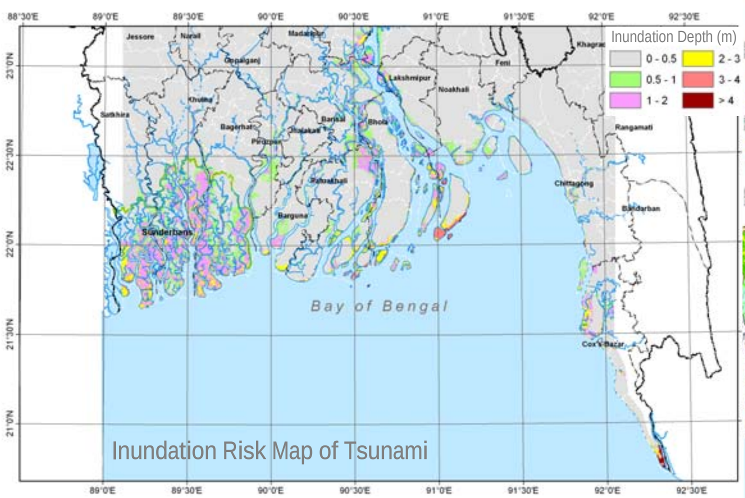
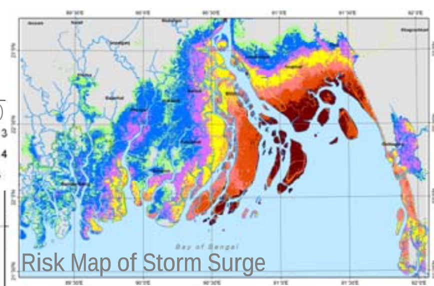
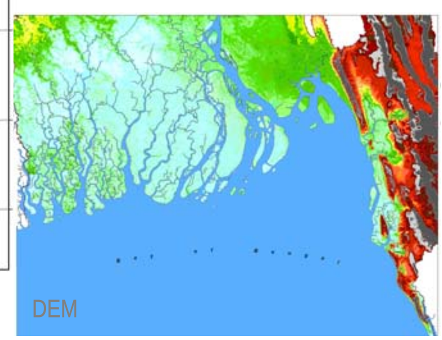
Ministry of Food and Disaster Management
Comprehensive Disaster Management Programme

EC-Funded Component 4a:
Earthquake and Tsunami Preparedness

Use Existing Data on Available Digital Elevation Models to Prepare Useable Tsunami and Storm Surge Inundation Risk Maps for the Entire Coastal Region







FINAL REPORT

Volume-I: Tsunami and Strom Surge Inundation of the Coastal Area of Bangladesh

April 2009

Institute of Water Modelling, Bangladesh

Bangladesh Institute of Social Research

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April 2009

Institute of Water Modelling, Bangladesh
House # 496,Road # 32,New DOHS,Mohakhali,Dhaka,Bangladesh. Phone: 8822105-6, Fax: 880-2-8279011

Bangladesh Institute of Social Research
15/H/1 (3rd. Floor), Zigatala, Dhaka-1209, Bangladesh. Phone: 880-2-8612916

FINAL REPORT

Volume-I: Tsunami and Strom Surge Inundation of the Coastal Area of Bangladesh

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ACRONYMS AND ABBREVIATIONS

BIWTA	Bangladesh Inland Water Transport Authority
BMD	Bangladesh Meteorological Department
BWDB	Bangladesh Water Development Board
CDMP	Comprehensive Disaster Management Programme
CERP	Coastal Embankment Rehabilitation Project
CPP	Cyclone Protection Project
CSPS	Cyclone Shelter Preparatory Study
DEM	Digital Elevation Model
DFID	Department for International Development
DHI	Danish Hydraulic Institute
FAP	Flood Action Plan
GIS	Geographic Information System
HRA	High Risk Area
IPSWAM	Integrated Planning for Sustainable Water Management
IWM	Institute of Water Modelling
KJDRP	Khulna Jessore Drainage Rehabilitation Project
MCSP	Multipurpose Cyclone Shelter Programme
MES	Meghna Estuary Study
MHWS	Mean High Water Spring
MoWR	Ministry of Water Resources
MPO	Master Planning Organization
MSL	Mean Sea Level
PWD	Public Works Department
RFP	Request for Proposal
RZ	Risk Zone
SoB	Survey of Bangladesh
TAG	Technical Advisory Group

EXECUTIVE SUMMARY

E.1 Introduction

This is the final report of the study titled "*Use existing data on available digital elevation models to prepare useable tsunami and storm surge inundation risk maps for the entire coastal region*". This report contains the inundation risk maps of tsunami and storm surge for the coastal region of Bangladesh. The risk maps have been developed based on the simulation results of tsunamis and storm surges and the updated Digital Elevation Model. This report has been finalized after incorporating the comments received from the International Workshop on "*Tsunami Hazard Assessment and Management in Bangladesh*" held on 21-22 January 2009 and the TAG meeting held on 28 March 2009.

The study area covers the coastal region of Bangladesh. The main objective of this study is to prepare tsunami and storm surge inundation risk maps for the entire coastal region of Bangladesh using existing data. The main outputs of the study are:

- Digital Elevation Model (DEM), Landuse and Geo-morphological maps;
- Tsunami model;
- Updated storm surge model;
- Potential sources of tsunami for Bangladesh;
- Decay factors for landuse, geomorphology and slope;
- Inundation risk map for tsunami; and
- Inundation risk map for storm surge;

E.2 Inundation Risk Map of Tsunami

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. Its amplitudes are typically small in the open sea but can reach to damaging amplitudes near the shore or in shallow or confined waters. They are also called oceanic seismic waves.

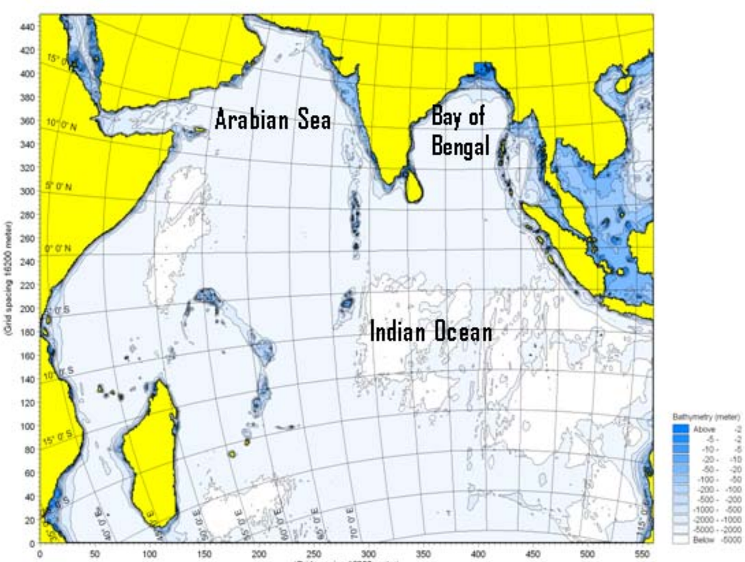


Figure E.1: Regional model domain of tsunami

The present study focussed mainly three processes of tsunami namely generation, propagation and inundation. A tsunami model has been developed for the Indian Ocean, the Arabian Sea, the Bay of Bengal and the coastal region of Bangladesh using MIKE21 modelling system of $DHI_{Water.Environment.Health}$. The coastal region of Bangladesh has been resolved in 600m grid resolution. Figure E.1 shows the regional model of tsunami. The model has been calibrated with the tsunami of December 26, 2004, which occurred at the West Coast of Sumatra due to the earthquake.

In total four potential sources of tsunami due to earthquake in the Bay of Bengal have been identified based on the geophysical and geological data under this study. Initial surface level maps for all the scenarios of tsunami have been generated using QuakeGen, a geological model and MIKE 21 modelling system. Then all tsunamis have been simulated with respective initial surface level maps under Mean High Water Spring (MHWS) tide condition. The maximum inundation map for each scenario of tsunami has been generated based on the simulation results. Finally inundation risk map has been generated using GIS tool. Figure E.2 shows the inundation risk map for tsunami.

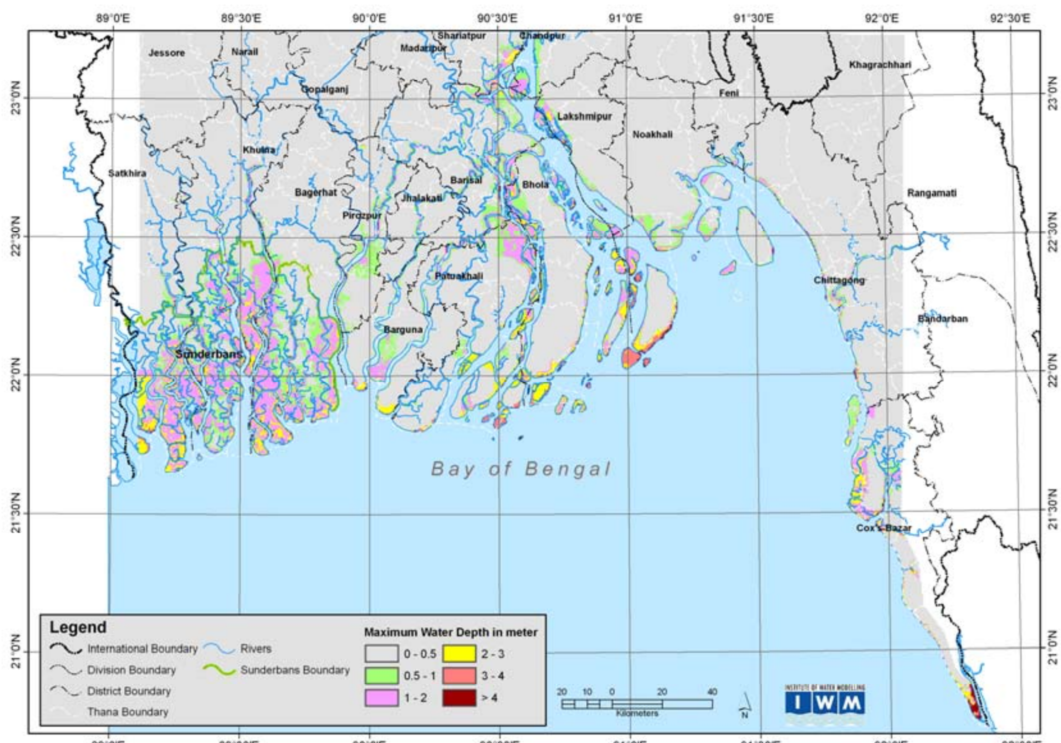


Figure E.2: Inundation risk map of tsunami in the coastal region of Bangladesh

The inundation risk map for tsunami shows that Sundarban area, Nijhum Dwip, south of Hatia (outside polder) and Cox's Bazaar coast get inundated during tsunami. Maximum inundations have been found at Nijhum Dwip in the range of 3-4 m, and at Sundarban area, Moheskhali and Cox's Bazar coast in the range of 1-3 m. Small islands and part of the Manpura island in the Meghna Estuary get inundated by 1-3 m. The maximum inundation in the other locations remains within 1-2 m, which are mainly due to the MHWS tide. Bauphal upazila under Patuakhali district is one of them.

E.3 Inundation Risk Map of Storm Surge

Over the past decades (1960-2007), eighteen (18) cyclones hit the coast of Bangladesh. The most recent one is the Cyclone SIDR of 2007. These cyclones have been considered in preparing the inundation risk maps. The source of cyclone data is the Bangladesh Meteorological Department (BMD). The storm surge modelling study has been done based on the two-dimensional Bay of Bengal Model developed under 2nd CERP using MIKE21 modelling system. In this study the model has been updated with existing data and upgraded in 200 m grid resolution incorporating Sundarban area and it has been extended to the sea up to 16º latitude (Figure E.3).

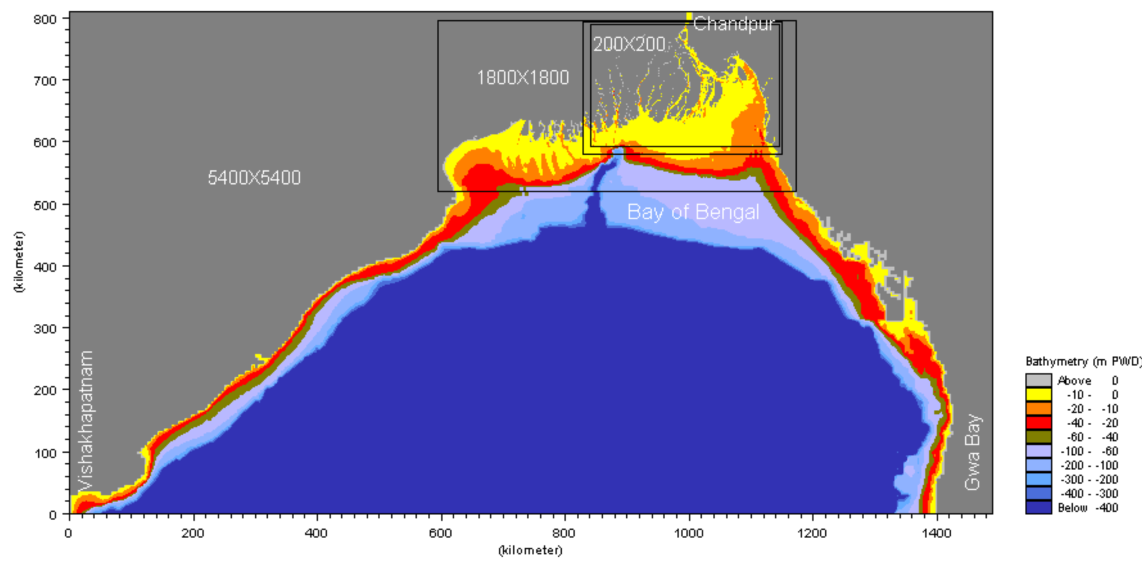


Figure E.3: Nested bathymetry of Bay of Bengal Model

The model has two open boundaries; one is in the Lower Meghna river near Chandpur and another one is in the open sea located along the line extending from Vishakhapatnam of India to Gwa Bay of Myanmar. The model has been recalibrated for the cyclones of 2007, 1998 and 1988 in this study.

Eighteen (18) cyclones occurred during the period 1960-2007 have been simulated using MIKE 21 modelling system. Maximum inundation maps for cyclones have been generated based on the simulation results. Finally inundation risk map for 18 cyclones has been generated using GIS tool (Figure E.4).

The inundation risk map for storm surge shows that the highest inundation depth having range between 5 m and 7.5 m lies in the Noakhali coast, Bhola, Urir Char, Sandwip and small islands in the Meghna Estuary. The eastern coast experiences maximum inundation between 4m and 6 m and western coast experiences inundation within the range of 3-5 m. One meter inundation-depth contour line shows that Sundarban area, Bagerhat, Pirozpur, Barguna, Jhalakati, Barisal, Patuakhali, Bhola, Lakshmipur, Noakhali, Chittagong and Cox's Bazar districts get inundated more than one meter.

A statistical analysis has been carried out with the maximum inundation maps of 18 cyclones in order to find the probability of inundation depth of different magnitude. Probability of inundation exceeding 1 m inundation depth shows that Urirchar, Nijhum Dwip, Noakhali coast, Shitakunda coast and the small islands of the Meghna Estuary are likely to be inundated by more than 1 meter with a probability of 50%. The Cox's Bazar Area is likely to be flooded with a probability of 30 % time. The risk of inundation of Anwara by 1 meter inundation depth is 15%.

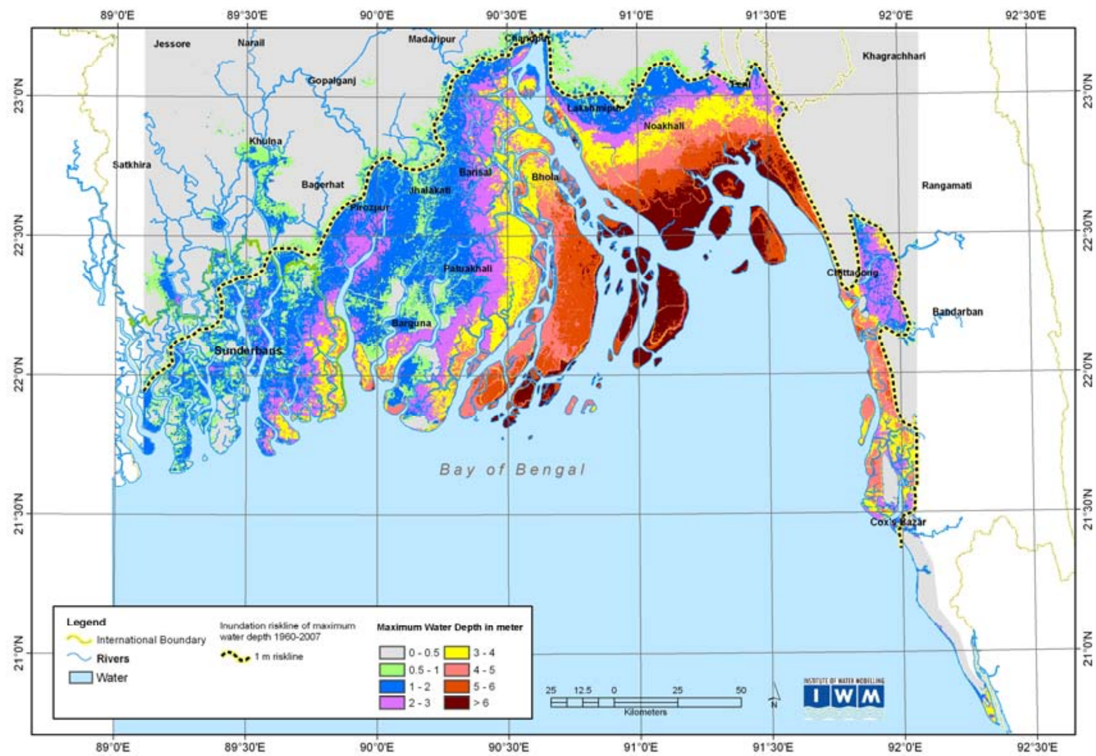


Figure E.4: Inundation risk map generated from 18 cyclones from 1960-2007

Four worst case scenarios of cyclone-induced storm surge have been developed considering wind and pressure field of SIDR 2007, four different tracks covering different coasts of Bangladesh and landfall during high tide. Another risk map has been generated based on 18 real cyclones and four synthesized cyclones. It shows that inundation increases at the Sundarban coast and around Baleshwar River by 1-2 m, at Bhola island by 0.5-1 m, at Sitakunda coast by 2-3m, at Anwara and around the Karnaphuli River mouth by 2-3 m, at Bashkhali by 1-2 m, at Kutubdia island by 0.5-1 m, and at Cox's Bazar by 0.5-1 m.

1. INTRODUCTION

This Final Report contains the inundation risk maps of tsunami and storm surge, the Digital Elevation Model (DEM), the Landuse map and the Geo-morphological map for the coastal region of Bangladesh. The inundation risk maps have been presented in volume-I and the rest in volume-II. The risk maps have been developed based on the simulation results of tsunamis and storm surges. Two separate models have been used for tsunami and storm surge simulations. The tsunami model has been developed under the present study. The storm surge model applied in 2nd CERP (Coastal Embankment Rehabilitation Project) has been used in this study after further updating and upgrading. This report has been finalized after incorporating the comments received from the International Workshop on "Tsunami Hazard Assessment and Management in Bangladesh" held on 21-22 January 2009 and the TAG meeting held on 28 March 2009.

CDMP commissioned Institute of Water Modelling (IWM) to carry out this study titled "*Use existing data on available digital elevation models to prepare useable tsunami and storm surge inundation risk maps for the entire coastal region*" in December 2007.

1.1 Background

Bangladesh is one of the largest deltas in the world and it is formed mainly by the Ganges-Brahmaputra-Meghna river system, except for the hilly regions in the northeast and southeast and terrace land in northwest and central zones. It has about 710 km long coastline. About 28% of the population live in coastal region.

The coastal region of Bangladesh is prone to multihazard threats such as cyclones, storm surges and floods, as well as earthquakes, tsunamis, and above all, climate change. It is frequently visited by the cyclone-induced storm surge. During the last 48 years eighteen (18) major cyclones devastated the coastal area, where 1970 cyclone was the most severe one. It killed about 300,000 people. Most recent one is the cyclone SIDR of November 2007, which caused 3, 363 deaths affecting 8.9 million people and damaged houses, livestock, crops, educational institutions, roads and embankments as reported by Disaster Management Information Centre, Ministry of Food and Disaster Management of Bangladesh.

In recent years, the threat of tsunamis has taken on added urgency after a 9.3-magnitude earthquake off Indonesia's Sumatra island in December 2004 triggered a tsunami that killed more than 230,000 people and left a half million homeless in a dozen countries. Bangladesh suffered relatively minor damage from the tsunami, with 2 people killed. Phil R. Cummins, a seismologist at the national Geoscience Australia agency in Canberra, is the first to suggest a big quake could spawn a tsunami that could have pronounced impact on the Chittagong coast and the Ganges-Brahmaputra delta at the northern tip of the Bay of Bengal.

In August, 2006 the European Commission and UNDP signed a cooperation agreement related to the funding of three new components within the CDMP framework. *Component 4a: Earthquake and Tsunami Preparedness* is one of them. Component 4a recognizes growing urban vulnerability to earthquake caused by increasing population densities and unplanned development and responds to the tsunami risk which 2004 Indonesian tsunami brought to public attention. Request for Proposal (RFP) IV is one of the assignments under component

4a. This assignment is mainly concerned with the development of vulnerability of the coastal infrastructures and livelihood due to tsunami event. The activities under RFP IV have been differentiated into four smaller areas: RFP IV.1, RFP IV.2, RFP IV.3 and RFP IV.4. This study is included in RFP IV.1.

1.2 Study Area

The study area is the coastal region of Bangladesh. The coastal zone covers 19 out of 64 districts facing, or in proximity to, the Bay of Bengal, encompassing 153 *upazilas*/ *thanas* (MoWR, 2005). In 12 of these districts, 48 *thanas* face a combination of cyclone risk, salinity and tidal water movement above critical levels and are designated as "exposed coast" (MoWR, 2005). The country has a coastline of 710 km along the Bay of Bengal. The zone constitutes 32 percent of the area of Bangladesh.

The coastal zone of Bangladesh forms the lowest landmass and is part of the delta of the extended Himalayan drainage ecosystem. Sixty-two percent of the land of the coastal zone has an elevation of up to three meters and 86 percent up to five meters (MoWR, 2005). **Figure 1.1** shows the coastal region of Bangladesh which has been considered for the preparation of inundation maps for tsunami and storm surge.

