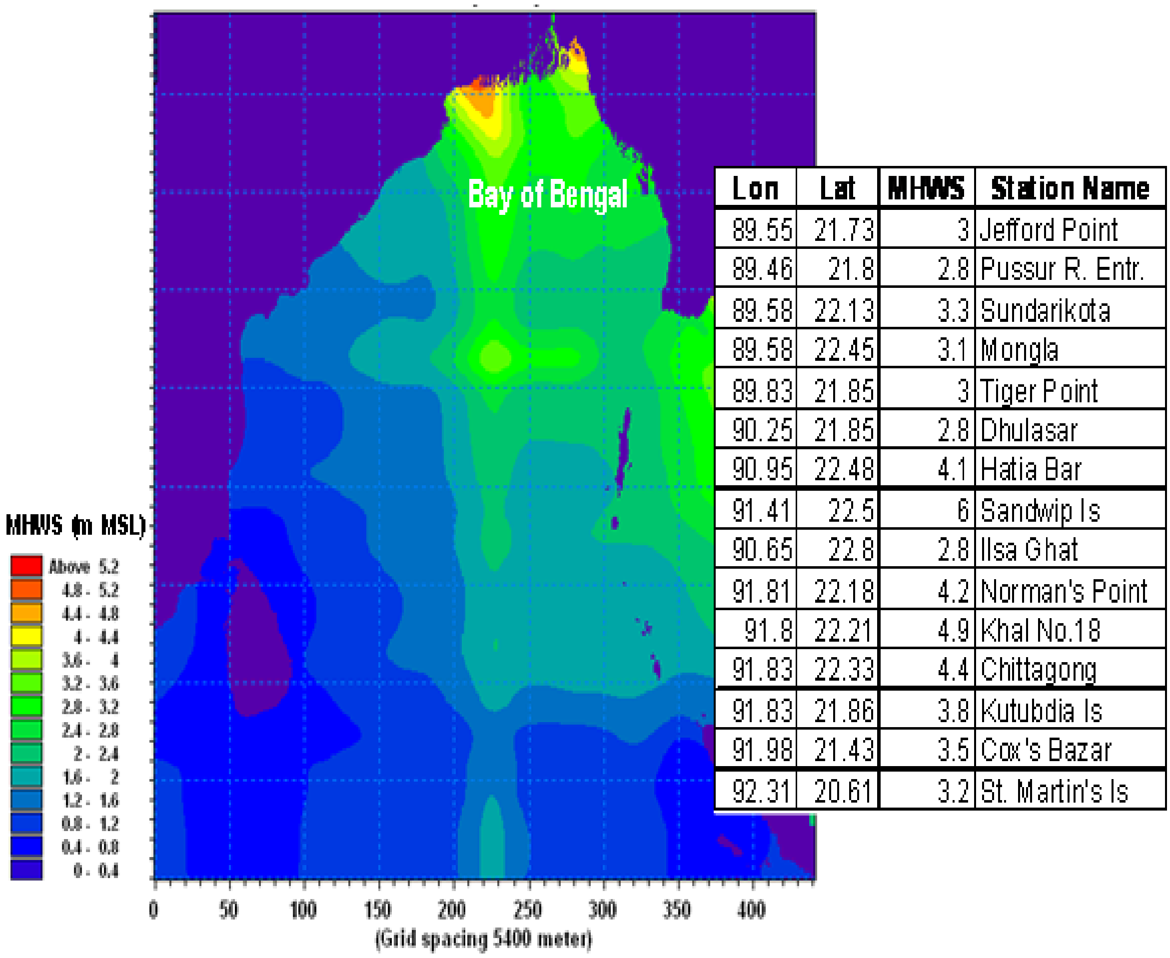
The land use map for coastal area of Bangladesh shows that the coastal area is covered mainly by agriculture, settlement and reserved forest [5]. For simulation of tsunami wave, two categories of the land use were considered; one is for agriculture and settlement and other one is for Sundarban reserved forest. The Manning number of 25 $m^{1/3}/s$ (n=0.04 $s/m^{1/3}$) was considered for the agriculture and settlement area and 15 $m^{1/3}/s$ (n=0.07 $s/m^{1/3}$) for the Sundarban reserve forest [4].

