Masters Program in **Geospatial Technologies**

Integrated Approach to Assess Vulnerability of the Coastal Region of Bangladesh due to Climate Change

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Integrated Approach to Assess Vulnerability of the Coastal Region of Bangladesh due to Climate Change

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Author's Declaration

This is to certify that, this research work is entirely my own and not of any other person's, unless explicitly acknowledged (including citation of published and unpublished sources). All views and opinions expressed therein remain the sole responsibility of the author, and do not necessarily represent those of the institutes.

It is hereby also declared that this dissertation or any part of it has not been submitted elsewhere for the award of any degree or diploma.

ARFANARA NAJNIN

February 28, 2014

Dedication

I wish to dedicate this research work to

My beloved Parents,

Md. Ashraful Alam

and

Mrs. Ayesha Alam

Abstract

The coastal zone of Bangladesh is characterized by an evolving flat delta subject to very high tides and frequent cyclones coming from the Bay of Bengal. People in coastal region in Bangladesh are under threat to climate change and are becoming vulnerable, leading to relatively higher poverty than the other parts of the country. Potential impacts of sea-level rise in coastal zone include shoreline erosion, saltwater intrusion, inundation of wetlands and estuaries, threats to cultural and historic resources along with infrastructures. The primary objective of this research is to simulate and calculate a Population Vulnerability Index (PVI) Model of the coastal zone of Bangladesh to assess the coastal exposure and vulnerability due to natural calamities. Another objective is to evaluate model sensitivity to different scenarios of inundation and change of natural habitats. Seven geophysical and climatic parameters i.e., relief, wind speed, wave exposure, surge height, tidal water depth, population density and natural habitats has been considered to simulated the model. Water depth has been calculated from the tidal gauge water level dataset and interpolated to know the inundated area. All the parameters have been pre-processed, analysed, normalized (rescaled) and ranked from low to high vulnerability ranges from 1 to 5. Firstly the Coastal Vulnerability Index (CVI) Model has been simulated and the final PVI model has been calculated by multiplying all the parameters. After that, PVI^7 model has been evaluated by considering different scenario of water depth and presence and absence of natural habitat (mangrove forest). Finally the impact on coastal population has been identified from the PVI model and land use information of the study area. The study outcome shows that north-western part of the study area (Shatkhira district) is highly vulnerable to climate change. High densely populated area is high exposed to climatic hazards and around 434.88sq.km area is highly vulnerable to climate change issues. Most of the area is moderately exposed to natural calamities. This research approach can be applied other coastal areas at the regional scale to identify the climatic impact on the coastal community in a simple way for future development and planning by the scientists, researchers and decision makers.

Key Issues: Climate Change, Sea Level Rise (SLR), Mangrove Forest, Marine InVEST Model, Geographic Information System (GIS), Coastal Vulnerability, Coastal Population.

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Abbreviation and Acronyms

ANN	Artificial Neural Network
ANFIS	Artificial Neuro-Fuzzy Inference System
AOI	Area of Interest
BBS	Bangladesh Bureau of Statistics
CCC	Climate Change Cell
CEI	Coastal Exposure Index
CEGIS	Centre for Environmental and geographic information Services
CVI	Coastal Vulnerability Index
CZMAI	Coastal Zone Management Authority and Institute
DEM	Digital Elevation Model
EEZ	Exclusive Economic Zone
GBM	The Ganges, the Brahmaputra, and the Meghna
GCM	Global Circulation Model
GIS	Geographic Information System
GMSL	Global Mean Sea Level Rise
GPW	Gridded Population of the World
ICZMP	Integrated Coastal Zone Management and Planning
InVEST	Integrated Valuation of Environmental Services and Trade-offs
IPCC	Inter-Governmental Panel of Climate Change
LDCs	Least Developing Countries
MES	Meghna Estuary Study
ME	Mean Error
MHVM	Multi-Hazard Vulnerability Maps
MSL	Mean Seal Level
NAPA	National Adaptation Programme of Action

NatCap	Natural Capital Project
NCCOE	National Committee on Coastal and Ocean Engineering
NWRD	National Water Resources Database
PVI	Population Vulnerability Index
RCPs	Representative Concentration Pathways
RMSE	Root Mean Squared Error
RSL	Relative Sea Level
RS	Remote Sensing
SIZ	Sundarban Impact Zone
SLR	Sea Level Rise
SRTM	Shuttle Radar Topography Mission
UNFCCC	United Nations Framework Convention on Climate Change
UNEP	United Nation Environment Programme
USGS	U.S. Geological Survey
WAPO	Water Resources Planning Organization
WAIS	West Antarctic Ice Sheet
WCA	West Coast Aquatic Management Board
WGII	Working Group II
WL	Water Level
WMO	World Meteorological Organization
WWIII	WAVEWATCHIII

Chapter 1
Introduction

1.1 Research Background

In general climate change is the change of natural environment due to global warming, sea level rise etc., is an emerging issue all over the world. Climate change has adverse impact on the livelihoods, agricultural sector, fisheries, forestry's, marine life etc. Also it will eventually create risk for poverty and food security (Laila 2013). Climate change affects the national development and it has the possibility to slow down nations' abilities to achieve sustainable development. Coastal regions are associated with high economic value and income generation as they offer work opportunities for people. Potential impacts of sea-level rise (SLR) in coastal zone include shoreline erosion, saltwater intrusion into groundwater aquifers, inundation of wetlands and estuaries, threats to cultural and historic resources along with infrastructures. Small Island in the Pacific, Indian, and Atlantic Oceans, often with low elevation, are particularly vulnerable to sea level rise and climate change impacts. These impacts can result of ecosystem disruption, decreased agricultural productivity, changes in disease patterns, economic losses and population displacement - all of which reinforce vulnerability to extreme weather events. Some remedial measures and initiatives that reduce exposure and vulnerability across a range of hazard trends such as maintenance of drainage systems, well technologies to limit saltwater contamination of groundwater, improved early warning systems, regional risk pooling, mangrove conservation, restoration and replanting etc., (IPCC 2012).