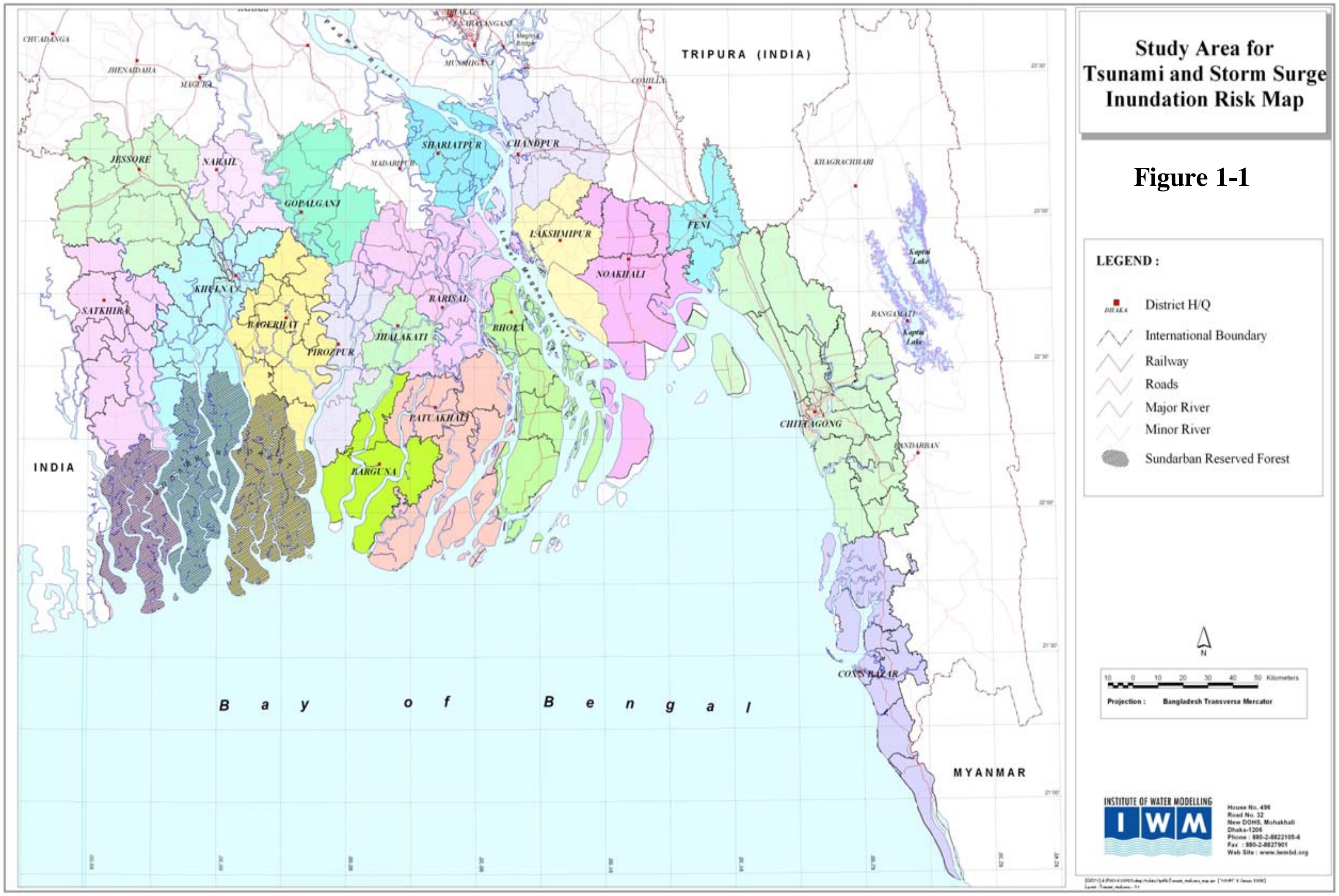


Figure 1.1: Coastal region of Bangladesh

1.3 Objectives

The main objective of this study is to prepare tsunami and storm surge inundation risk maps for the entire coastal region of Bangladesh using existing data.

1.4 Outputs

The outputs presented in this report are:

- Tsunami model;
- Updated storm surge model;
- Potential sources of tsunami for Bangladesh;
- Decay factors for landuse, geomorphology and slope;
- Inundation risk map for tsunami; and
- Inundation risk map for storm surge;

1.5 Approach & Methodology

In this study tsunami and storm surge inundation risk maps for the coastal region of Bangladesh has been developed based on the model results. Two separate models have been used for tsunami and storm surge simulations. The tsunami model has been developed under the present study. The storm surge model applied in 2nd CERP has been used in this study after further updating and upgrading. Decay factors of the propagation of tsunami and storm surge waves on land have been incorporated in the model using Manning number (M, $m^{1/3}/s$). Approaches and methodologies applied to develop the inundation risk maps for tsunami and storm surge have been described in the following.

Inundation Risk Map for Tsunami

The tsunami model has been developed using existing data and MIKE 21 modelling tool. The model comprises four (4) nested levels having grid sizes vary from 16200 m to 600 m. The regional model covers the Indian ocean, the Arabian sea, the Bay of Bengal and the coast of Bangladesh. The fine grid model covers the coastal region of Bangladesh. In total eleven potential sources of tsunami were identified based on the potential sources of earthquake in the Bay of Bengal. After the international workshop on “Tsunami and Strom Surge Hazard Assessment and Management for Bangladesh” held during 21-22 January 2009 organized by CDMP, the potential sources of tsunami in the Bay of Bengal were reduced to four numbers. Initial surface level maps for all the scenarios of tsunami have been generated using QuakeGen, a geological model and MIKE 21 modelling system. Then all tsunamis have been simulated with respective initial surface level maps. The maximum inundation map for each scenario of tsunami has been generated based on the simulation results. Finally inundation risk map for tsunami based on four potential sources of tsunami has been generated using GIS tool. Figure 1.2 shows the flow diagram of inundation risk map generation for tsunami.

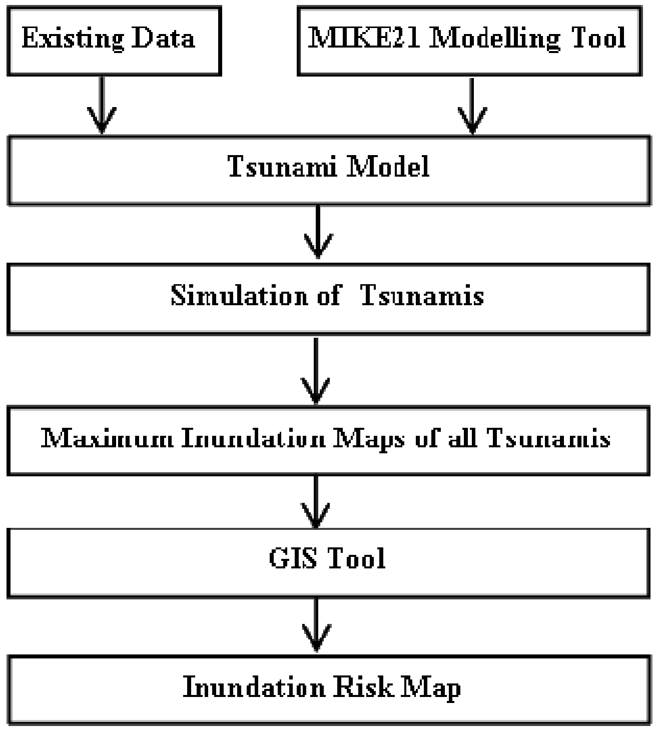


Figure 1.2: Flow diagram of inundation risk map generation for tsunami

Inundation Risk Map for Storm Surge

The storm surge modelling study has been done based on the two-dimensional Bay of Bengal Model of 2nd CERP. In this study the model has been updated with the existing data and upgraded in 200 m grid resolution incorporating Sundarban area and it has been extended to the sea up to 16º latitude. The storm surge model is the combination of Cyclone and Hydrodynamic models. Eighteen (18) cyclones occurred during the period 1960-2007 have been simulated using MIKE 21 modelling system. Maximum inundation maps for cyclones have been generated based on the simulation results. Finally inundation risk map for 18 cyclones has been generated using GIS tool. Another risk map has been generated incorporating four synthesized cyclones under worst condition. The worst case scenarios have been developed considering the wind & pressure field of 2007 cyclone, four different tracks covering all the coasts of Bangladesh and landfall during high tide. Figure 1.3 shows the flow diagram of inundation risk map generation for storm surge.

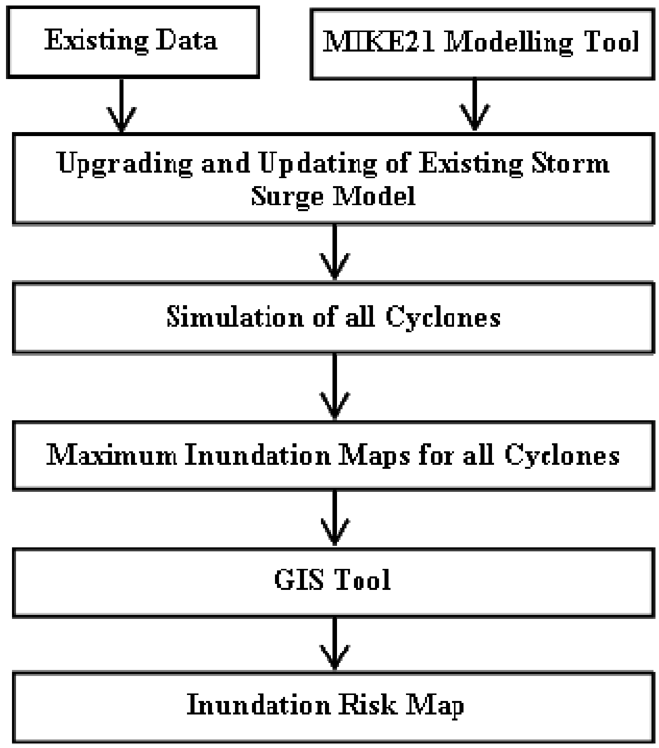


Figure 1.3: Flow diagram of inundation risk map generation for storm surge

1.6 Structure of the Report

The Final Report consists of two volumes; Volume-I: Main Report and Volume-II. The Main Report comprises four (4) chapters and five appendices. The brief contents of each chapter of this report are as follows:

- Chapter-1 describes the study area, objectives and approach of the study;
- Chapter-2 outlines the data used for both tsunami and storm surge models;
- Chapter-3 describes the decay factor for tsunami and storm surge waves and also the incorporation of decay factors in the model;
- Chapter 4 describes the tsunami generation, potential sources of tsunami, model and inundation risk map for tsunami in the coastal region of Bangladesh;
- Chapter 5 describes elaborately the storm surge model and inundation risk map for storm surge in the coastal region of Bangladesh; and
- Chapter 6 provides the conclusions and the recommendations of the study.

Literature review under this study has been presented in Appendix-A, Scientific background of MIKE 21 modelling system has been given in Appendix-B, Model set-up and calibration of the tsunami and the storm surge models have been discussed in Appendix-C and cyclone data has been provided in Appendix-D. All the comments and responses on the study have been presented in Appendix-E.

The Volume-II includes the reports on Digital Elevation Model, Landuse Map and Geo-morphological Map. Soft copies of all the data have been presented in a CD attached to it.

2. DATA

2.1 Bathymetry and Digital Elevation Model

Bathymetric data have been collected from different sources and used for the generation of bathymetry of tsunami and storm surge models. Main source of bathymetric data of the Bay of Bengal, Indian Ocean and Arabian sea is the ETOPO2 of National Geophysical Data Centre and C-Map of Hydrographic Office of UK. Bathymetric data for the Meghna Estuary have been collected from Meghna Estuary Study I & II (1998-99), Land Reclamation Study (2007) and Nijhum Dwip X-dam Study (2006) and for the internal rivers from Mongla Port Study (2004), IPSWAM (2008) and KAFCO Study (2007). Digital Elevation Model (DEM), Geo-morphological map and Landuse map developed under the present study and the polder levels and alignment surveyed under 2nd CERP have been used for model development.

Main source of data of the DEM is the FINNMAP land survey. The relative accuracy of the data within Sundarban Reserved Forest (SRF) is (x, y) 10's of centimetres and (z) 1m and the absolute accuracy is +/- 2 m (including the difference between Datum and reality) according to the Technical Report–TR No. 09, Sundarban Biodiversity Conservation Project, 2001.

Information of the bathymetry and topographic data have been presented in Table 2.1.

Table 2.1: Land-water data used for generating the bathymetry

Model components	Type of Data				
	Water	**Source**	**Land**	**Source**	**Land-water boundary**
Coarse	C-Map	Hydrographic Office (UK)	-	-	C-Map
Intermediate			-	-	C-Map
Fine & 200 m Grid	Part of the Meghna Estuary	Land Reclamation Study, BWDB, 2007	FINMAP (1991)	CDMP	LANDSAT
	Pussur and Sibsha rivers	Mongla Port Study, 2004	BWDB	CSPS	
	Around Nijhum Dwip	Nijhum Dwip X-Dam Study, BWDB, 2006	Digital Elevation Model	CDMP	
	Internal Rivers of South west region	IPSWAM, 2008			
	The Karnaphuli River	KAFCO, 2007			
	Admiralty maps	MES I			
	FAP 5B Survey (1997)	MES I			
	MES II survey (1998, 99)	MES II			
	BIWTA maps	MES II			

In addition polder levels and alignment surveyed under 2nd CERP have been used.

2.2 Tsunami

Four (4) potential fault sources of earthquake which may trigger tsunami in the Bay of Bengal have been identified in this study. Genesis of tsunami and analysis of the tsunamigenic fault sources with earthquake parameters are discussed in Section 4.4.

2.3 Cyclones

During the period of 1960-2007, eighteen (18) cyclones hit the coast of Bangladesh. The most recent one is the Cyclone SIDR of 2007. These cyclones have been considered in this study. Tracks of major cyclone crossed Bangladeshi coast during the period 1960-2007 and the information on landfall date and maximum wind speed have been presented in Figure 2.1. The source of cyclone data is the Bangladesh Meteorological Department (BMD). The data of the recent cyclone was collected under present study and rest of the cyclones' data were collected under 2nd CERP. The cyclones' information includes cyclone period, position of cyclone, cyclone intensity, pressure drop (ΔP), maximum wind speed (W_m) and radius to maximum wind (R_m). All these data have been presented in Appendix-D.

Surge heights at different locations of the coastal region during past major cyclones have been collected under the present study from the field offices of Bangladesh Water Development Board (BWDB) and Mongla Port Authority (MPA) and also by interviewing local people in the coastal region of Bangladesh. The field investigators mainly interviewed elderly people in the market places and permanent residents in the villages who experienced storm surge during the cyclone in the past. In order to check the reliability of reported data at each site investors cross-checked with 4-5 elderly persons.

Table 2.2 shows the storm surge height information of three major cyclones with respect to ground level at different locations of the coastal region. These data have been used for verification of the simulated storm surge levels in the coastal region.

Table 2.2: Information of storm surge height at different locations observed during the past major cyclones.

District	Upazilla	Storm Surge Height w.r.t. ground (m)		
		2007 Cyclone	1991 Cyclone	1970 Cyclone
1. Bhola	Charfasson	1.0-1.5	0.6 to 0.9	2.1 to 2.4
2. Pirojpur	Mathbaria	1.2 to 2.1		
	Kawkhali	0.9 to 1.5		
	Bhandaria	1.5 to 2.4		
	Nesarabad	0.5 to 1.1		
	Nazirpur	0.6 to 0.9		
	Pirojpur Sadar	0.5 to 0.9		
3. Bagerhat	Sarankhola	0.9 to 1.8		
	Morrelganj	0.9 to 2.4		
4. Satkhira	Shyamnagar	0.9	0.6	
5. Jhalokhathi	Jhalokhathi Sadar	0.9		
	Kathalia	0.5 to 0.9		
	Nalchity	0.5 to 0.9		
	Rajapur	0.5 to 1.2		
6.Laxmipur	Laxmipur Sadar		0.3 to 0.9	
	Ramgoti		0.6 to 1.5	
	Raypur		0.3 to 0.6	
7.Chittagong	Banshkhali		5.0 to 6.0	
	Anwara		1.5 to 3.0	
	Putiya		3.0 to 3.7	
	Bandar thana		3.0 to 3.7	
	Potenga		3.0 to 3.7	
	Sitakunda		2.4 to 4.6	
	Sandwip		7.6 to 9.1	
	Mirsarai		3.7 to 4.6	
	Channaish		1.2 to 2.1	
8. Barisal	Barisal Sadar	1.8 to 2.1		
	Babuganj	1.5 to 1.8		
	Mehediganj	1.2 to 1.8		
	Hizla	1.5 to 1.8		
	Gournadi	1.8 to 2.1		
	Agailjara	1.2 to 1.5		
	Uzirpur	1.2 to 2.1		
	Bakerganj	1.5 to 1.8		
	Banaripara	0.9 to 1.8		
9. Borguna	Borguna Sadar	4.6 to 6.1		
	Betagi	2.1 to 3.0		
	Bamna	2 to 3.0		
	Pathorghata	5.5 to 6.1		
	Amtoli	4.6 to 6.1		
10. Patuakhali	Patuakhali Sadar	2.1 to 2.7		
	Kolapara	4.0 to 6.1		
	Doshmina	2.1 to 3.0		
	Baufall	1.8 to 2.4		
	Golachipa	1.5 to 2.4		
	Mirzaganj	2.4 to 3.0		

Landfall of Cyclone		Max. Wind Speed (kph)
Date	Location	
31.10.1960	Sandwip-Shitakunda	208
09.05.1961	Kalapara	142
29.05.1963	Shitakunda	175
12.05.1965	Patharghata	161
15.12.1965	Cox's Bazar	175
01.10.1966	Sandwip-Mirsharai	145
12.11.1970	Sarankhola-Bhola Noakhali	222
28.11.1974	Char Rangabali	161
9.11.1983	Chakaria	122
25.05.1985	Bashkhali	145
09.11.1986	Sundarban	116
29.11.1988	Sundarban	150
30.04.1991	Patenga	224
25.11.1995	Cox's Bazar	110
15.05.1997	Patenga	200
24.09.1997	Shitakunda	150
20.05.1998	Patenga	165
15.11.2007	Patharghata	240

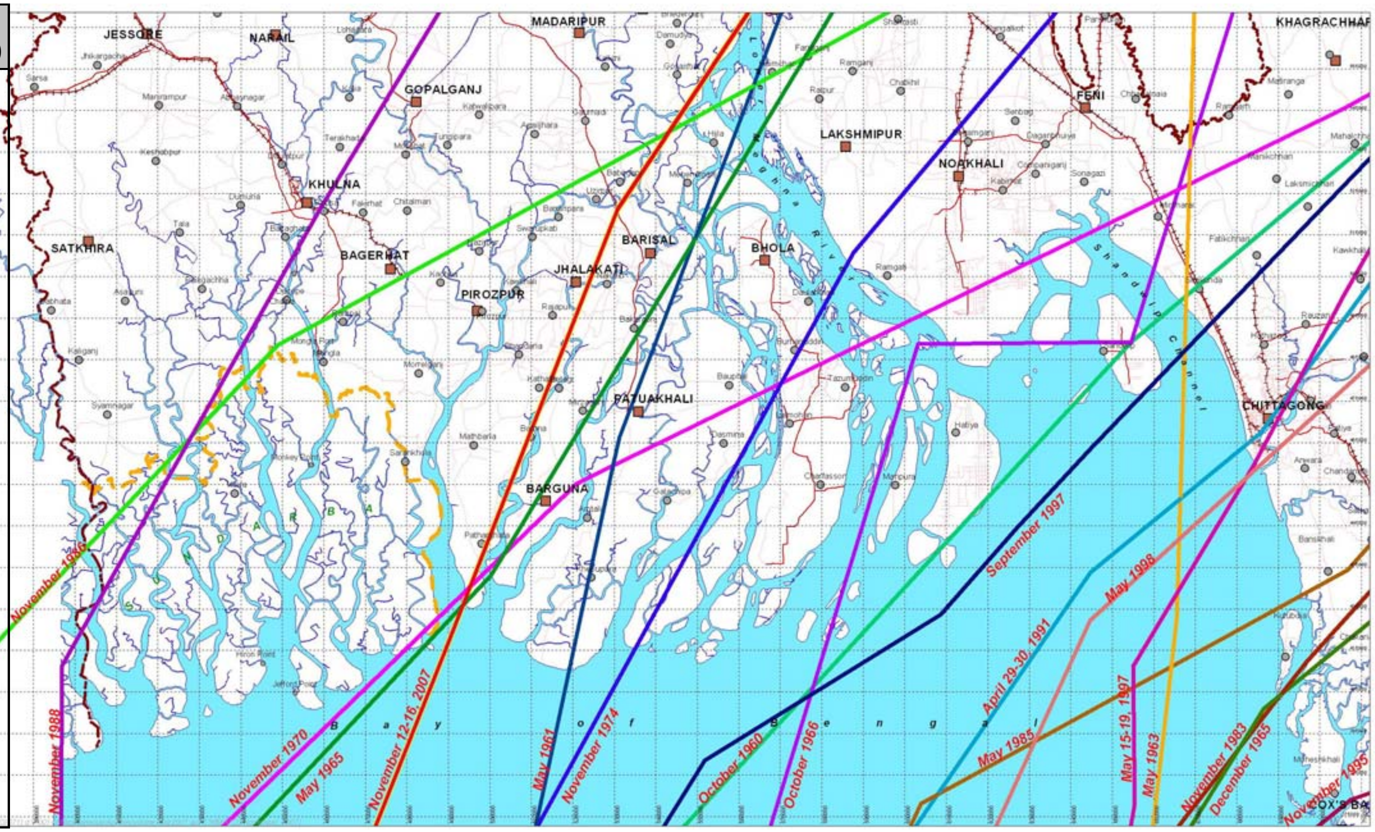


Figure 2.1: Tracks of major cyclones crossed Bangladeshi coast during the period 1960-2007 with information on landfall date and maximum wind speed

3. DETERMINATION OF DECAY FACTOR OF TSUNAMI WAVE

3.1 Tsunami Propagation Characteristics across the Continental Shelf

Wave transformation takes place as a tsunami propagates across the continental shelf. Wave height increases because of shoaling and wave speed decreases as the waves approach the shoreline. This effect is more pronounced if the continental shelf is relatively shallow as the one off the coast of Bangladesh. Figure 3.1 schematically shows the main characteristics of wave transformation across the continental shelf. Wave height increases and the waves start to break as the waves cross the edge of the continental shelf. Partially broken waves propagate across the continental shelf and cross the land boundary or the shoreline at MHWS. The remaining wave energy is dissipated as water flows overland up to the runup limit. As a first approximation, tsunami propagation and landward incursion may be described by the linear wave theory. However, the solitary wave theory gives more accurate description of these shallow water gravity waves (see Heitner, 1969).