3.4 Inundation Risk Map of Tsunami

Inundation risk map for the coastal region of Bangladesh was prepared based on the six scenarios of tsunami originated from six potential sources of earthquake in the Bay of Bengal. The map was prepared considering the land level based on digital elevation model and the existing polders in the coastal region of Bangladesh.

Initially all the tsunamis generated from the potential sources were simulated using MIKE 21 modelling system. Simulations were carried out for Mean Sea Level (MSL) condition and for Mean High Water Spring (MHWS) level condition. In all the simulations only the MHWS condition shows the influence of tsunami along the coast of Bangladesh. Maximum inundation maps for all of the tsunami events (i.e. 6 scenarios) were generated from the simulation results under MHWS condition. Finally the inundation risk map was generated based on the maximum inundation maps using GIS tool.

In order to determine the MHWS level for the coast of Bangladesh, a map was produced for the Bay of Bengal. The MHWS data at different locations were taken from the Admiralty Tide Tables [8]. Figure 9 shows the MHWS level along the coast of Bangladesh, which is 3 mMSL at western coast and higher in Sandwip channel. In this study 3.46 mPWD has been considered for the simulation of tsunami at the coast of Bangladesh.



Lon	Lat	MHWS	Station Name
89.55	21.73	3	Jefford Point
89.46	21.8	2.8	Pussur R. Entr.
89.58	22.13	3.3	Sundarikota
89.58	22.45	3.1	Mongla
89.83	21.85	3	Tiger Point
90.25	21.85	2.8	Dhulasar
90.95	22.48	4.1	Hatia Bar
91.41	22.5	6	Sandwip Is
90.65	22.8	2.8	Ilsa Ghat
91.81	22.18	4.2	Norman's Point
91.8	22.21	4.9	Khal No.18
91.83	22.33	4.4	Chittagong
91.83	21.86	3.8	Kutubdia Is
91.98	21.43	3.5	Cox's Bazar
92.31	20.61	3.2	St. Martin's Is

Figure 9: MHWS level in Bay of Bengal

Maximum inundation maps for 6 scenarios of tsunami show insignificant influence in the coastal region of Bangladesh under MSL condition but some influence was found under MHWS tide condition.

Inundation risk map for tsunami was generated based on the maximum inundation maps of six tsunamis and presented in Figure 10. It shows that Sundarban area, Nijhum Dwip, south of Hatia (outside polder) and Cox's Bazaar coast are likely to be inundated during tsunami. Maximum inundation is seen at Nijhum Dwip in the range of 3-4 m, and at Sundarban area and Cox's Bazar coast in the range of 1-3 m. Small islands and part of the Manpura island in the Meghna Estuary may get inundated by 1-3 m. Bauphal upazila of Patuakhali district is low lying area which may experience inundation of 1-2 m in MHWS tide.