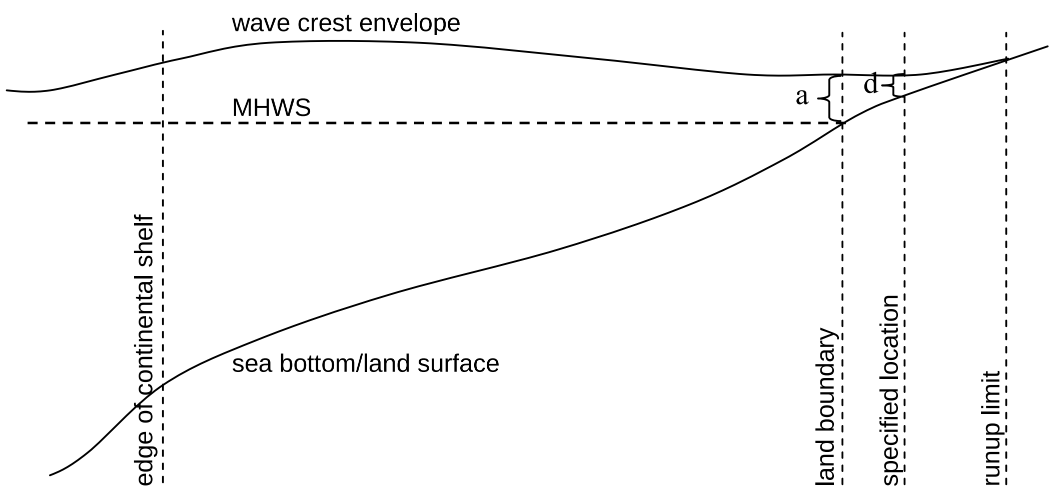


Figure 3.1: Schematic diagram showing wave transformation across the continental shelf and nearshore region.

Figure 3.2 shows a typical transformation of tsunami waves across the continental shelf off the coast of Bangladesh. Water level variations with time computed by the model at four locations, t1 through t4, as shown in Figure 3.3, indicate that because of shoaling the peak water level increases from t1 to t3. The peak attenuates a little after t3. Figure 3.2 also shows that there are at least two secondary peaks after the main event. The drawdown just before the peak is distinct at t1 and t2. The irregular water levels during drawdown at t3 and t4 indicate that the waves start to break somewhere after t2, after they hit the continental shelf, and carries the broken waves to t3 and t4. Other model outputs also show a sharp decline in the wave crest envelope and irregular waves created at the edge of the continental shelf indicating wave breaking at the edge of the shelf. The peak time at each location shows that the travel time for the peak from t1 to t2 is less than that from t2 to t3, and so on. Since the space intervals from t1 through t4 are approximately equal, the wave speed decreases as the waves approach the shoreline. Model results show that the wave speed decreases from approximately 31 m/s at the edge of the continental shelf to 9-19 m/s along the shoreline in the Scenario 9 of tsunami.

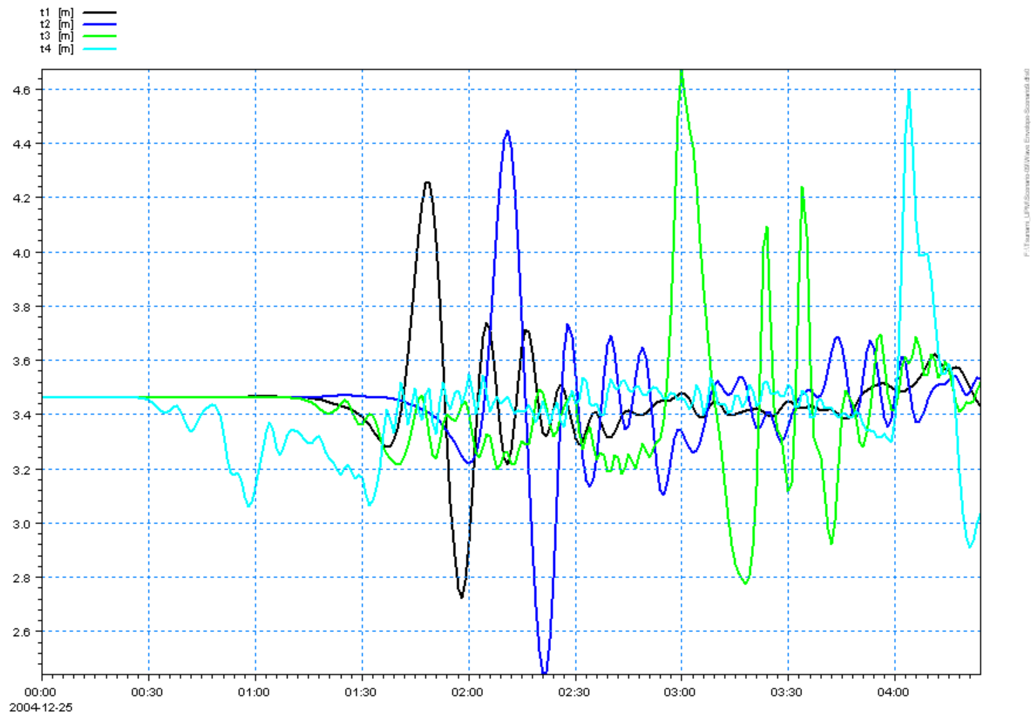


Figure 3.2: Wave transformation across the continental shelf in Scenario 9.

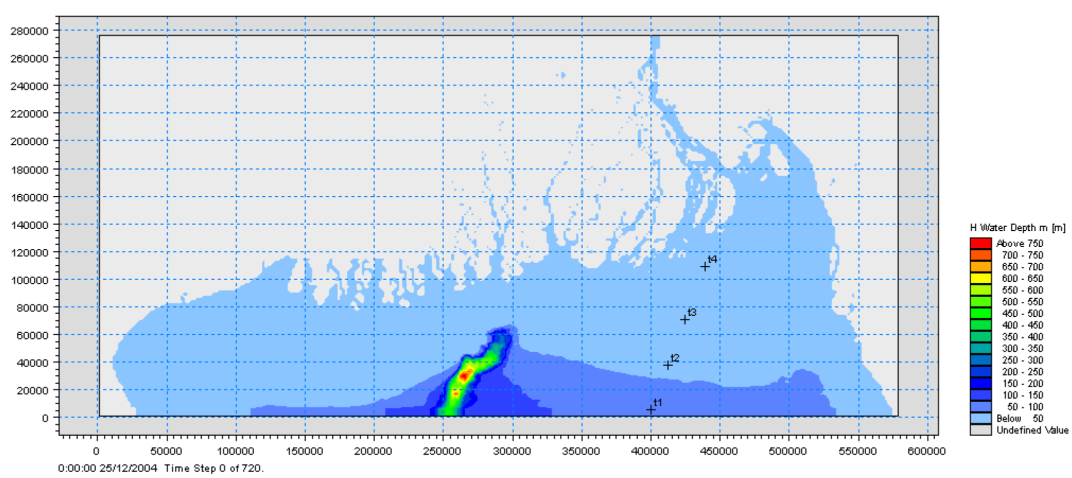


Figure 3.3: Water level computation locations across the continental shelf in Scenario 9.

3.2 Wave Decay at the Coast

Inundation occurs as the tsunami waves propagate landward after crossing the land boundary. The waves dissipate energy and gradually decay up to the runup limit. Figure 3.4 shows a typical decay in water level during landward propagation of tsunami. The approach velocity at the coast along with magnitude of currents during wave runup determines the scale of destruction. Coastal devastation correlates stronger with inundation flow velocities. However, since the inundation flow is non-linear, wave height and flow velocity do not necessarily correlate. During overland flow the maximum flow velocity occurs when the depth is the minimum. Therefore the runup height is not an accurate indicator of the severity of the wave impact (Gonzalez et al., 2007).

The inundation process is complicated by the complex flow fields created near the tip of the rising or receding waves, and the interaction between the rising and receding waves. In relatively flat terrains, the geomorphological characteristics and flow resistance elements dominate the inundation process while the approach velocity and water height above the mean water level at the coast determines the incursion distance and depth. Flat coastal areas may not drain all the water intruded from the previous tsunami wave before the next wave brings in additional water. Because of these complexities, the duration of inundation may be much longer than the tsunami period at the coast, and the local inundation depth at a specified location may be higher than the water height above the mean water level at the coast.

Tsunami waves may propagate a considerable distance inland through the rivers and estuaries. Often a bore forms after breaking of the tsunami wave due to non-linearity in tsunami front in shallow water near the coast. This steep, turbulent, rapidly moving wave front may inundate the areas inland where overland flow may not reach directly. On the other hand, tsunami waves decay faster on relatively steep slopes and inundate relatively short distances.

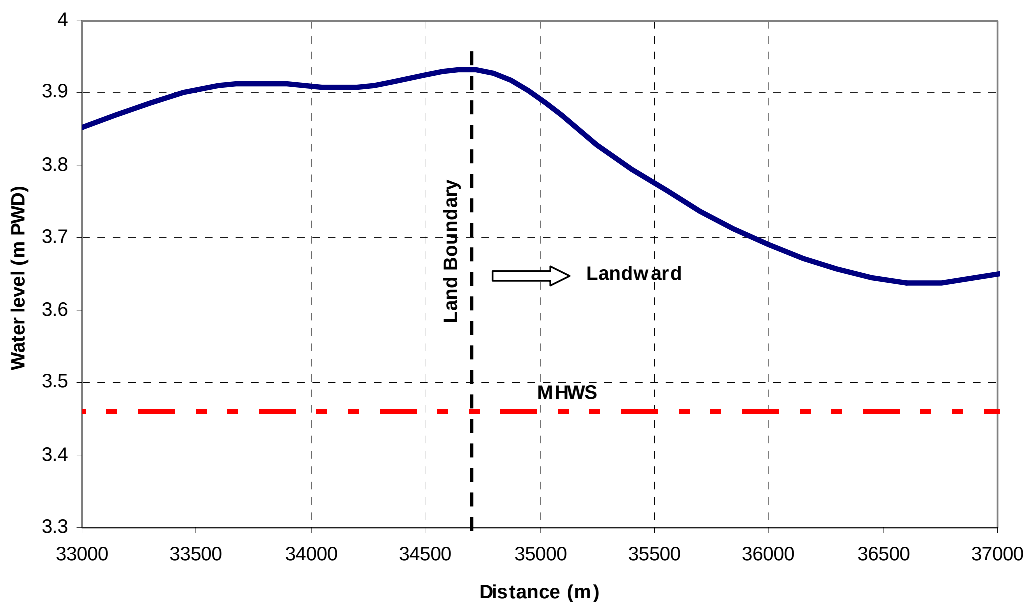


Figure 3.4: Decay of water level during landward propagation of tsunami.

3.3 Decay Factor for Bangladesh Coast

Tsunami wave decay primarily depends on the forces resisting the tsunami driving forces. Therefore the decay will depend on several factors including approach velocity, surface friction, land slope and geomorphological characteristics. Hence a dimensionless expression is proposed for decay factor,

$$\delta = \frac{G\,S\,D^2}{v^3 n^3} \qquad (3\text{-}1)$$

Where,

G = a proposed regional geomorphological coefficient (dimensionless),
n = Manning's roughness coefficient that includes skin friction and form drag ($s/m^{1/3}$),
v = maximum wave approach velocity at the land boundary (m/s),
S = average landward slope from the land boundary (m/km), and
D = average distance of a specified location from the coast or major river (km).

n and S are available from secondary information and topographic data, and v is computed by the model. G varies with land use, terrain feature, and river network and estuarine characteristics. A higher value of G indicates less favorable conditions for landward travel of wave. After reviewing the physical characteristics of the Bangladesh coast in the context of wave propagation and inundation, four different zones are proposed for which different values of G should be assigned. These four zones are characteristically different in terms of geomorphology, land use, river network and terrain features. These zones are: (1) The Sundarbans coastal areas, (2) Ganges tidal plain, (3) Meghna estuary, and (4) Chittagong coastal plain.

The decay can be also found from the difference in water levels computed by the model at the coast and at a specified location. Thus decay factor,

$$\delta = \frac{d-a}{a} = \frac{d}{a} - 1 \qquad (3\text{-}2)$$

where
d = local water depth at a specified location (m), and
a = maximum water height above MHWS at the land boundary (m).

Nine profiles are selected across the coastal region to determine the decay factor and to estimate G in the four proposed zones (see Figure 3.5). Table 3.1 gives v, S and n based on model output and secondary data for locations on the profile. Model output also gives ‘a’ for each profile and ‘d’ for each location. The decay factor (δ) for each location is calculated by Eqns. (3-1) and (3-2) and plotted (see Figure 3.6). G for each zone is changed until the data points are reasonably aligned along a 45^o line, indicating a good agreement of δ calculated by Eqns. (3-1) and (3-2). The decay factor can now be calculated for a given location with the values of G given in Table 3.1 using Eqn. (3-1), and the inundation depth at the specified location can be estimated using Eqn. (3-2).

Table 3.1: Characteristic tsunami decay parameters in four coastal zones.

Zone	Approach velocity, v (m/sec)	Average land surface slope, S (m/km)	Manning's n (s/m$^{1/3}$)	Geomorphological coefficient, G
1	9	0.05	0.07	4.20
2	10	0.40	0.04	1.30
3	11	0.10	0.03	0.46
4	19	1.00	0.04	0.80

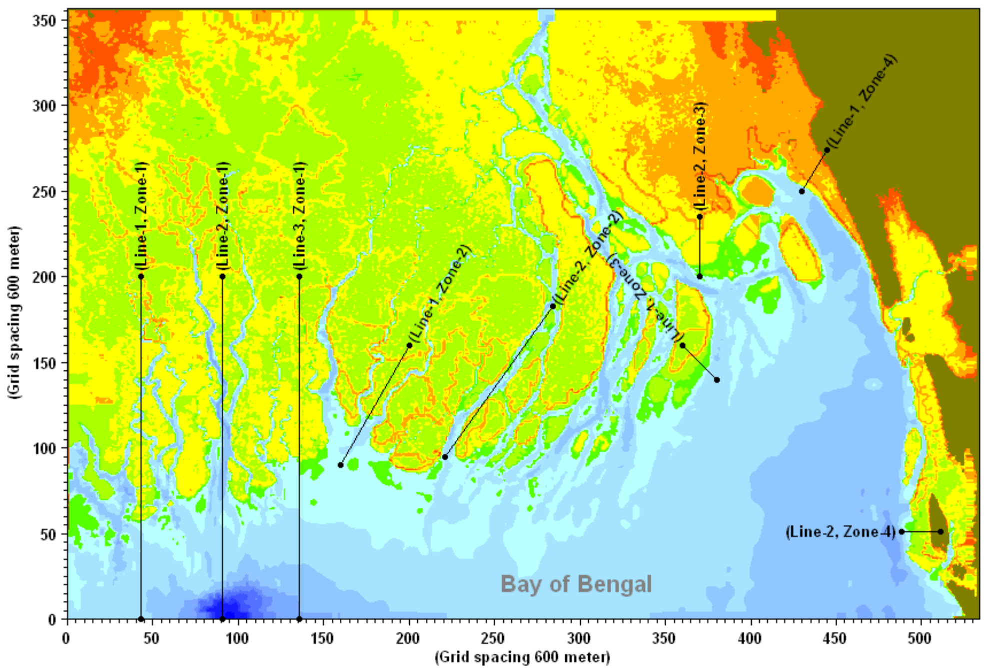


Figure 3.5: Profiles considered for decay factor computation for tsunami.

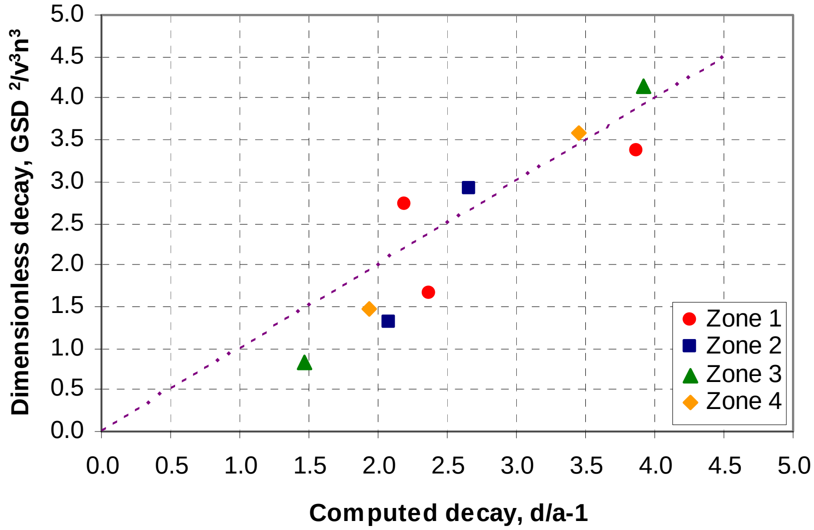


Figure 3.6: Relationship between decay computed from model out put and analytical dimensionless expression.

3.4 Incorporation of Decay Factor in the Model

Decay factors of the propagation of tsunami and storm surge waves on land have been 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). Various Manning's coefficients of roughness (n) have been estimated through experiments over the years. Table 3.1 shows a list of Manning's coefficients and its corresponding Manning Number typically used for calculating water flow through different type of land use.

Table 3.1: Manning's coefficient for roughness and its corresponding Manning number for different landuse

Categories	Roughness Coefficient	
	Manning's Coefficient, n ($s/m^{1/3}$)	Manning Number, M = 1/n ($m^{1/3}/s$)
Aida (1977)		
Dense vegetation	0.07	**14**
Relatively dense vegetation	0.05	20
Nearshore, including trees	0.04	**25**
Others	0.02	50
Kotani et al. (1998)		
High density residential area	0.08	13
Middle density residential area	0.06	17
Low density residential area	0.04	**25**
Forest	0.03	33
Rice field	0.02	50
Water area, rivers and trees	0.025	40
Ven Te Chow (Open Channel Hydraulics, 1973)		
Flood plains		
a. Pasture, no brush	0.03-0.035	33-29
b. Cultivated areas	0.03-0.04	33-**25**
c. Brush	0.05-1.00	20-1
d. Trees	0.15-0.12	7-8
Second Coastal Embankment Rehabilitation Project (2002)		
Mangrove Forest	0.07	**15**
Rice field and cultivated areas	0.04	**25**

The table 3.1 shows that the Manning's coefficient for dense vegetation is 0.07 $s/m^{1/3}$ (corresponding M= 14 $m^{1/3}/s$) and for nearshore (including trees) is 0.04 $s/m^{1/3}$ (i.e. M= 25 $m^{1/3}/s$) according to the Aida (1977). According to Kotani et al. (1998) the Manning's coefficient for low density residential area is 0.04 $s/m^{1/3}$ (i.e. M= 25 $m^{1/3}/s$). According to the text book named *Open Channel Hydraulics* of Ven Te Chow, the Manning's coefficient of cultivable areas of flood plains is 0.04 $s/m^{1/3}$ (i.e. M= 25 $m^{1/3}/s$).

In Second Coastal Embankment Rehabilitation Project (2nd CERP), the Manning number (i.e. M) of the rice fields was estimated 25 $m^{1/3}/s$ on the basis of both basic hydraulics and information found in Ozara and Ibe (1999). In both the cases the possible range is rather wide. Following this estimation a value on the low side was chosen to take into account the resistance by buildings, trees and roads etc. Mangrove forests are known to give a very high-energy loss (Brinkman et al. 1997). The Manning number for the mangrove forests were estimated on the basis of basic hydraulics combined with crude estimates of involved length scales.

The land use map for coastal area of Bangladesh has been developed under this study. It shows that the coastal area is covered mainly by agriculture, settlement and reserved forest. For simulation of tsunami and storm surge waves, two categories for the land use have been considered; one is for agriculture and settlement and other one is for Sundarban reserved forest. The Manning number of 25 $m^{1/3}/s$ ($n=0.04$ $s/m^{1/3}$) has been 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. TSUNAMI

4.1 Introduction

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. 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 4.1 shows the subduction of one plate under another continental plate during earthquake.

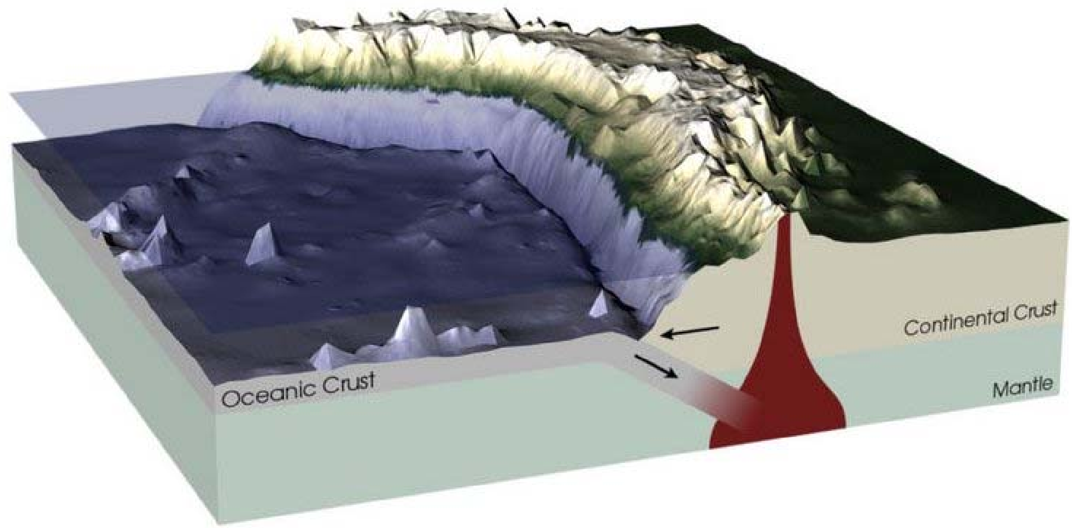


Figure 4.1: Subduction of one plate under another continental plate

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 4.2). But the normal dip-slip and the reverse dip-slip causing seafloor subsidence and uplift respectively will be able to create a Tsunami.

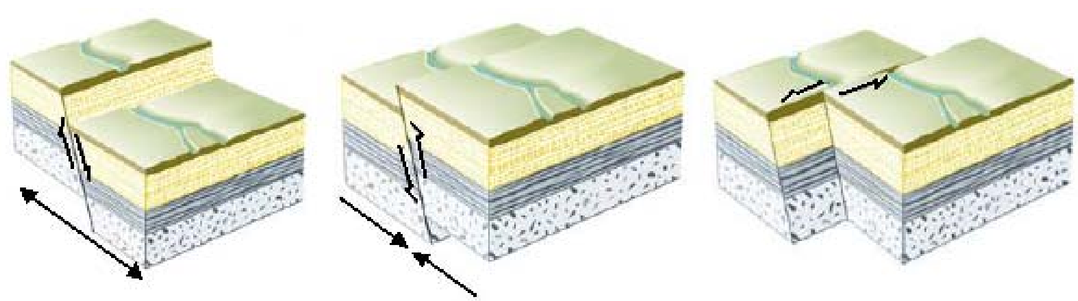


Figure 4.2: Normal Dip-Slip (left one), Reverse Dip-Slip (middle one) and Strike-Slip

The sudden upward vertical offset of the major fault rupture under the sea floor moves the water as if it were being pushed by a great paddle producing long water waves at the ocean surface (Figure 4.3) and move across the ocean until it reach the coastline. The water height increases greatly and crash down upon the shore with disastrous effects (Figure 4.4).

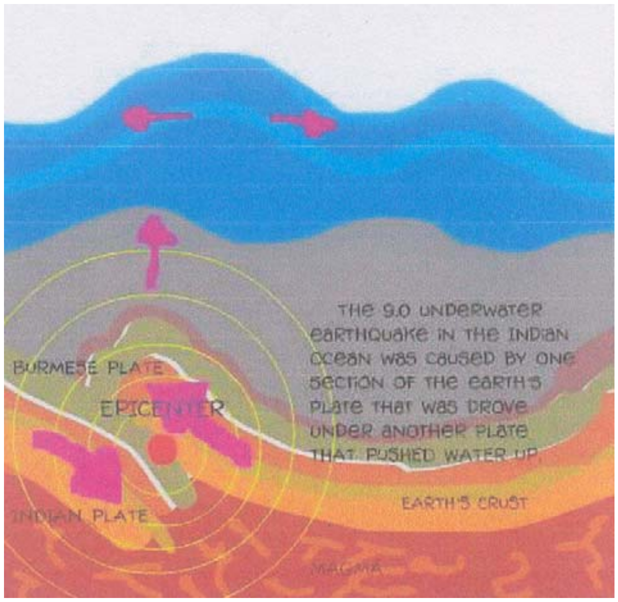


Figure 4.3: Thrust fault rupture of the ocean bed producing tsunami wave.

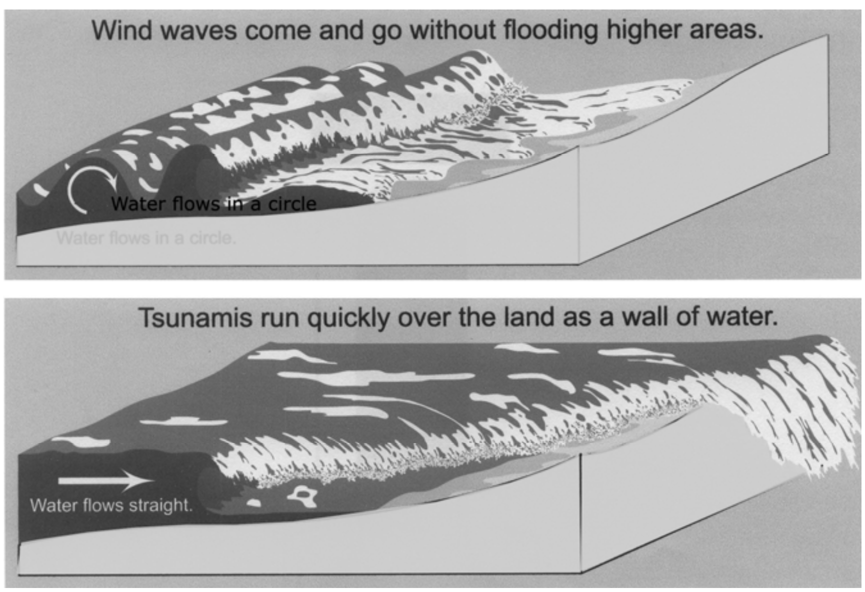


Figure 4.4: Propagation of tsunami wave and wind wave.

A typical wave length of a Tsunami is 100 – 300 Km with amplitude of 0.5 to 1m in deep water. When the wave approaches shallow water the speed reduces due to the bed friction and the wave height increases due to Shoaling (Figure 4.5). The wave grows even larger when it enters a bay due to funneling effect.

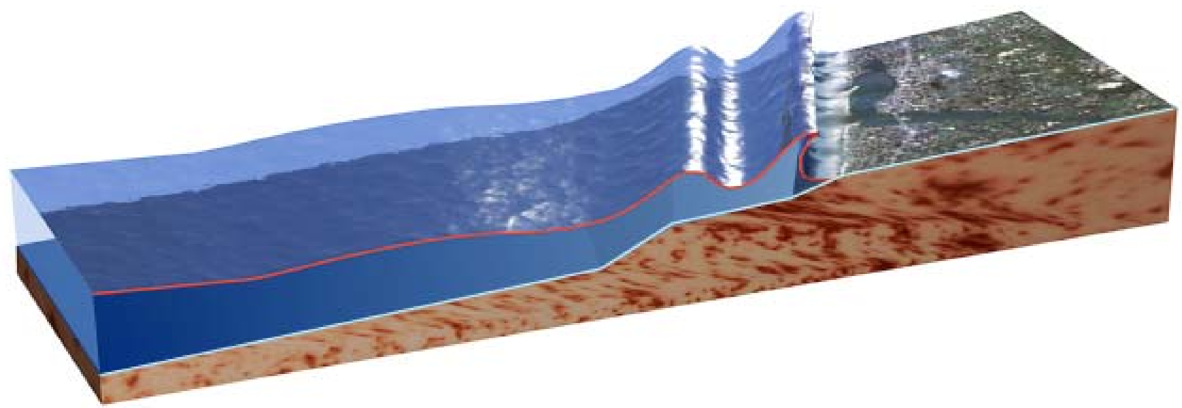


Figure 4.5: Tsunami approaching shallow water causing high waves due to Shoaling

4.2 Genesis of Tsunami

Prior to characterizing an area from tsunami vulnerability, it is important to know the genesis of a tsunami. Most great water waves are caused by rupture and displacement along the submarine faults without which no tsunami would occur. Most large magnitudes (> 7.5 M_w) and shallow focus (≈ 15 km) earthquakes under the sea are tsunamigenic and are located mostly along the active subduction zones of the lithospheric plate collision margins. The nature, extent, and magnitude of fault ruptures play an important role in the genesis of tsunami. Tectonically, an active subduction zone is characterized by under thrusting of oceanic crust and up-thrusting of continental crust. This mechanism produces series of thrust sheets riding over the oceanic segments resulting in the development of thrust fault ruptures. Any thrust sheet when encounters water column in front and above can cause water column to be stressed and moved. However, this would happen only when the subduction direction is perpendicular to the line of convergence. When subduction direction is oblique to the line of convergence a combination of vertical and horizontal movements occur along the rupture planes resulting in the development of combination of thrust and strike-slip fault rupture. In such condition, the outward stress vector is a resultant one thus reducing the impact on the water column in front and above of the rupture plane. Devastating episode of a tsunami depends on the volume of on-rush stressed water and the velocity of the on-rush water front. Hence, 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. The orographic pattern of the Bay of Bengal suggests the nature and magnitude of the tsunami wave propagation.

The entire Bay of Bengal has been studied from the above geological and geophysical aspects to determine potential fault rupture source zones.

4.3 Analysis & Interpretation

The orographic map of the Bay of Bengal (Figure 4.6) clearly demonstrates that the continental shelf-break occur all along the coasts of the bay close to shore-line starting from Sumatra to Srilanka except Bangladesh where the shelf-break occurs about 200 km ocean-ward from the coast. In addition, the extended shallow bathymetric profile of the continental shelf plays a key role in flattening the waveform through a defocusing process (Ioualalen et al., 2007) that has greatly reduced the impact of any trans-oceanic tsunami.

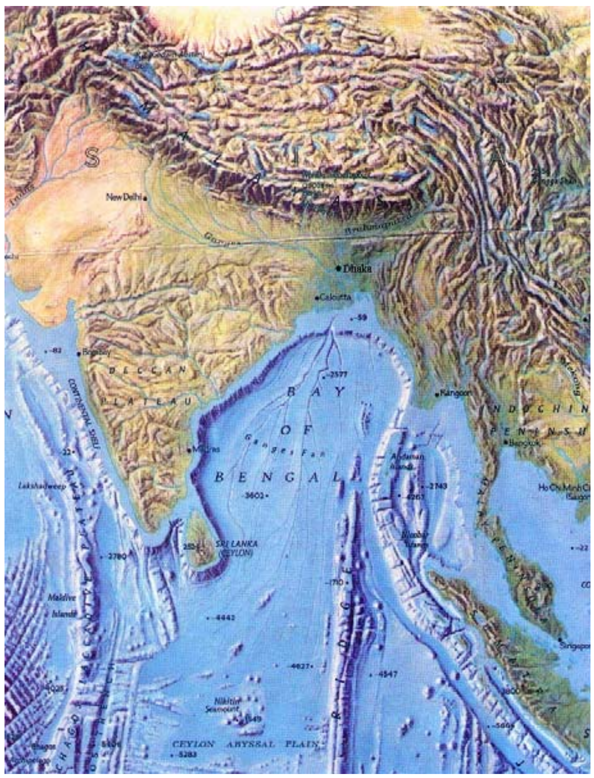


Figure 4.6: Orographic map of the Bay of Bengal

The earthquake distribution (Figure 4.7) in the Bay of Bengal clearly identify the various fault source zones those are intrinsically associated with the locations of earthquake epicenters. Further the source zones are distinctly correlated with the occurrence of known tectonic elements such as Ninety East Ridge Mega-shear, Eighty Five Ridge Mega-shear (Raiverman, 1986), Sunda Trench, Andaman Trench, Chittagong-Arakan Fault Zone, and Peri-craton & Basin-margin Fault Zone (Khan & Akhter, 1999). Sumatra fault zone and Chittagong-Arakan fault zone are already geologically established fault zones those are

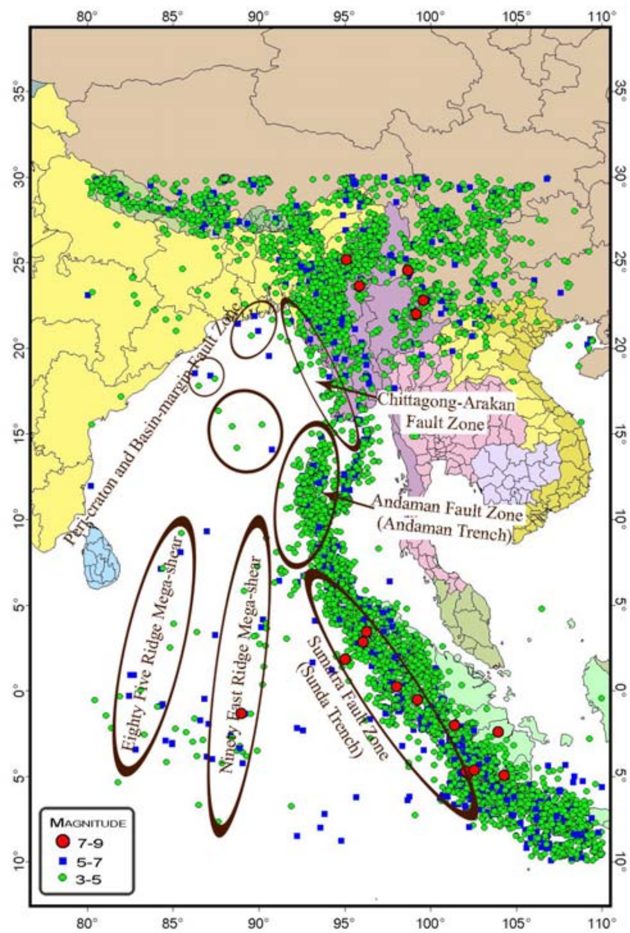


Figure 4.7: Fault source map derived from seismological data

available in the scores of publications. Andaman fault zone has also been documented as in the Figure 4.8 (Paul and Lian, 1975).

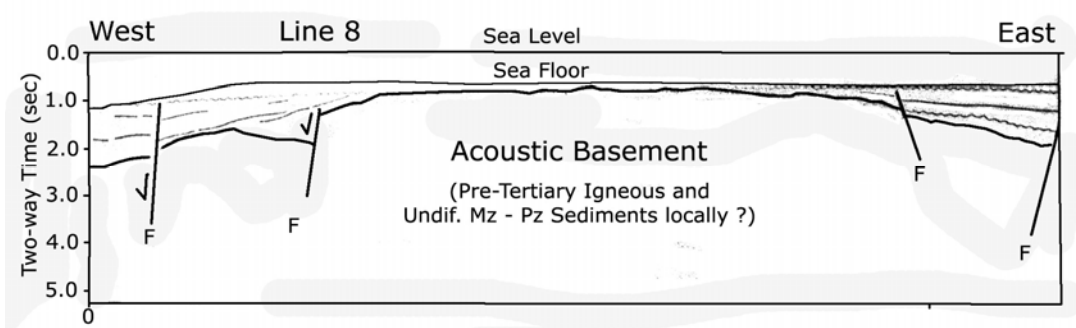


Figure 4.8: Andaman Fault zone derived from seismic section

The regional structural configuration of the Bay of Bengal as envisaged from the vertical component magnetic anomaly map (Figure 4.9) is quite consistent with the regional crustal features of the Bay of Bengal like Ninety East Ridge, Eighty Five East Ridge, and the elevated crust in the north Bay of Bengal.

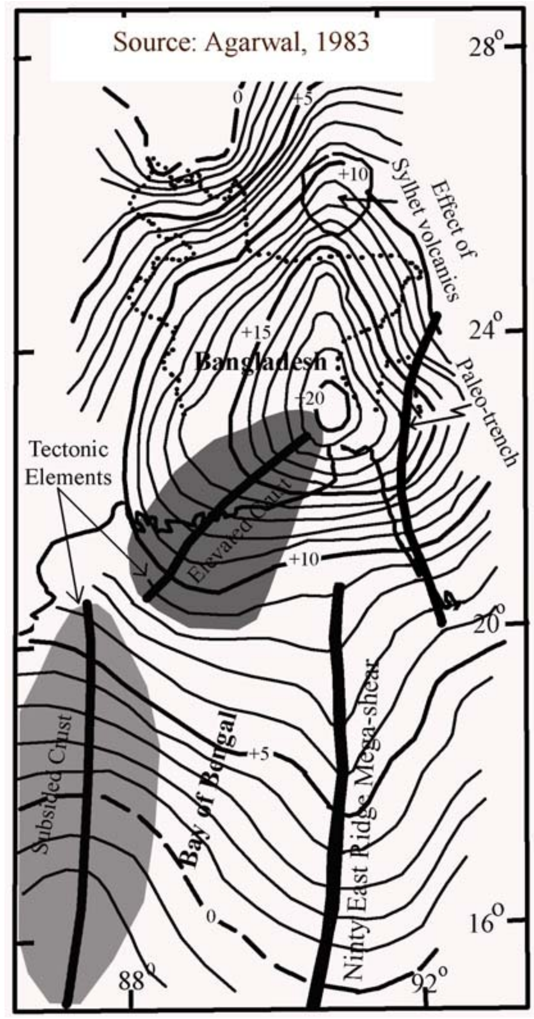


Figure 4.9: Regional crustal features of the Bay of Bengal derived from vertical magnetic data.

East-West seismic section along 19°N latitude in between 87°E and 91°E longitudes (Figure 4.10) clearly exhibits a regionally long wavelength crustal feature representing an elevated and subsided older surface respectively (Curray amd Moore, 1971). Further, the normal faults occurring along the location of “Swatch of No Ground” in the 19°N seismic section suggest that the zone occupied by the “Swatch of No Ground” is a faulted zone resulted from the upward bulge of the older crust. The western part of the Bay of Bengal along the Eastern Ghat Mobile Belt, the focal mechanism solutions of four earthquake events also show pure strike-slip faulting (Khan, 1991) (Figure 4.11).

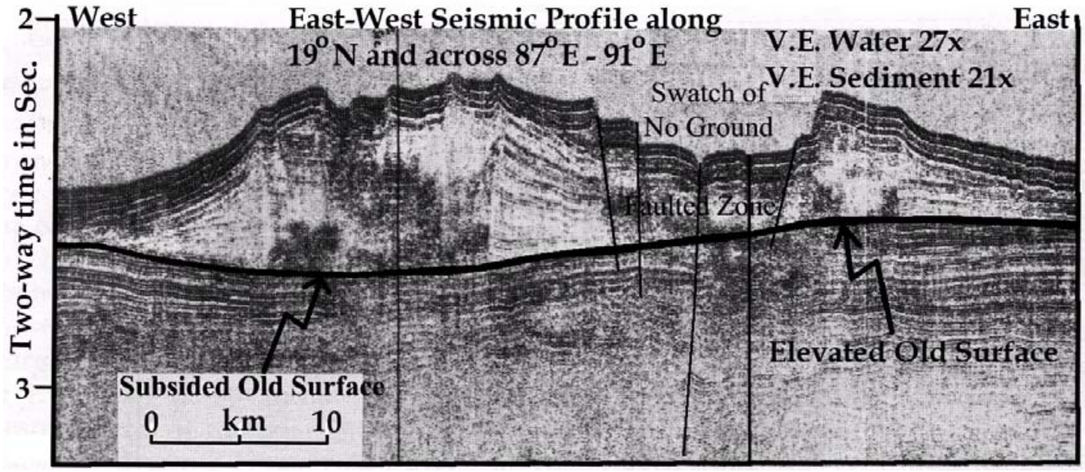
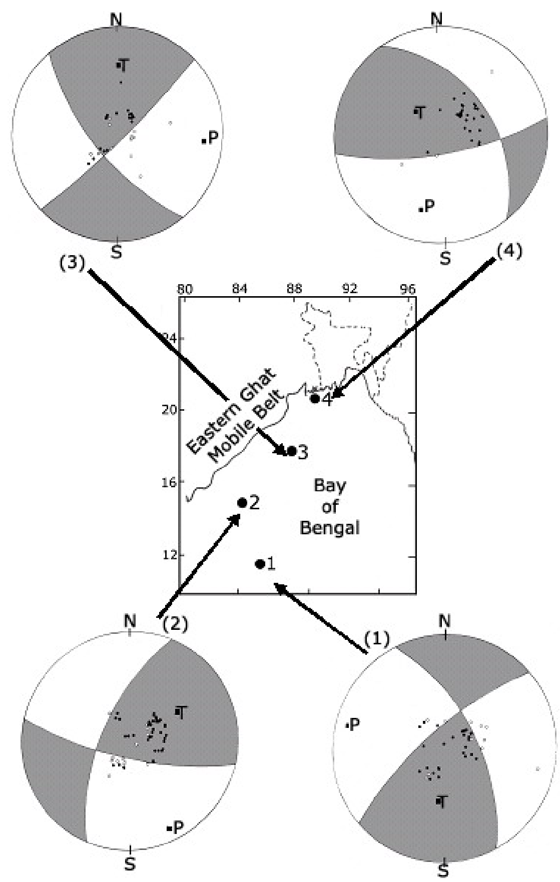


Figure 4.10: Seismic section showing crustal features of the Bay of Bengal

Figure 4.11: Western region of the Bay of Bengal exhibit a clear strike-slip fault mechanism.



4.4 Tsunamigenic Fault Source

Based on the aforesaid geophysical and geological data, the potential fault source map of the Bay of Bengal has been prepared and presented in Figure 4.12. It shows four (4) potential tsunamigenic fault-sources. The parameters of the fault sources such as the rupture length, slip offset, dip angle, slip angle, strike angle and the moment magnitude have been calculated from geophysical and seismological data for purpose of tsunami modelling. Initially 4 potential sources of tsunami were identified and presented in an International Workshop organized by CDMP on "T*sunami and Strom Surge Hazard Assessment and Management for Bangladesh*" held during 21-22 January 2009. Later the potential sources of tsunami were reduced to four numbers according to the suggestions of the international experts.

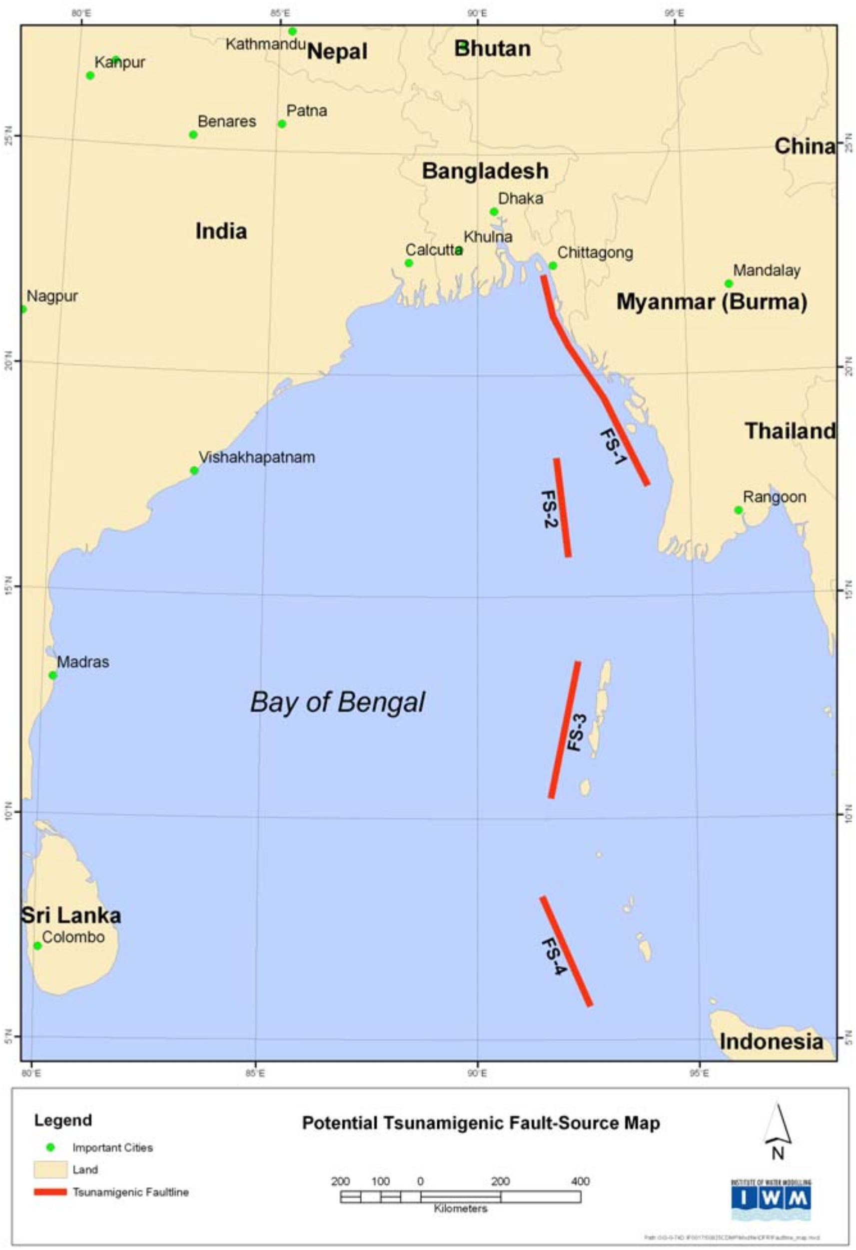


Figure 4.12: Potential Tsunamigenic fault-source map

The position of the potential sources of tsunami with earthquake parameters are presented in Table 4.1.