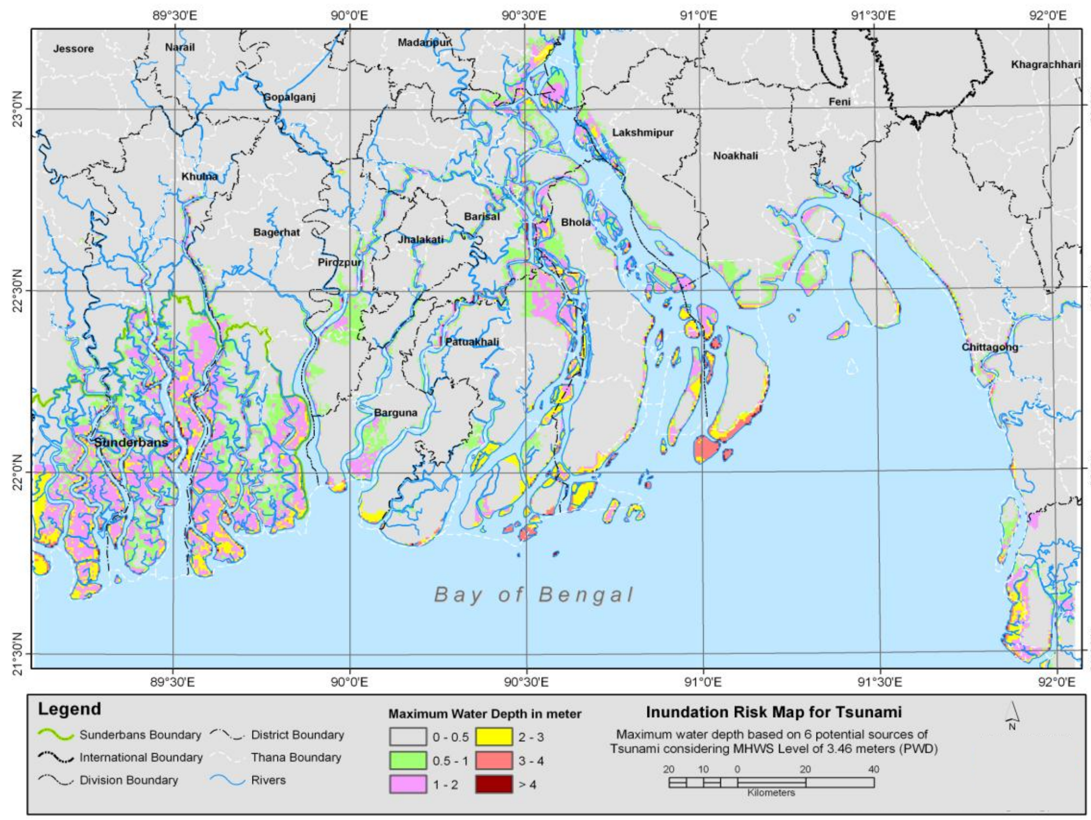


Figure 10: Inundation risk map of tsunami in the coastal region of Bangladesh

IV. Conclusions

A tsunami model was developed covering the Indian Ocean, the Arabian Sea, the Bay of Bengal and the coastal region of Bangladesh to assess the vulnerability of tsunami along the coastal area of Bangladesh. It is evident from the model results that Sundarban area, Nijhum Dwip, south of Hatia (outside polder) and Cox's Bazaar coast are the most vulnerable region during tsunami in respect of inundation depth. Maximum inundations were found at Nijhum Dwip in the range of 3-4 m, and at Sundarban area and Cox's Bazar coast in the range of 1-3 m. Small islands and part of the Manpura island in the Meghna Estuary may also get inundated by 1-3 m. This is high the time to take necessary precautions against tsunami especially along the vulnerable area by using structural and non-structural measures where applicable

In this study the inundation risk map of tsunami was prepared considering 6 potential sources of tsunami, there might be other potential sources which may cause different level of risk at other areas. That needs further investigation to ascertain the level of risk.

Acknowledge

The authors express their gratitude to Institute of Water Modelling (IWM) for the support to use the study findings in the paper.

References

[1]. Comer, R., 1980. Tsunami height and earthquake magnitude: theoretical basis of an empirical relation. Geophys. Res. Lett., Volume 7, pp. 445-448.
[2]. Curray, J. a. M. D., 1971. Growth of the Bengal Deep-Sea Fan and denudation in the Himalayas. Geol. Soc. Am. Bull., Volume 82, pp. 563-572.
[3]. ENR/UNEP, 2006. Damage to Coastal Ecosystems and Associated Terrestrial Environments of Sri Lanka by the Tsunami of 26th December 2004, Draft Final Report: Ministry of Environment and Natural Resources of Srilanka and United Nations Environment Programme.
[4]. MES, 2001. Hydro-morphological dynamics of the Meghna Estuary, Meghna Estuary Study (MES) Project, Meghna Estuary Study: DHV/IWM/DHI.
[5]. NOAMI, 2007. Tsunami vulnerability assessment of the urban growth centres in the south-eastern Bangladesh. s.l.:s.n.
[6]. Okada, Y., 1985. Surface Deformation due to Shear and Tensile Faults in a Half-space. Bulletin of the Seismological Society of America , 75(4), pp. 1135-1154.
[7]. Pedersen, N. R. P. S., 2005. Modelling of the Asian tsunami off the coast of northern Sumatra. KL, Malaysia, DHI User's Conference 2005.
[8]. Tide Tables, 1995. Admiralty Tide Tables and Tidal stream Tables, Volume 2: the Hydrographer of the Navy.