Table 4.1: 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)-(18.5N, 93.5E)	410	3-7	0	30-40	45-65	340	10	**8** (Potential)
FS-2	17N, 92E	250	5	0	50	40	20	10	**8**
FS-3	12N. 92E	350	5	0	50	45	30	10	**8** (Potential)
FS-4	07N, 92E	300	9	0	40	50	320	10	**8**

4.5 Numerical Modeling of Tsunami

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

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

Source Modelling:

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 has been used for calculation of deformation in bed level based on the geophysical and seismological data. Description of the QuakeGen model has been presented in Appendix-C.

Initial surface level has been generated using hydrodynamic module of MIKE 21 modelling system based on the output from QuakeGen model. A sample plot of initial surface level of tsunami scenario FS-3 has been presented in Figure 4.13 and rest of the plots are presented in Appendix-C.

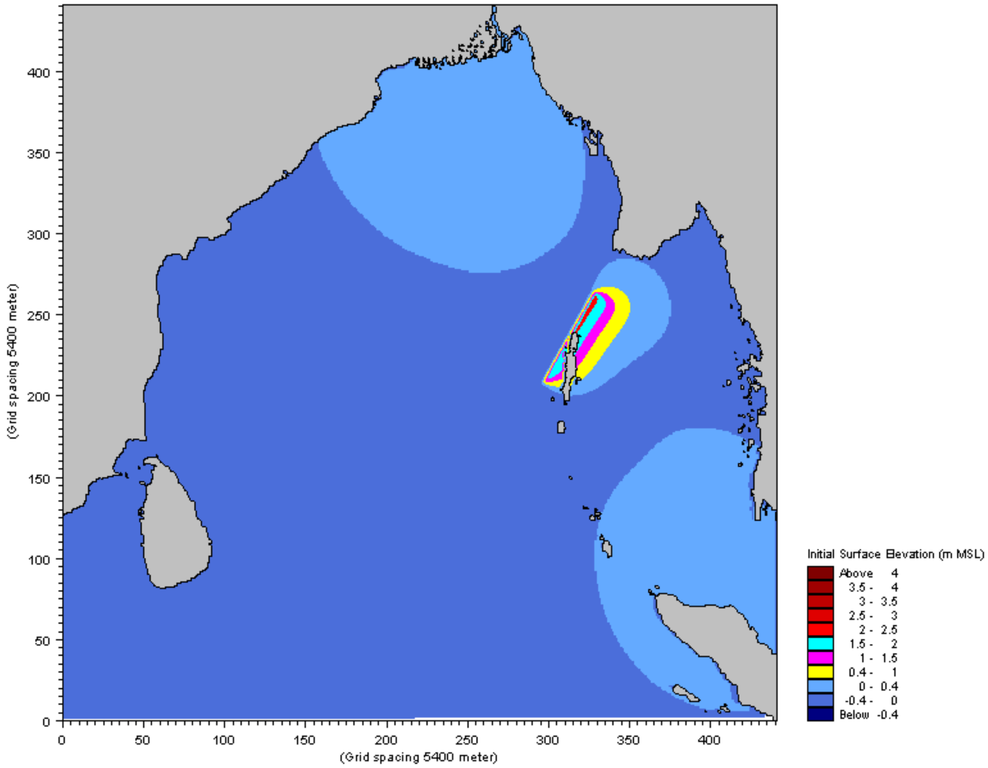


Figure 4.13: Initial Surface level of tsunami scenario FS-3

Tsunami Wave Propagation and Inundation Modelling:

The main module of MIKE21 used in this study is Flow Module. Scientific background of this module is presented in **Appendix-B**.

A tsunami model has been 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 has been 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 Meghna Estuary is resolved on a 600m grid resolution. The fine grid model domain covers the whole coastal region except Ukhia and Teknaf upazilas. The coarser grid model results have been used for Ukhia and Teknaf upazilas.

The model is two-way nested and it is driven though the release of the applied initial surface elevation only. The Regional model has been used to absorb energy at the boundary and to avoid reflection from internal boundaries. All the boundary conditions at the regional model have been 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 has been applied. The intermediate grid model serves only as a transition to the local fine grid model. The fine grid Model is used for detailed study of the inundation and flood risk due to the Tsunami wave. Figure 4.14 shows the regional model domain.

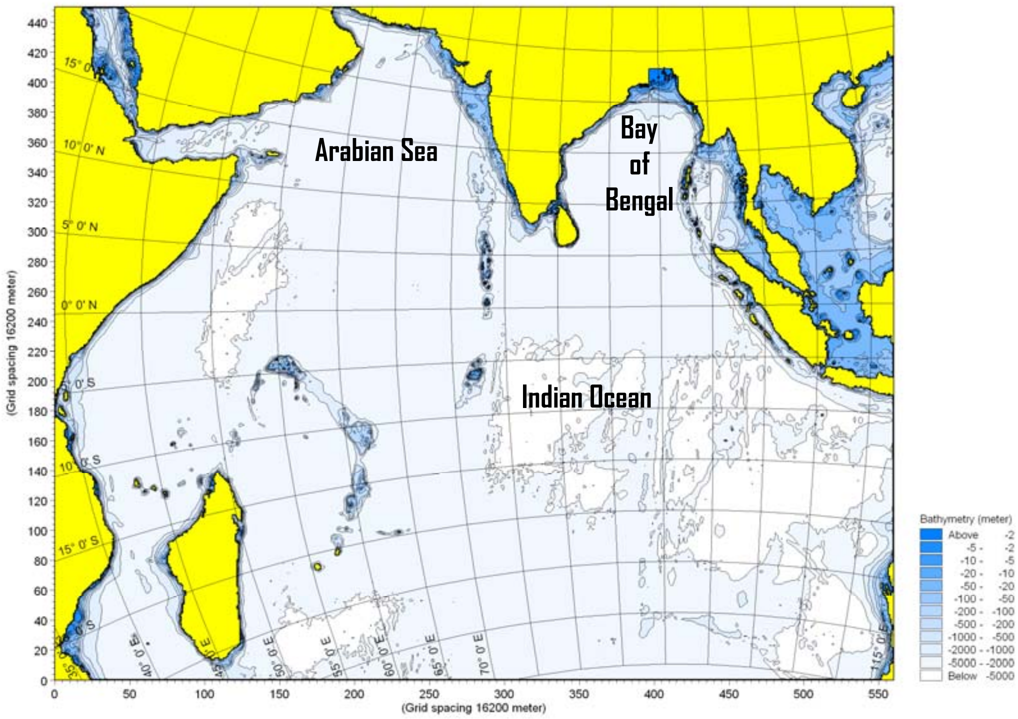


Figure 4.14: Regional model domain

The simulation parameters of the tsunami model are shown in Table 4.2.

Table 4.2: Tsunami Simulation Parameters

Tsunami Simulation		
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	

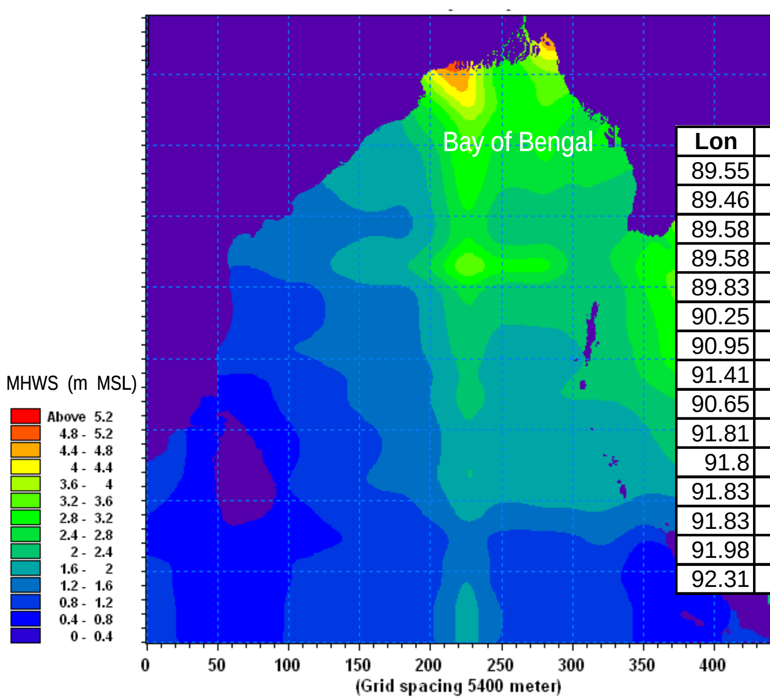
The regional grid model of tsunami was developed and calibrated by DHI$_{\text{Water.Environment.Health}}$ using MIKE 21 modelling system. It has been calibrated with the tsunami of December 26, 2004, which occurred at the West Coast of Sumatra due to the earthquake. The model setup and calibration of tsunami model has been presented in Appendix-C.

4.6 Inundation Risk Map

Inundation risk map for the coastal region of Bangladesh has been prepared based on the four scenarios of tsunami originated from four potential sources of earthquake in the Bay of Bengal. The map has been 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 have been simulated using MIKE 21 modelling system. Simulations have been 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. 4 scenarios) have been generated from the simulation results under MHWS condition. Finally the inundation risk map has been generated based on the maximum inundation maps using GIS tool.

In order to determine the MHWS level for the coast of Bangladesh, a map has been produced for the Bay of Bengal. The MHWS data at different locations have been taken from the Admiralty Tide Tables (1995). Figure 4.15 shows the MHWS level along the coast of Bangladesh, which is 3 m MSL at western coast and higher in Sandwip channel. In this study 3.46 m PWD 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 4.15: MHWS level in Bay of Bengal

Maximum inundation maps for 4 scenarios of tsunami show insignificant influence in the coastal region of Bangladesh under MSL condition. But some influence has been found under MHWS tide condition. Following figures show the maximum inundation maps for 4 scenarios of tsunami under MHWS tide condition (Figure 4.16- 4.19).

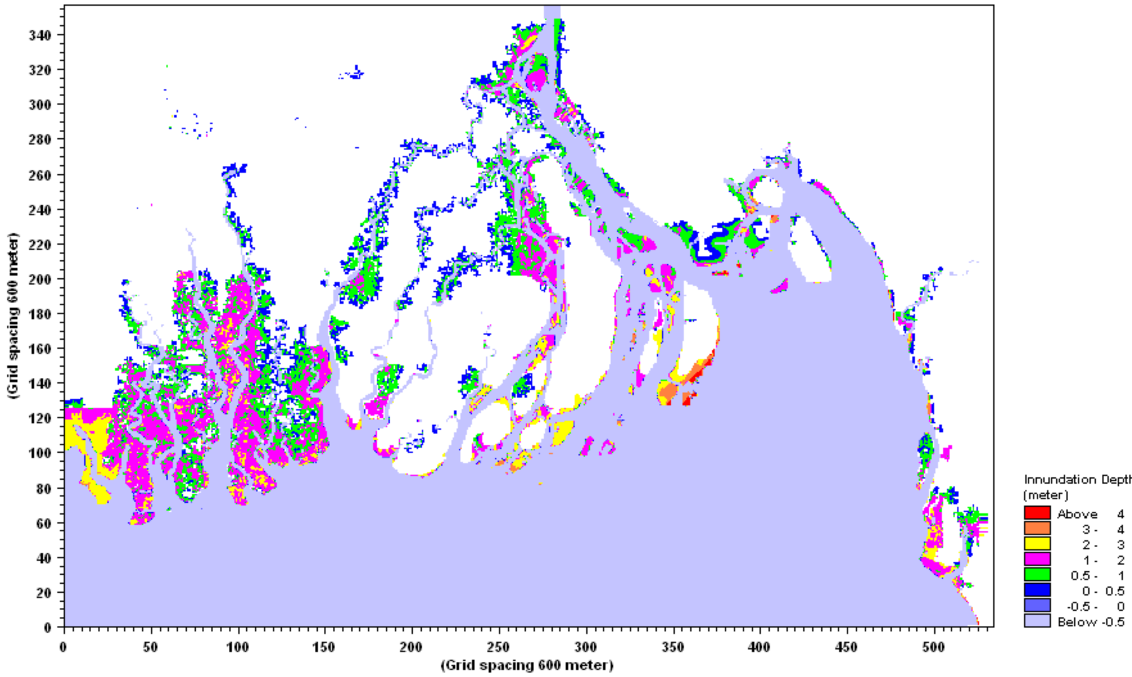


Figure 4.16: Maximum inundation map for scenario FS-1 of tsunami

Tsunami scenario FS-1 generates in front of Chittagong coast and propagates in all direction away from the coast. The tsunami inundates Nijhum Dwip and flood plain of south Hatia (outside polder) in opposite direction in the range of 3 to 4 m, Noakhali coast, Urirchar and Sandwip in northern direction in the range of 1-2 m, Cox's Bazar coast in south direction in the range of 1-3 m and Sundarban coast in the range of 1-3 m. Small islands in the Meghna Estuary also get inundated due to this tsunami.

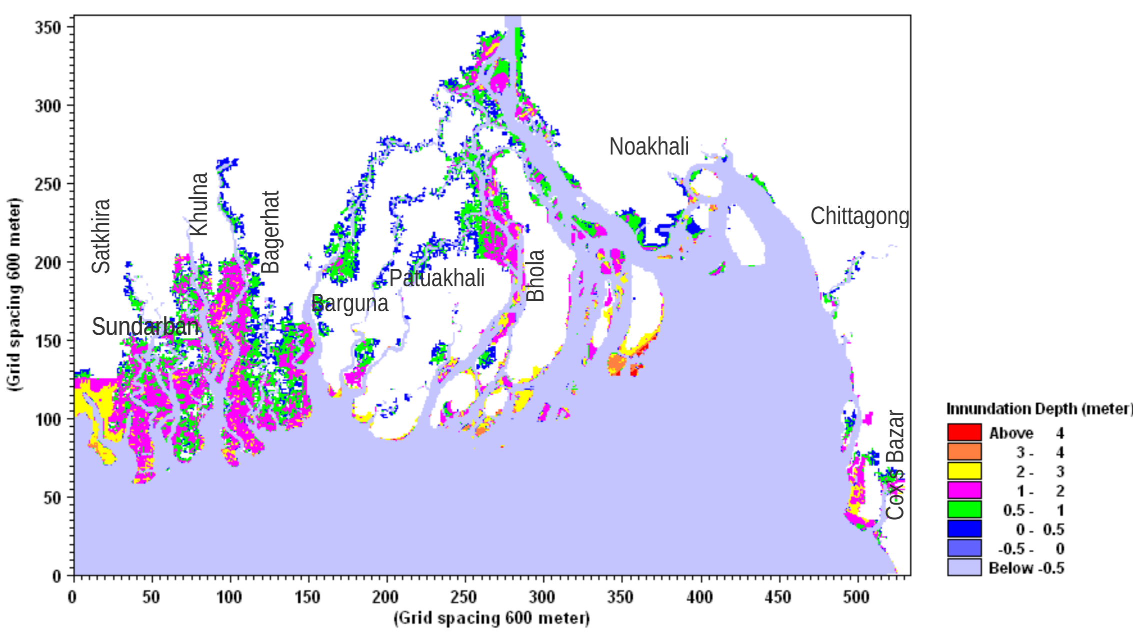


Figure 4.17: Maximum inundation map for scenario FS-2 of tsunami

Tsunami under scenario FS-2 originates in front of Myanmar coast and hits mainly the coast between Kuakata and Noakahali. Highest inundation in the range of 2-4 m has been found at Nijhum Dwip. Other coasts like Sundarban and Cox's Bazar get inundated by about 1-3 m.

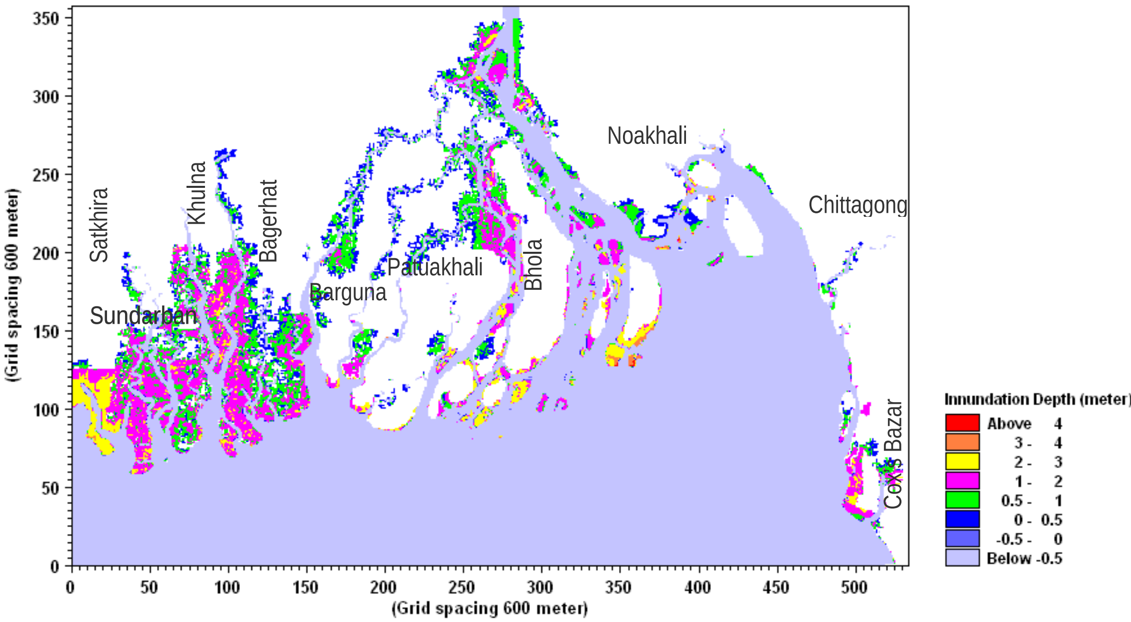


Figure 4.18: Maximum inundation map for scenario FS-3 of tsunami

Tsunami under scenario FS-3 originates at the north of Anadaman island and propagates towards the coast of Bangladesh. It mainly affects the coast between Kuakata and Nijhum Dwip. Other areas have been found less affected in the simulation result.

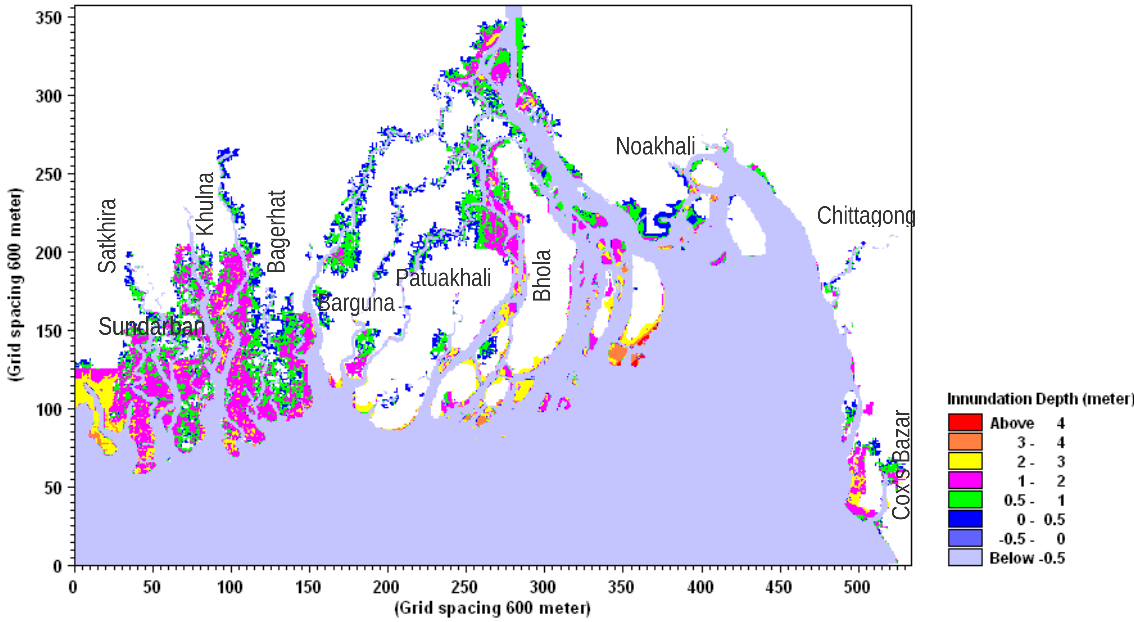


Figure 4.19: Maximum inundation map for scenario FS-4 of tsunami

Tsunami under scenario FS-4 originates at the north-west side of Nicobar islands and it hits all coasts of Bangladesh. Highest range of inundation within the range of 2-3 m has been found at Nijhum Dwip.

All the maps show that maximum inundation takes place at Sundarbans area, Nijhumdwip, Shonadia island, Bauphal upazila of Patuakhali district and small islands in the Meghna Estuary. Maximum inundation is found at Nijhum Dwip in the range of 3-4 m, and at Sundarban area, Moheskhali and Cox's Bazar coast in the range of 1-3 m. Small islands and part of the Manpura island in the Meghna Estuary get inundated by 1-3 m. The maximum inundation in the other locations remains within 1-2 m, which are mainly due to the MHWS tide. Bauphal upazila under Patuakhali district is one of them.

Tsunami level with travel time at five different locations of Bangladeshi coast has been extracted from the simulation results of four scenarios and presented in Table 4.3.

Tsunami level at Nijhum Dwip varies from 4.15 to 5.00 m PWD with minimum travel time of 1 hour 45 minutes for scenario FS-1. Tsunami level at Sandwip varies from 3.65 to 4.5 m PWD with minimum travel time of 20 minutes for scenario FS-1.

Table 4.3: Tsunami level with travel time from the source under different scenarios

Sources	Hiron Point		Kuakata		Nijum Dwip		Sandwip		Cox's Bazar	
	Tsunami level (m PWD)	Travel Time (Hr:Min)	Tsunami level (m PWD)	Travel Time (Hr:Min)	Tsunami level (m PWD)	Travel Time (Hr:Min)	Tsunami level (m PWD)	Travel Time (Hr:Min)	Tsunami level (m PWD)	Travel Time (Hr:Min)
FS-1	3.57	06:30	4.40	04:35	5.00	01:45	4.50	00:20	5.60	00:05
FS-2	3.64	02:45	4.79	03:20	4.29	04:15	3.70	04:40	4.08	02:30
FS-3	3.6	03:45	4.11	04:30	4.15	05:20	3.65	05:45	3.69	03:40
FS-4	3.8	04:00	4.45	04:35	4.45	05:40	3.89	06:30	3.91	04:10

Inundation risk map for tsunami has been generated based on the maximum inundation maps of four tsunamis and presented in Figure 4.20. 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 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. In this area the influence of tsunami wave is insignificant.

The Digital Elevation Model (DEM), presented in Figure 2.2 of Volume-II, shows that Ukhia, Teknaf and part of the Cox's Bazar are hilly region. The inundation risk map shows that the Teknaf beach is likely to be inundated by maximum 4.5 m.

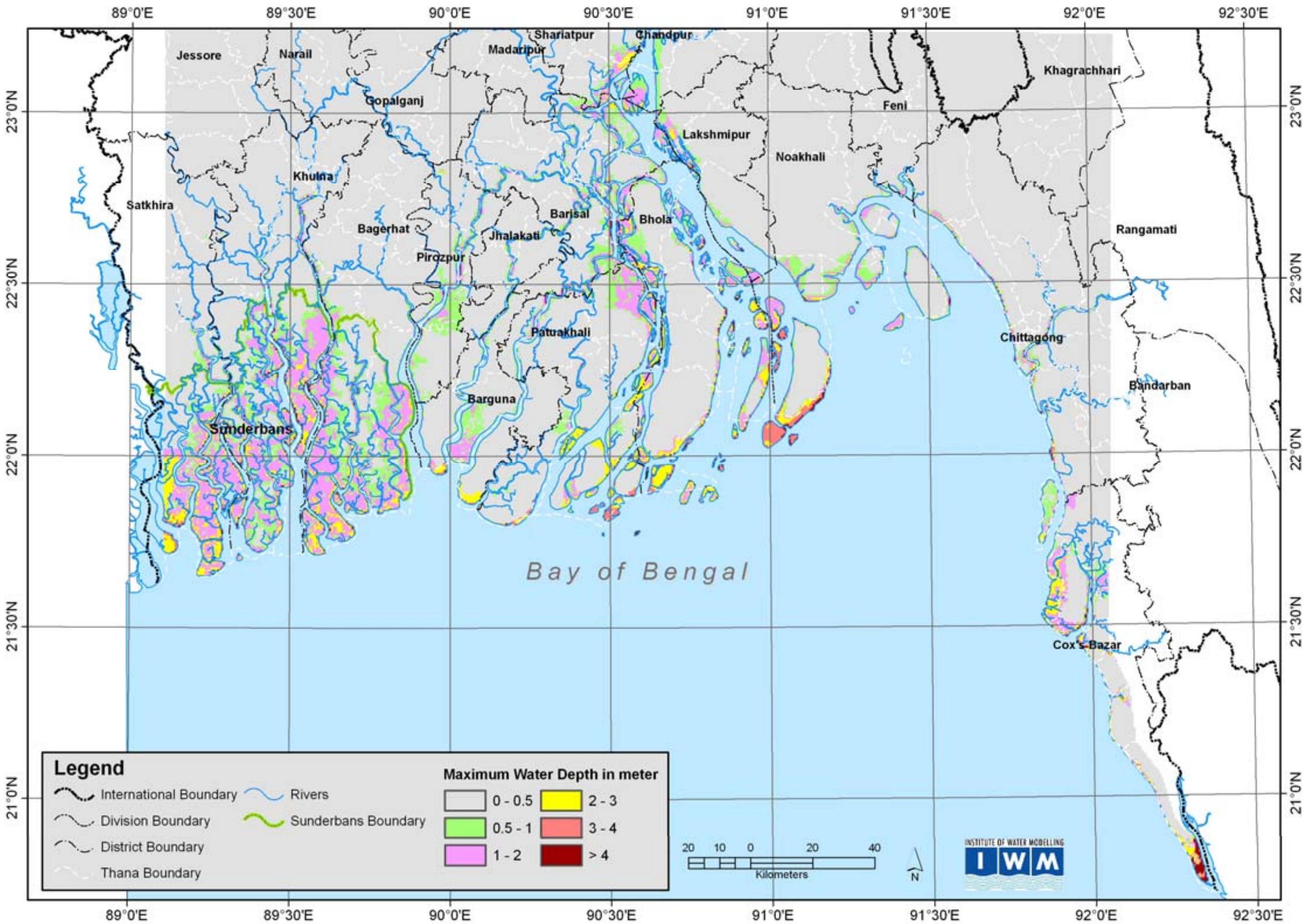


Figure 4.20: Inundation risk map of tsunami in the coastal region of Bangladesh

5. STORM SURGE

5.1 Introduction

The Bay of Bengal is one of the favourable areas for the generation of tropical cyclones. In this region cyclones occur in the pre- and post monsoon seasons. Most of the cyclones hit the coasts of Bangladesh with north-eastward approaching angle. During the period 1960-2007, 18 cyclones hit the coast of Bangladesh. Cyclone tracks of the 18 cyclones along with data have been presented in Appendix-D.

About one-tenth of the global total cyclones forming in different regions of the tropics occur in the Bay of Bengal (Gray, 1968; Ali, 1980). Not all

The Bangladeshi coast is always vulnerable to cyclone-induced storm surge. There are mainly three reasons behind it. The first one is that the continental shelf is long and shallow and the shape of the coast tends to concentrate and amplify the surge in the northern part of the Bay. The second one is that the coastal zone is low-lying with 62% of the land have an elevation of up to 3 metres and 86% up to 5 metres from mean sea level. The third reason is that the coastal area is densely populated. About one third of the country belongs to coastal zone (ref. coastal zone policy, 2005). According to 2001 population census, population of coastal zone is 3 crore and 48 lakh.

Since 1995, IWM is maintaining the two-dimensional Bay of Bengal Model. The first version of the model was applied in Cyclone Protection Project (CPP, 1991) and was further developed as a part of the Cyclone Shelter Preparatory Study (CSPS, 1998). The model was further updated as a part of 2nd Coastal Embankment Rehabilitation Project (2nd CERP, 2000). In the Cyclone Shelter Preparatory study and 2nd CERP, the model applied for the simulation of cyclone, cyclone related storm surge for a number of past major cyclones to generate the high risk zoning map for the planning and management of cyclone shelter. In this study the existing Bay of Bengal Model of 2nd CERP has been upgraded in 200 m grid resolution incorporating Sundarban area, updated with the recent bathymetric data and the model has been extended to the sea up to 16º latitude.

5.2 Storm Surge Modelling

For simulating the storm surge and associated flooding, Bay of Bengal model based on MIKE21 hydrodynamic modelling system has been adopted. Storm surge model comprises of Cyclone model and Hydrodynamic model. In the hydrodynamic model simulations meteorological forcing like cyclone 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. Detailed model set-up and calibration is presented in **Appendix-C.**

Hydrodynamic Model

The model is two way nested and includes four different resolution levels in different areas (Figure 5.1). The coastal region of Bangladesh and the Meghna estuary are resolved on a 200 m grid. The fine grid model domain covers the whole coastal region except Ukhia and Teknaf upazilas. The coarser grid model results have been used for Ukhia and Teknaf upazilas. Information of the grids is presented in Table 5.1.

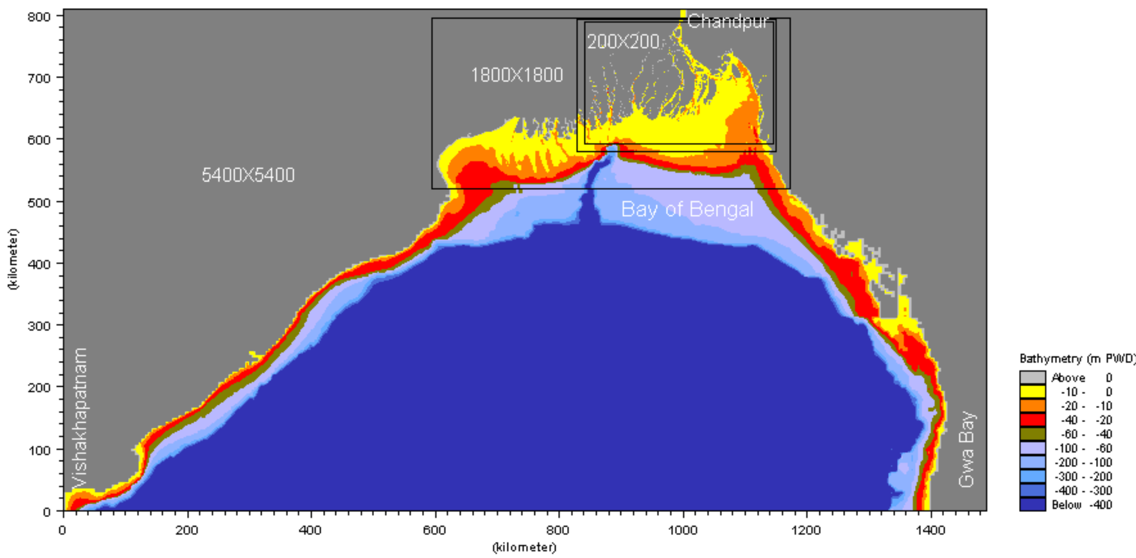


Figure 5.1: Nested bathymetry of Bay of Bengal Model

Table 5.1: Information of the grids of Bay of Bengal Model

Model	***Origin (degree)***		***Orientation (degree)***	***Grid Spacing (m)***	***Grid Numbers***
	Longitude	***Latitude***			
Coarse grid	81.2408	16.0044	-2.19	dx=5400 dy=5400	277X151
Intermediate grid	86.7473	20.8165	0.9147	dx=1800 dy=1800	322X154
Fine grid	88.9939	21.3397	-0.1238	dx=600 dy=600	535X358
200 m grid	89.1094	21.4483	0.0833	dx=200 dy=200	1525X994

Cyclone Model

A proper cyclone description together with information of land levels is important and essential in order to simulate realistic flood depths. The cyclone description includes:

- Radius of maximum winds;
- Maximum wind speed;
- Cyclone tracks, forward speed and direction;
- Central pressure; and
- Neutral pressure.

The cyclone model developed under CSPS and updated under 2nd CERP has been used for simulation of 18 cyclones from 1960 to 2007. The model was calibrated and validated for the April 1991 cyclone and validated against the November 1988 cyclone under CSPS. In 2nd CERP it was validated against wind speed and pressure for cyclone May 1997, September 1997 and May 1998. Scientific background of the cyclone model has been presented in **Appendix-B.**

Storm Surge Model

The storm surge model was calibrated and verified during CSPS and 2nd CERP. In this study the model has been validated for the cyclone of 2007 at Hiron Point, for the cyclone of 1998 at Charchenga and Khepupara and for the cyclone of 1988 at Khepupara. Sample comparison plots of water level during the cyclone 2007 and the cyclone 1988 have been presented in Figure 5.2 and 5.3 respectively. Other comparisons are presented in **Appendix-C**.

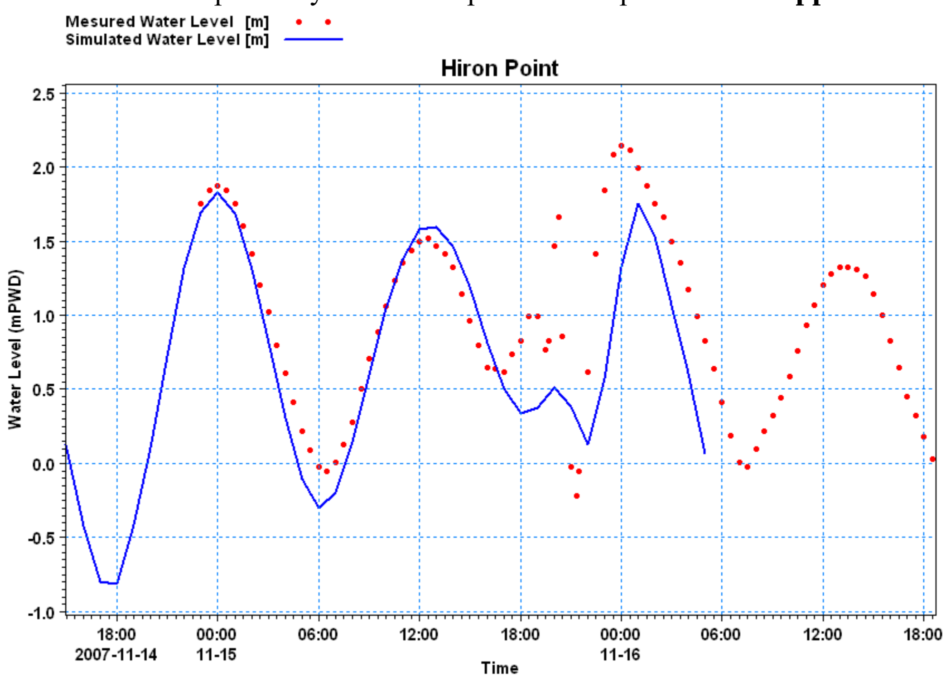


Figure 5.2: Calibration Plot at Hiron Point during Cyclone SIDR, 2007

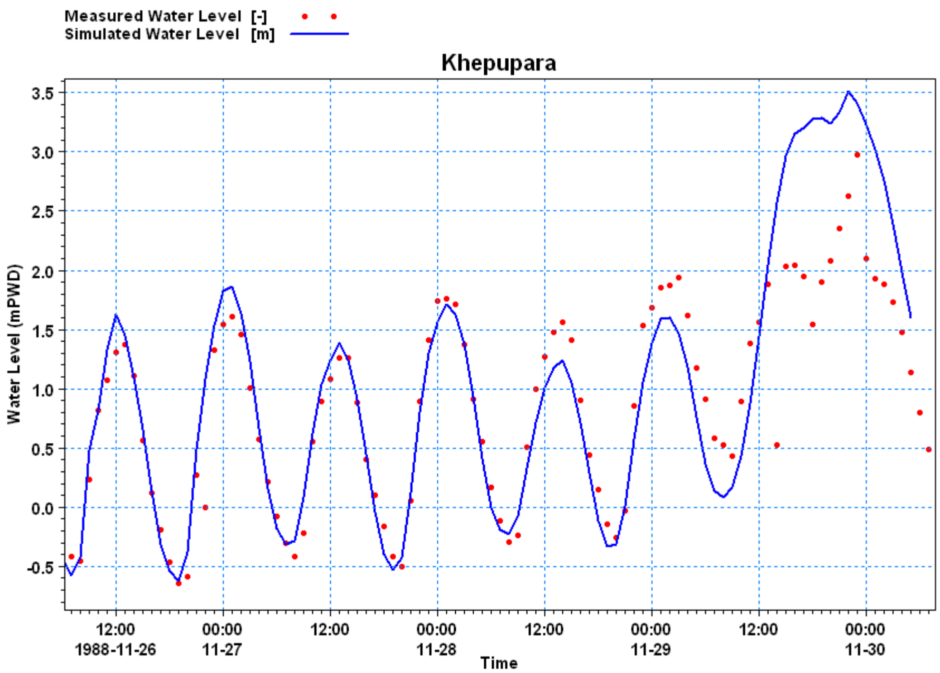


Figure 5.3: Calibration Plot at Khepupara during 1988 Cyclone

5.3 Maximum Inundation Maps

Maximum inundation maps for 18 cyclones have been generated from the simulation result. All simulations have been carried out considering existing polders in the coastal region. Results show that the different coast of Bangladesh gets inundated due to different tracks of cyclones. Table 5.2 shows the coast of Bangladesh affected by cyclones during the period 1960-2007.

Table 5.2: Cyclones caused inundation at different coast of Bangladesh

Coast of Bangladesh	Affected by Cyclones	Cyclones caused maximum inundation
Central coast lies in the Meghna Estuary	1960, 1963, 1966, 1970, 1974,	1970, 1974
Eastern Coast	Dec. 1965, 1983, 1985, 1991, 1995, Sept. 1997, May 1997, 1998	1991
Western Coast	1961, May 1965, 1986, 1988, 2007	1988, 2007

Table 5.2 shows that maximum inundation at the central coast occurred in 1970 and 1974 cyclones, at the eastern coast in 1991 cyclone and at the western coast in 1988 and 2007 cyclones.

Maximum inundations caused by severe cyclones have been presented in the following figures:

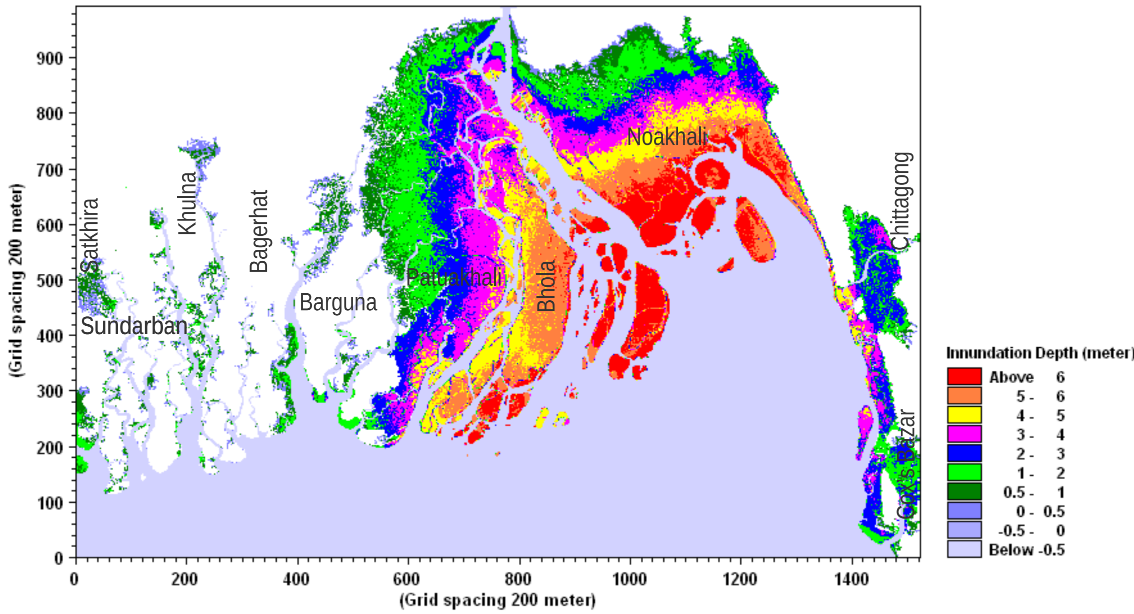


Figure 5.4: Maximum inundation map for1970 cyclone

1970 cyclone crossed Barguna district, Patuakhali district, Bhola island, Noakhali coast and Urirchar island with a maximum wind speed of 222 Kilometre per hour (kph). The cyclone hit the land during high tide. Simulation result shows that the cyclone-induced storm surge inundates all the coasts and islands in the Meghna Estuary and also the eastern coast of Bangladesh. Maximum inundation has been found in the range of 5-7 m at Bhola island, Hatia, Nijhum Dwip, Noakhali coast, Sandwip and Urirchar. In the simulation result the eastern coast gets inundated by 3-4 m (Figure 5.4).

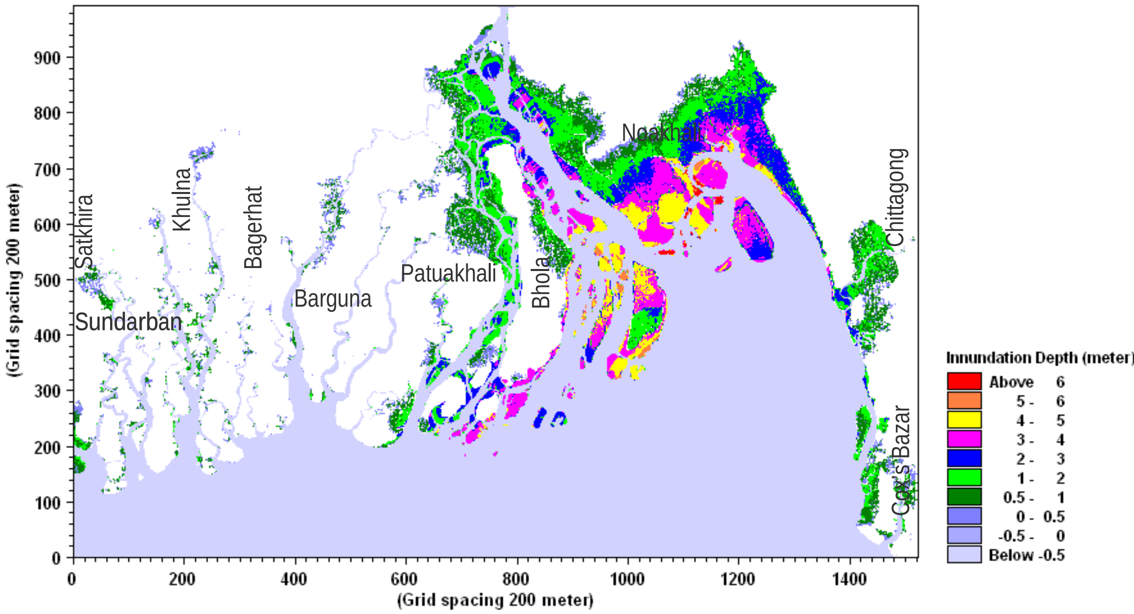


Figure 5.5: Maximum inundation map for1974 cyclone

1974 cyclone made landfall at Char Rangabali in the Tetulia River and crossed Bhola and Noakhali districts with a maximum wind speed of 161 kph. Simulation result of 1974 cyclone-induced storm surge shows that maximum inundation takes place in the range of 2-4 m at Hatia, Nijhumdwip, Noakhali coast, Sandwip and Urirchar (Figure 5.5).

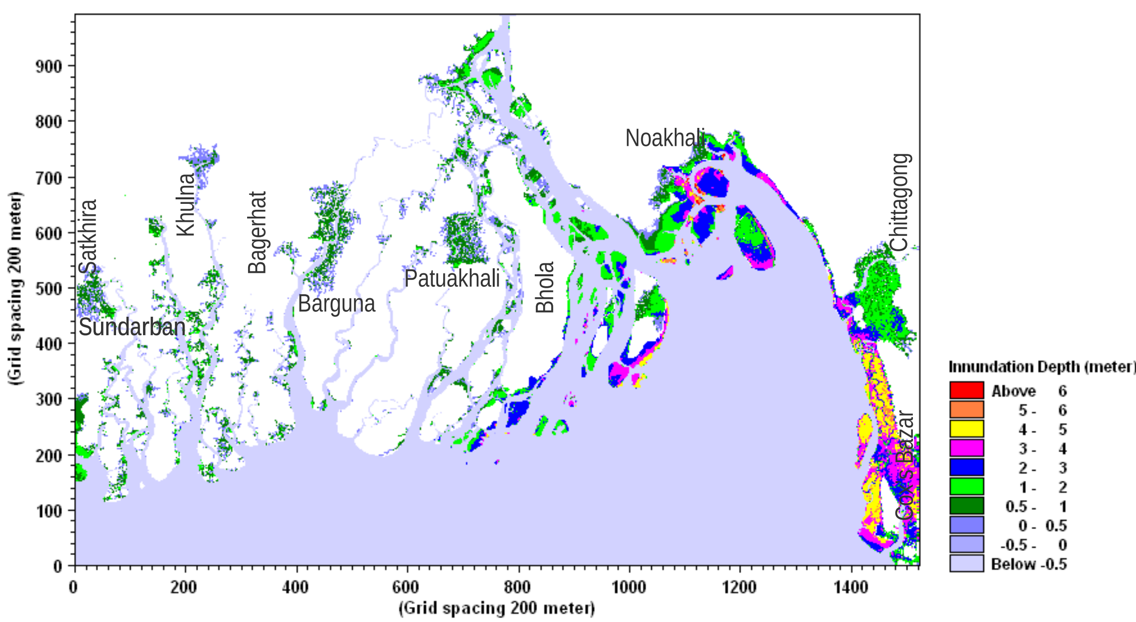


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Figure 5.6: Maximum inundation map for1991 cyclone

1991 cyclone crossed Chittagong coast at Patenga with a maximum wind speed of 225 kph during high tide. Simulation result of storm surge due to the 1991 cyclone shows that maximum inundation in the range of 4-5 m takes place at Chittagong and Cox's Bazar coasts. It also shows that Sandwip, Noakhali coast and Nijhum Dwip get inundated by 1-3 m (Figure 5.6).

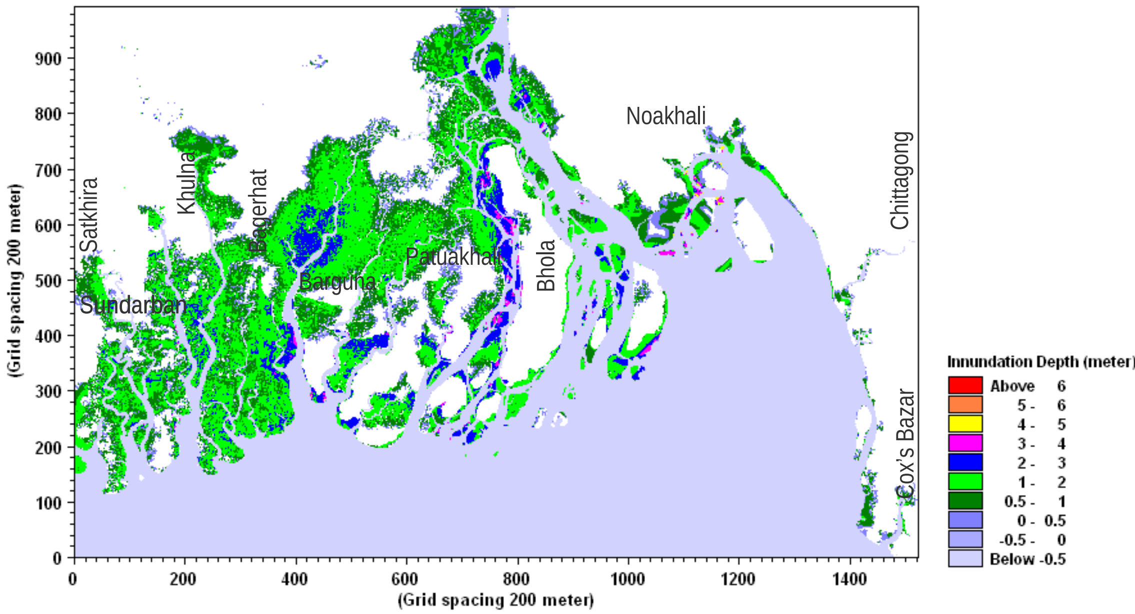

Figure 5.7: Maximum inundation map for1988 cyclone

1988 cyclone made landfall at Sundarban coast near the Raimangal River and crossed Khulna and Gopalganj districts with a maximum wind speed of 161 kph. Simulation result of the cyclone-induced storm surge shows that the western coast gets inundated by maximum 1-3 m and Pirozpur area gets inundated by maximum 2-3 m (Figure 5.7)

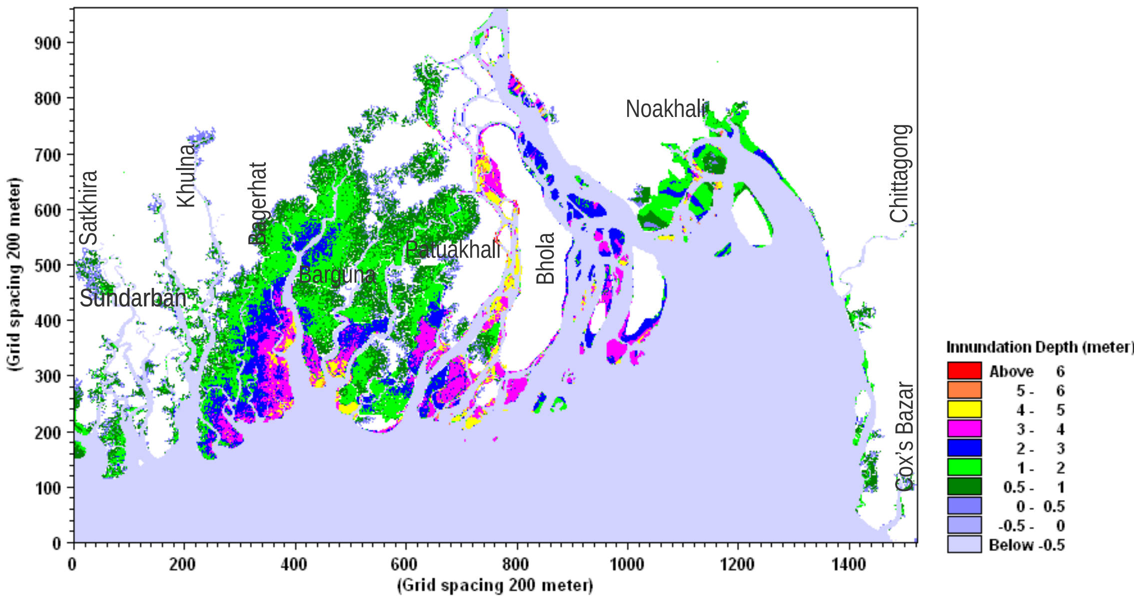

Figure 5.8: Maximum inundation map for 2007 cyclone

2007 cyclone made landfall at Patharghata under Barguna district and crossed Barguna and Jhalakati districts with a maximum wind speed of 240 kph. Simulation result of the cyclone-induced storm surge shows that the areas around the Baleshor river get inundated by maximum 4-5 m (Figure 5.8)

5.4 Inundation Risk Map

The propagation of storm surge in land and its extent of inundation vary widely along the coast. It depends on several regional and local factors related to hydrology, topography and oceanography. Some of the important factors are:

- Storm surge height at the coast;
- Angle of cyclone track with respect to the coast line;
- Tidal condition;
- Offshore and near-shore bathymetry;
- Slope of the land;
- Curvature of the coastline;
- Width and depth of river mouth through which the surge travels;
- Presence of islands and chars;
- Land topography; and
- Landuse.

During the period 1960 to 2007, 18 cyclones and its associated storm surges hit the Bangladesh coast at different locations and inundated different coastal areas of Bangladesh time to time. The inundation in land due to these cyclones covers the entire coast of Bangladesh. In this study inundation risk map has been prepared based on the mathematical model results of these cyclones.

5.4.1 Inundation Risk Map Prepared under Previous Studies

Multipurpose Cyclone Shelter Programme (MCSP) was the first to demarcate the Risk Zone (RZ) and the High Risk Area (HRA) for the coastal region of Bangladesh based upon the results of mathematical model studies, observed propagation characteristics of tides and field data on inundation due to previous storm surge.

An approximate mathematical model of maximum flooding distance of a storm surge wave over dry bed with gentle slope in a purely one-dimensional flow domain was developed under MCSP. The model study shows that the distance of storm surge flooding remains small at steep slope and it is not sensitive to resistance at steep slope. The flooding distance is sensitive to resistance in areas with small slope.

For predicting the average maximum surge heights at the sea coast of a region, a model developed by Tareque and Chowdhury (1992) was used which required the maximum wind speed and the length of the continental shelf as input data. The annual maximum cyclone wind speed data was fitted by a Gumbel distribution, in order to estimate the probability of occurrence of storm surge. The coast of Bangladesh was divided into two parts based upon the configuration of coastline and the density of storm tracks and cyclone land-fall points. Each part was further subdivided based on configuration of the 30m and the 200m depth contours on the continental shelf. The design surge heights for return periods of 20, 50 and 100 years were computed for five divisions.

In that study the area prone to storm surge flooding was termed as the Risk Zone (RZ) where there was a risk of loss of lives and damages to properties due to inundation by storm surge water. The Risk Zone was further subdivided into the High Risk Area (HRA), where there was a possibility of loss of lives due to appreciable inundation by storm surges. The Risk Zone (RZ) and the High Risk Area (HRA) for the coastal region of Bangladesh were demarcated based on these criteria. The locations of one meter inundation depth were linearly interpolated between model predicted surge height at the coast and the predicted limit of the intrusion distance of the surge water.

In MCSP following criteria were adopted in delineating the Risk Zone (RZ) and High Risk Zone (HRA):

1. The RZ extends from the coastline (sea coast or river bank) to an inland limit up to which surge water can reach;
2. The HRA includes a strip of land within the RZ. It extends from the coastline up to a limit where the depth of storm surge inundation may reach one metre.

5.4.2 Inundation Risk Map under Present Study

The inundation risk map has been generated under the present study from the maximum inundation maps of 18 cyclones and presented in Figure 5.9. The map has been prepared considering land level of the digital elevation model and the existing polders in the coastal region of Bangladesh.

It shows that the highest inundation depth having range between 5 m and 7.5 m lies in the Noakhali coast, Bhola, Urir Char, Sandwip and small islands in the Meghna Estuary. The eastern coast experiences maximum inundation between 4m and 6 m and western coast experiences inundation within the range of 3-5 m. Ukia and Teknaf main lands remain risk free due to hilly region only the teknaf beach is likely to be inundated by 3-4 m. Upazila-wise inundation area in the coastal region of Bangladesh has been prepared based on the inundation risk map and presented in Table 5.3.

A High Risk Area (HRA) has been delineated by a one meter inundation depth line according to the criteria adopted by the MCSP (July 1993) and presented in Figure 5.10. It shows that Sundarban area, Bagerhat, Pirozpur, Barguna, Jhalakati, Barisal, Patuakhali, Bhola, Lakshmipur, Noakhali, Chittagong and Cox's Bazar districts fall under HRA. Another two lines having depth of 3 m and 6 m have been drawn in order to delineate the affected zone with maximum inundation. It shows the central part of the Meghna Estuary area experiences maximum inundation.

A statistical analysis has been carried out with the maximum inundation maps of 18 cyclones in order to find the probability of inundation depth of different magnitude. Probability of inundation (risk of inundation in percent) exceeding 1 m inundation depth has been presented in Figure 5.11. It shows that Urirchar, Nijhum Dwip, Noakhali coast, Shitakunda coast and the small islands of the Meghna Estuary are likely to be inundated by more than 1 meter with a probability of 50%. The Cox's Bazar Area is likely to be flooded with a probability of 30 % time. The risk of inundation of Anwara by 1 meter inundation depth is 15%.

During the period 1960 to 2007 the coast of Bangladesh was hit by three severe cyclones at three different coasts. Those were 2007 cyclone which hit the western coast with maximum wind speed of 240 kph, 1991 cyclone which hit the eastern coast with maximum wind speed of 224 kph and 1970 cyclone which affected the central part of the Bangladesh coast with maximum wind speed of 222 kph. Among these three cyclones only 2007 cyclone made landfall during low tide and others made landfall during high tide. Four worst case scenarios of cyclone-induced storm surge have been developed considering following cyclone parameters:

- wind and pressure field of SIDR 2007 with the track of same cyclone (Tack-1) and made the landfall of cyclone at Baleshwar River during high tide;
- wind and pressure field of SIDR 2007 with 1970 cyclonic track (Track-2), which passed through Bhola and made landfall at Noakhali coast during high tide;
- wind and pressure field of SIDR 2007 with imeginary cyclonic track (Track-3), which made landfall at Urir Char during high tide; and
- wind and pressure field of SIDR 2007 with 1991 cyclonic track (Track-4), which made landfall at Chittagong coast during high tide;

Another risk map has been generated incorporating the worst case scenarios of cyclone. Figure 5.12 shows that the inundation risk map based on 18 real cyclones and four synthesized cyclones. A difference map between the two risk maps has been prepared to distinguish the affected area due to the worst scenarios and presented in Figure 5.13. It shows that inundation increases at the Sundarban coast and around Baleshwar River by 1-2 m, Bhola island by 0.5-1 m, at Sitakunda coast by 2-3m, at Anwara and around the Karnaphuli River mouth by 2-3 m, at Bashkhali by 1-2 m, at Kutubdia island by 0.5-1 m, and at Cox's Bazar by 0.5-1 m.

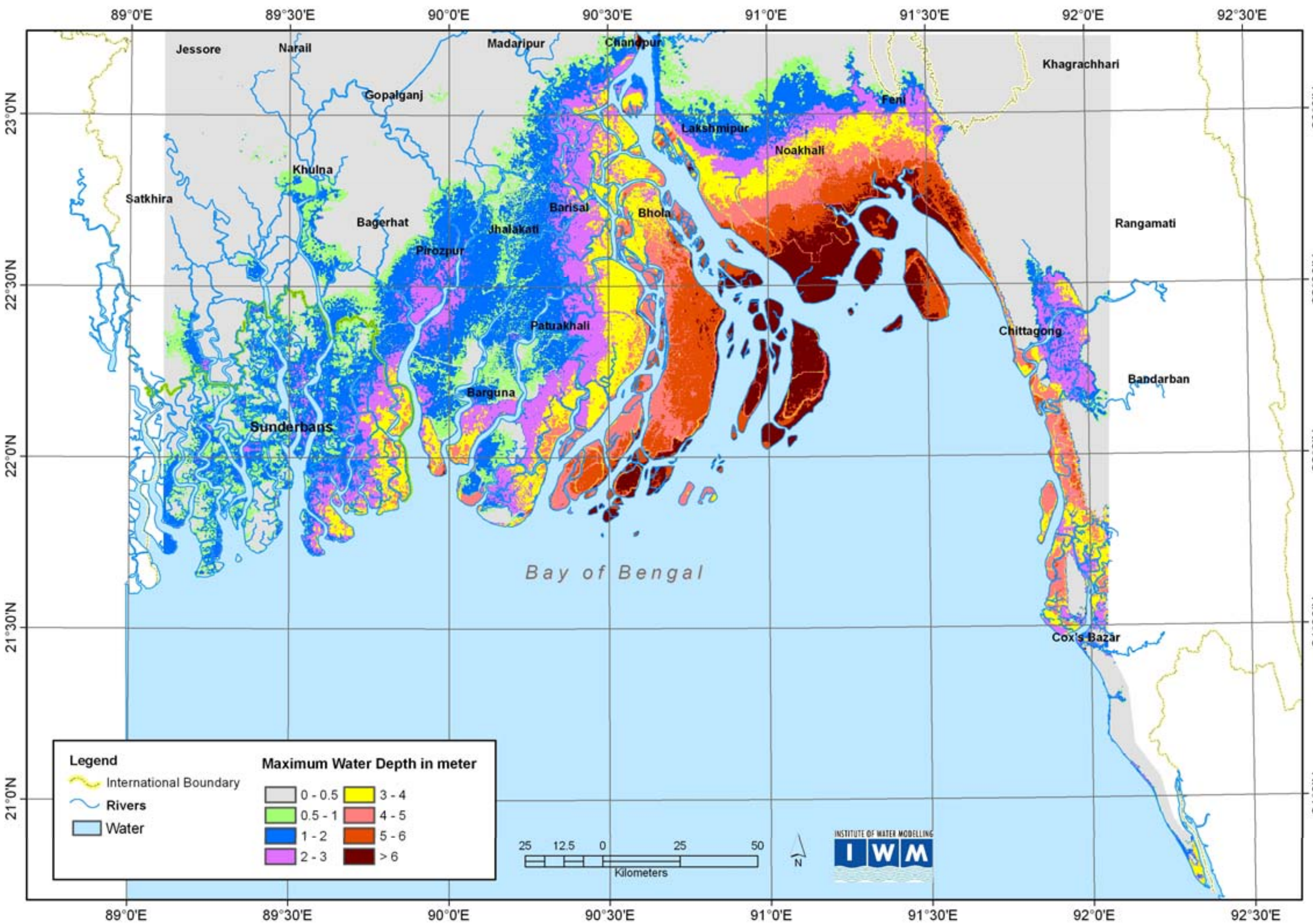

Figure 5.9: Inundation risk map generated from 18 cyclones from 1960-2007

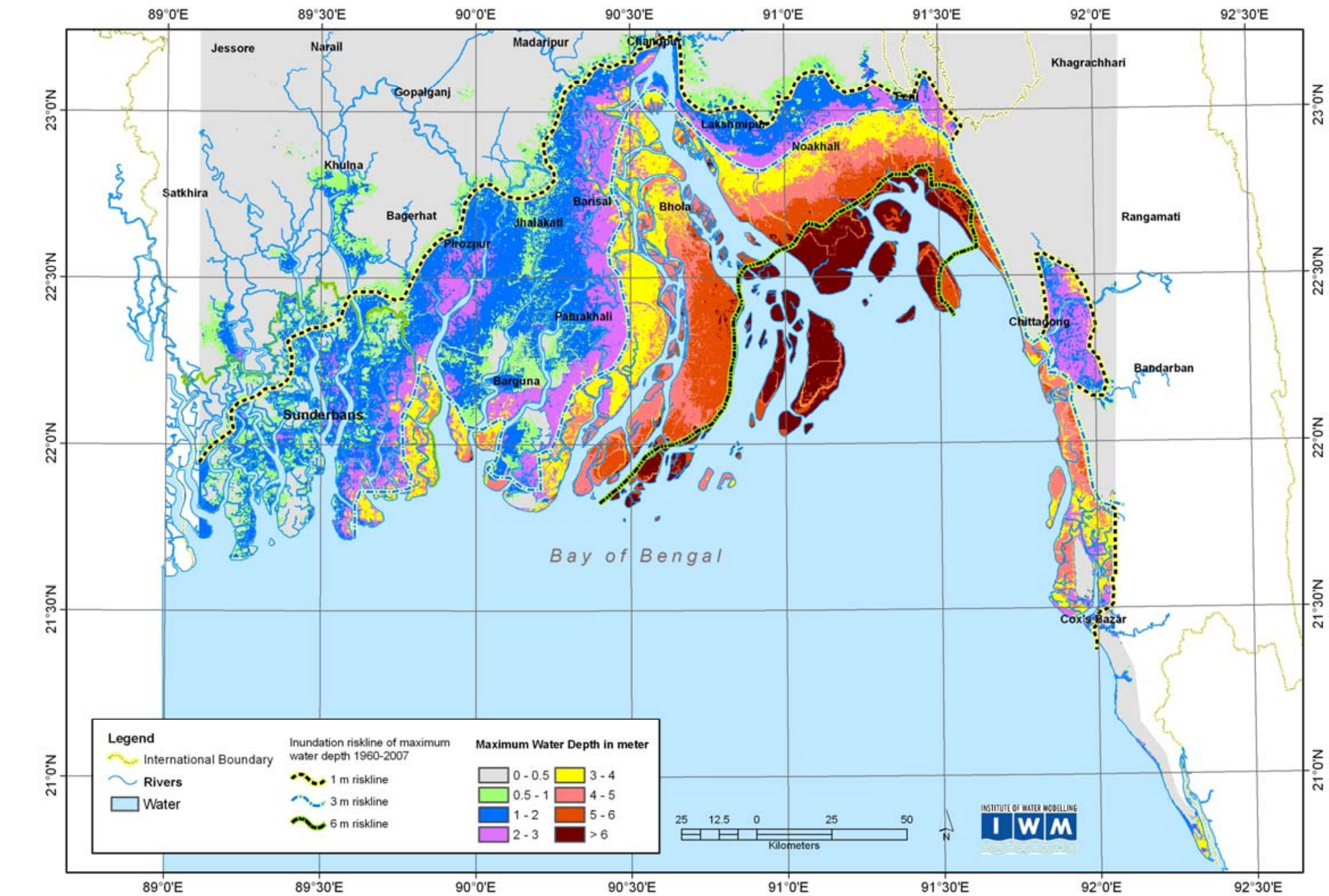

Figure 5.10: Inundation risk map with different inundation-depth contour lines

Table 5.3: Upazilas under inundation risk

SL No.	Name of Upzilla	Area, ha (excluding river)	Innundation							
			d*<=1m		1m>d*<=3m		3m>d*<=6m		d*>6m	
			Area, ha	%	Area, ha	%	Area, ha	%	Area, ha	%
1	Agailjhara	16176	15916	98	260	2	0	0	0	0
2	Amtali	50972	15916	31	27696	54	7296	14	64	0
3	Anowara	14404	1212	8	6208	43	6884	48	100	1
4	Assasuni	33132	32464	98	628	2	24	0	16	0
5	Babuganj	14584	1560	11	12672	87	248	2	104	1
6	Bagerhat Sadar	26436	26436	100	0	0	0	0	0	0
7	Bakerganj	36772	848	2	27488	75	8304	23	132	0
8	Bamna	8696	7972	92	688	8	36	0	0	0
9	Banari Para	12572	11924	95	616	5	8	0	24	0
10	Banshkhali	34976	13580	39	2900	8	18376	53	120	0
11	Barguna Sadar	31792	7288	23	16980	53	7428	23	96	0
12	Barisal Sadar (kotwali)	27352	236	1	20832	76	6128	22	156	1
13	Batiaghata	21744	17160	79	4404	20	140	1	40	0
14	Bauphal	41204	4	0	9308	23	31392	76	500	1
15	Betagi	15068	6360	42	8672	58	36	0	0	0
16	Bhandaria	14708	424	3	14084	96	184	1	16	0
17	Bhola Sadar	33844	488	1	2820	8	30348	90	188	1
18	Burhanuddin	23020	0	0	96	0	22456	98	468	2
19	Chakaria	38168	7220	19	8980	24	21964	58	4	0
20	Chandanaish	9400	4680	50	4704	50	16	0	0	0
21	Char Fasson	55360	0	0	652	1	48872	88	5836	11
22	Chitalmari	19304	19296	100	8	0	0	0	0	0
23	Chittagong Port	3532	456	13	356	10	2632	75	88	2
24	Companiganj	28564	0	0	216	1	16384	57	11964	42
25	Cox's Bazar Sadar	11564	4260	37	5284	46	1988	17	32	0
26	Dacope	73556	46428	63	26268	36	732	1	128	0
27	Dashmina	21948	0	0	1380	6	20468	93	100	0
28	Daulatkhan	15616	12	0	360	2	14264	91	980	6
29	Fakirhat	16056	15820	99	236	1	0	0	0	0
30	Galachipa	79580	264	0	17588	22	53044	67	8684	11

Table 5.3 (continued): Upazilas under inundation risk

SL No.	Name of Upzilla	Area, ha (excluding river)	Innundation							
			d*<=1m		1m>d*<=3m		3m>d*<=6m		d*>6m	
			Area, ha	%	Area, ha	%	Area, ha	%	Area, ha	%
31	Gaurnadi	14112	8536	60	5576	40	0	0	0	0
32	Gopalganj Sadar	36572	36548	100	24	0	0	0	0	0
33	Gosairhat	16072	556	3	13356	83	2056	13	104	1
34	Haim Char	9184	1976	22	5228	57	1980	22	0	0
35	Hatiya	51136	4	0	452	1	5144	10	45536	89
36	Hizla	21088	0	0	5796	27	14800	70	492	2
37	Jhalokati Sadar	18396	8084	44	10296	56	16	0	0	0
38	Kachua	12596	10080	80	2516	20	0	0	0	0
39	Kala Para	42672	10292	24	16316	38	15928	37	136	0
40	Kanthalia	15048	3868	26	11164	74	16	0	0	0
41	Kawkhali	6956	120	2	6740	97	84	1	12	0
42	Kotali Para	36284	36276	100	8	0	0	0	0	0
43	Koyra	121452	87248	72	32888	27	1116	1	200	0
44	Kutubdia	6712	0	0	304	5	6348	95	60	1
45	Lakshmipur Sadar	46072	5888	13	34636	75	5192	11	356	1
46	Lalmohan	27188	0	0	448	2	25056	92	1684	6
47	Maheshkhali	25460.03	9728	38	6272	25	9288	36	172	1
48	Manpura	12704	0	0	0	0	2760	22	9944	78
49	Mathbaria	32252	7368	23	24468	76	416	1	0	0
50	Mehendiganj	31344	68	0	9268	30	21716	69	292	1
51	Mirsharai	49004	16928	35	2984	6	19072	39	10020	20
52	Mirzaganj	15436	4944	32	10392	67	28	0	72	0
53	Mollahat	20308	20308	100	0	0	0	0	0	0
54	Mongla	125776	33492	27	81064	64	11008	9	212	0
55	Morrelganj	41720	12904	31	28780	69	32	0	4	0
56	Muladi	20196	188	1	18280	91	1668	8	60	0
57	Nalchity	22180	2592	12	19544	88	32	0	12	0
58	Nazirpur	21604	16068	74	5536	26	0	0	0	0
59	Nesarabad (swarupkati)	17228	6484	38	10724	62	20	0	0	0
60	Noakhali Sadar (sudharam)	91800	4	0	4080	4	63980	70	23736	26

Table 5.3 (continued): Upazilas under inundation risk

SL No.	Name of Upzilla	Area, ha (excluding river)	Innundation							
			d*<=1m		1m>d*<=3m		3m>d*<=6m		d*>6m	
			Area, ha	%	Area, ha	%	Area, ha	%	Area, ha	%
61	Paikgachha	35264	33008	94	2180	6	64	0	12	0
62	Patharghata	22708	6304	28	10488	46	5852	26	64	0
63	Patiya	26580	9600	36	14748	55	2180	8	52	0
64	Patuakhali Sadar	40496	9156	23	31132	77	180	0	28	0
65	Pirojpur Sadar	23592	2488	11	20776	88	264	1	64	0
66	Rajapur	15416	3976	26	11368	74	72	0	0	0
67	Ramgati	40208	0	0	1484	4	36140	90	2584	6
68	Rampal	31012	26908	87	4092	13	12	0	0	0
69	Ramu	100	0	0	56	56	44	44	0	0
70	Roypur	19968	7576	38	9024	45	3136	16	232	1
71	Rupsa	9016	7940	88	1076	12	0	0	0	0
72	Sandwip	23676	0	0	12	0	11772	50	11892	50
73	Sarankhola	63796	1184	2	33560	53	28768	45	284	0
74	Shyamnagar	120388	82856	69	36576	30	844	1	112	0
75	Sitakunda	24652	12040	49	2040	8	9396	38	1176	5
76	Sonagazi	19952	0	0	48	0	16616	83	3288	16
77	Tazumuddin	17888	0	0	40	0	9236	52	8612	48
78	Tungi Para	12248	12248	100	0	0	0	0	0	0
79	Wazirpur	24140	19076	79	5052	21	0	0	12	0

*d is the depth of innundation

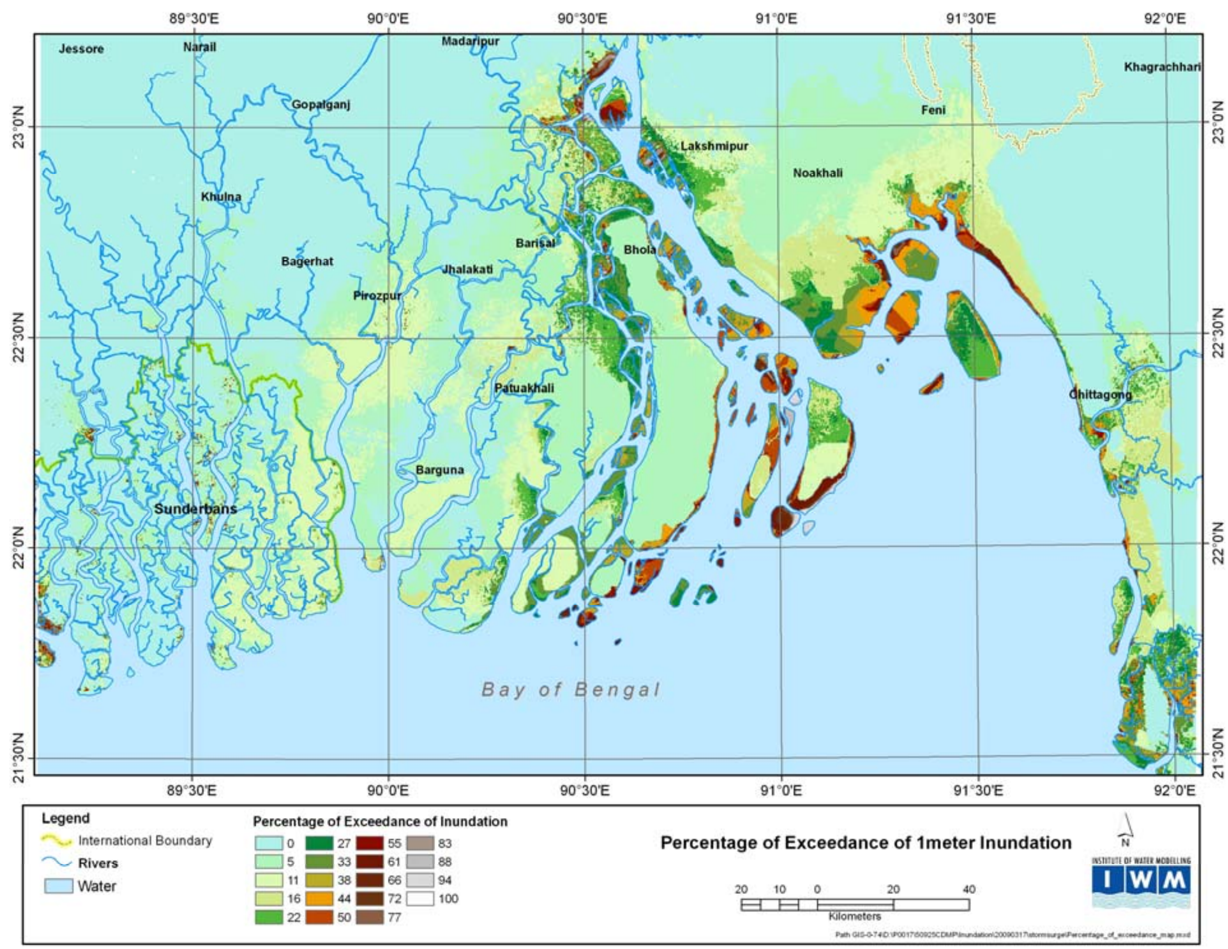

Figure 5.11: Probability of inundation (risk in percent) exceeding 1 meter inundation depth

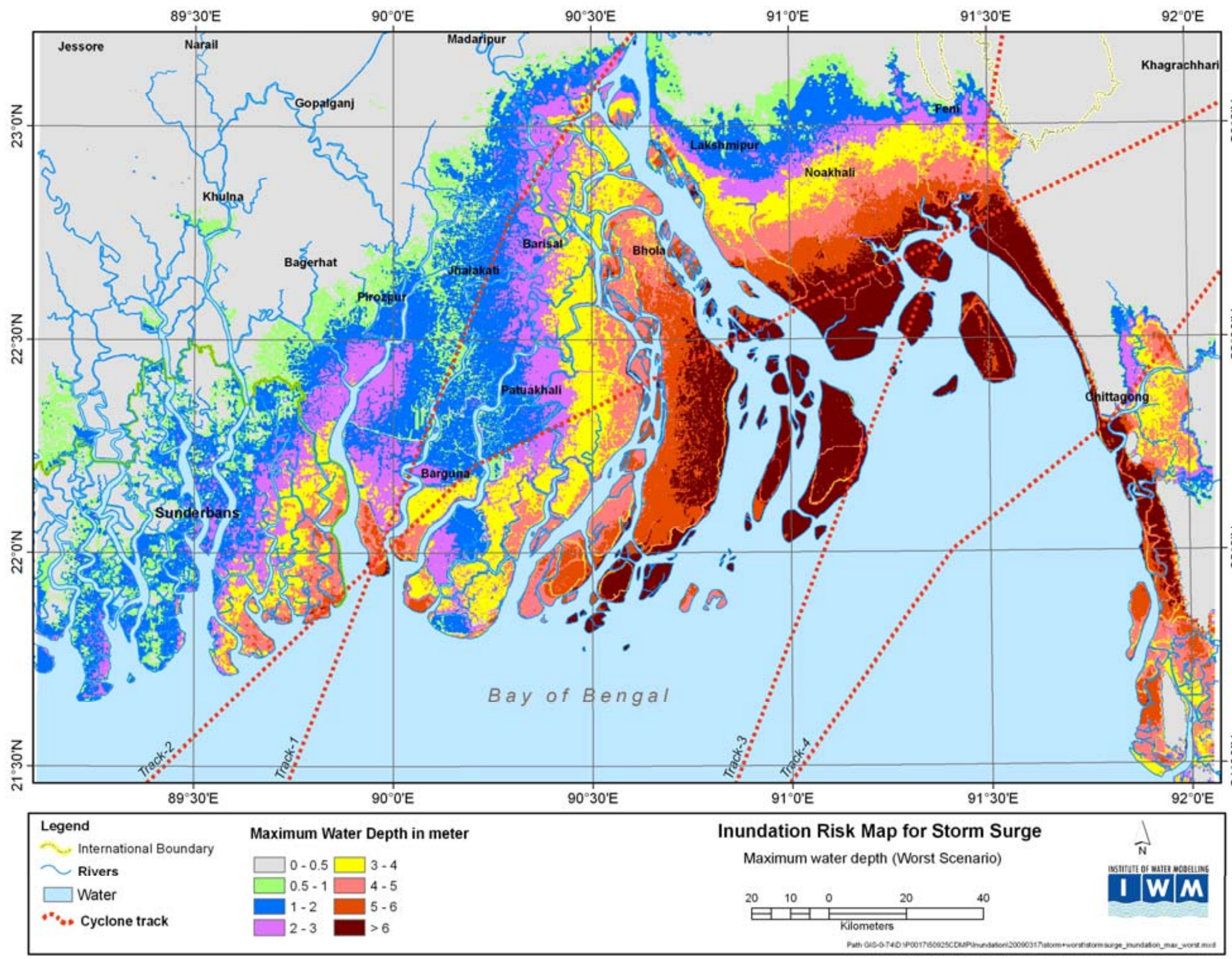

Figure 5.12: Inundation risk map generated from 18 cyclones from 1960-2007 and four synthesized cyclones

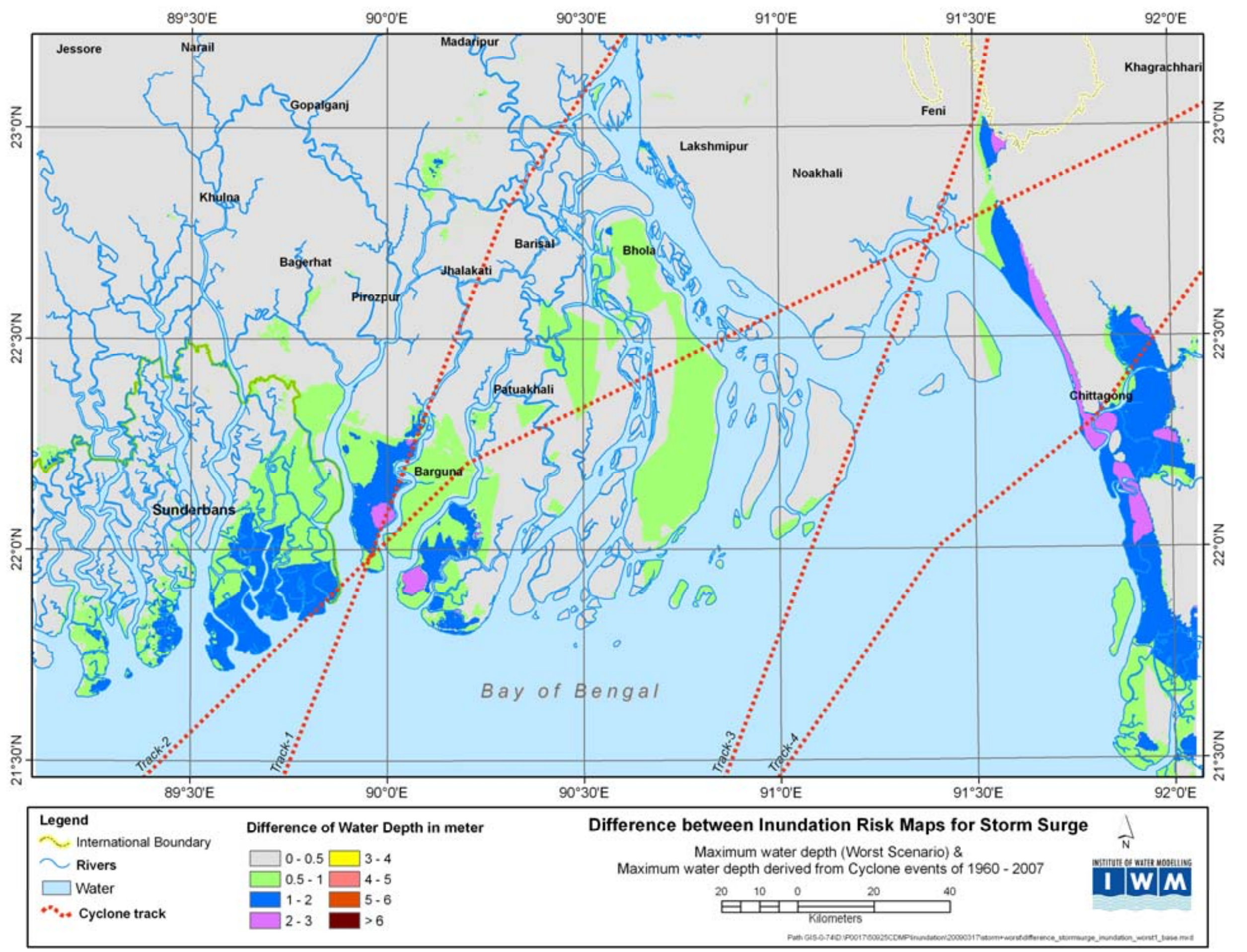

Figure 5.13: Difference map between the two inundation risk maps for storm surge

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

In this study inundation risk maps for tsunami and storm surge have been prepared for the entire coastal region of Bangladesh considering decay factor for landuse, geomorphology and slope. Two models have been used for preparation of the risk maps; one is the tsunami model developed under this study and another one is the existing Bay of Bengal model which is updated under this study and used for storm surge modelling. The available digital elevation model for the coastal area has been updated based on FINMAP topographic maps.

Tsunami wave decay primarily depends on the forces resisting the tsunami driving forces. Therefore the decay will depend on several factors including approach velocity, surface friction, land slope and geo-morphological characteristics. In this study a dimensionless expression for decay factor has been proposed, which can be used to calculate the decay factor for tsunami wave at different locations of the coastal region of Bangladesh.

Inundation Risk Map for Tsunami

Four (4) potential fault sources of earthquake which may trigger tsunami in the Bay of Bengal have been identified in this study based on the geophysical and geological data. A geological model named QuakeGen has been used for calculation of deformation in bed level based on the geophysical and seismological data. Initial surface level of tsunami has been generated using hydrodynamic module of MIKE 21 modelling system of $DHI_{Water.Environment.Health}$ using the output of QuakeGen model.

A tsunami model has been developed for the Indian Ocean, the Arabian Sea, the Bay of Bengal and the coastal region of Bangladesh using MIKE21 modelling system. The model has been calibrated with the tsunami of December 26, 2004, which occurred at the West Coast of Sumatra due to the earthquake. The model has been applied to simulate the tsunami propagation and inundation from its sources to the coast of Bangladeshi.

Inundation risk map for the coastal region of Bangladesh has been prepared based on the four scenarios of tsunami originated from four potential sources of earthquake in the Bay of Bengal. Initially all the tsunamis generated from the potential sources have been simulated using MIKE 21 modelling system. Maximum inundation maps for all of the tsunami events have been generated from the simulation results under Mean High Water Spring (MHWS) tide condition. Finally the inundation risk map has been generated based on the maximum inundation maps using GIS tool.

The inundation risk map for tsunami shows that Sundarban area, Nijhum Dwip, south of Hatia (outside polder) and Cox's Bazaar coast get inundated during tsunami. Maximum inundations have been found at Nijhum Dwip in the range of 3-4 m, and at Sundarban area, Moheskhali and Cox's Bazar coast in the range of 1-3 m. Small islands and part of the Manpura island in the Meghna Estuary get inundated by 1-3 m. The maximum inundation in the other locations remains within 1-2 m, which are mainly due to the MHWS tide. Bauphal upazila under Patuakhali district is one of them.

Inundation Risk Map for Storm Surge

The coastal area of Bangladesh is frequently visited by the cyclone-induced storm surge. During the last 48 years eighteen (18) major cyclones devastated the coastal area. Under the present study an inundation risk map for the coastal region of Bangladesh has been prepared based on the simulation results of the eighteen major cyclones.

The inundation risk map shows that the highest inundation depth having range between 5m and 7m lies in the Noakhali coast, Bhola, Urir Char, Sandwip and small islands in the Meghna Estuary. The eastern coast experiences maximum inundation between 4m and 6m and western coast experiences inundation within the range of 3 to 5 m.

A statistical analysis has been carried out with the maximum inundation maps of 18 cyclones in order to find the probability of inundation depth of different magnitude. Probability of inundation exceeding 1 m inundation depth shows that Urirchar, Nijhum Dwip, Noakhali coast, Shitakunda coast and the small islands of the Meghna Estuary are likely to be inundated by more than 1 meter with a probability of 50%. The Cox's Bazar Area is likely to be flooded with a probability of 30 % time. The risk of inundation of Anwara by 1 meter inundation depth is 15%.

Four worst case scenarios of cyclone-induced storm surge have been developed considering wind and pressure field of SIDR 2007, four different tracks covering different coasts of Bangladesh and landfall during high tide. Another risk map has been generated based on 18 real cyclones and four synthesized cyclones. It shows that inundation increases at the Sundarban coast and around Baleshwar River by 1-2 m, at Bhola island by 0.5-1 m, at Sitakunda coast by 2-3m, at Anwara and around the Karnaphuli River mouth by 2-3 m, at Bashkhali by 1-2 m, at Kutubdia island by 0.5-1 m, and at Cox's Bazar by 0.5-1 m.

6.2 Recommendation

- There is a need of improvement of digital elevation model on the basis of new topographic survey data and the storm surge model with the updated bathymetry;

- Identification of location of additional potential sources of tsunami and assessment of vulnerability of coastal area;

- The frequency and intensity of cyclone is likely to be increased due to climate change in accordance with the 4th IPCC report. It is also important to find the storm surge height considering the combined effect of sea level rise and climate change; and

- The forecasting of inundation depth at local level is very important for early warning and disaster preparedness along the Bay of Bengal and coastal area of Bangladesh for reduction of loss of life and property. The available Bay of Bengal Model, with further improvement, is also capable of forecasting the surge height and coastal flooding at local level. It is of immense importance to develop operational frameworks for sustainable coordination, collaboration and information sharing and management across DMB, BMD, FFWC, IWM and with main disaster management stakeholders during storm surge induced flooding.

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