Marine and coastal ecosystems in Asia are highly affected by sea-level rise and temperature increases. The ecological stability of mangroves and coral reefs around Asia is at risk. Projected SLR is very likely to result in significant losses of coastal ecosystems and a million or more people along the coasts of South and South-East Asia will likely be at risk from flooding. Global mean sea level has risen approximately 1.7 [1.5 to 1.9] mm between 1900 and 2010 for a total sea level rise of 0.19 [0.17–0.21] m. The global mean sea level has accelerated since the early 1900s, with estimates ranging from 0.000 to 0.013 [–0.002 to 0.019] mm yr^{-2}. The two major contributions to the 20th century global mean sea level rise (GMSL) is the thermal expansion and glacier melting with additional contributions from Greenland and Antarctic ice-bars. It is noticed that anthropogenic force has substantial contribution to Upper Ocean warming (above 700 m) observed since the 1970s. This anthropogenic ocean warming has a great contribution to global sea level rise over this period through thermal expansion. Climate models predict an additional rise of 0.62 [0.45 to 0.81] m by 2081 to 2100 based on RCP[1]8.5 scenario, which is more than double the rate of rise for the 20th century (IPCC 2013).

According to the global climate change risk index, Bangladesh is one of the highly vulnerable countries for climate change because of its flat and low-lying topography; high population density; high levels of poverty; reliance of many livelihoods on climate sensitive sectors, particularly agriculture, fisheries and water resources. Thus climate change tends to possess significant risks for the country. Between 30-70% of the country is normally flooded each year. The huge sediment brought by three Himalayan rivers, coupled with a negligible flow gradient add to drainage congestion problems and worsen the extent of flooding (CEGIS 2012).

A number of predictive approaches including: 1) extrapolation of historical data (e.g., coastal erosion rates), 2) inundation modelling 3) application of simple geometric model 4) application of sediment dynamics model or 5) Monte Carlo (probabilistic) simulation based on parameterized physical forcing variables were proposed to assess coastal vulnerability. However, each of these approaches has inadequacies or can be invalid for certain applications (N.R.C. 1990; N.R.C 1995; Pendleton, Thieler et al. 2004). Moreover, shoreline response to sea-level change is further complicating by human modifications of the natural coast such as beach nourishment projects and engineering structures such as seawalls, revetments, groins, and jetties. It is essential to know how a natural or modified coast will respond to sea-level change to preserving vulnerable coastal resources. Climate change is the greatest environmental challenge facing the all over the world today. If the global temperatures rise it will bring changes in weather patterns, rising sea levels and increased frequency and intensity of extreme weather events. A 1 m SLR could inundate 17% of the land of Bangladesh (Secretariat. 1989). The floods of 1987 and 1988 proved its devastating

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[1]RCPs (Representative Concentration Pathways) scenarios for the period of 2081–2100, which is an outcome of the integrated modelling approaches, the global mean sea level rise will be 0.26–0.54 m for RCP2.6, 0.32–0.62 m for RCP4.5, 0.33–0.62 m for RCP6.0, and 0.45–0.81 m for RCP8.5. IPCC (2013). Climate Change 2013: The Physical Science Basis. Working Group I Contribution to the IPCC Fifth Assessment Report, Final Draft Underlying Scientific-Technical Assessment. Stockholm.

impact to Bangladesh, forcing millions of people to the open field from their homes for long periods of time (IPCC 1990).

Exposure and vulnerability are dynamic, varying across temporal and spatial scales, and depend on economic, social, geographic, demographic, cultural, institutional, governance, and environmental factors (IPCC 2012). Mapping vulnerability is one item which can be resolved using a combination of Earth observation data, GIS data and local knowledge. Deriving land use information from multi temporal satellite imagery is a direct method. Existing GIS data e.g. land use, road networks and river networks can be overlaid with the earth observation derived information to present a visualization of the terrain and to analyse and simulate various scenarios. Collection of detail base data and information with high resolution satellite image is a major concern in most of the cases which would not be available for all regions especially in developing worlds.

1.2 Aim and Objectives

The aim of this research is to simulate and calculate Population Vulnerability Index Model (PVI) to assess the vulnerability of coastal community due to climate change and sea level rise. Therefore the present research will try to achieve the following three broad objectives:

- Simulate and calculate Population Vulnerability Index Model (PVI) of the coastal zone of Bangladesh,
- Evaluate model sensitivity to different scenarios of inundation and change of natural habitats,
- Identify the most vulnerable coastal communities due to natural calamities.

1.3 Research Questions and Hypotheses

The preliminary assumption of the research is that densely populated areas are more vulnerable to climatic hazards; where coastal mangrove forest plays a vital role in coastal protection and management. The following research questions have been considered to fulfil the above mentioned research objectives:

- How exposed is the coast to the effects of climate change?
- What will happen with and without mangrove?
- Where are people highly vulnerable to coastal cyclones and flood inundation?

1.4 Problem Statement

According to IPCC Third Assessment Report, South Asia is the most vulnerable region of the world to climate change impacts (McCarthy, Canziani et al. 2001). The international community also recognizes that Bangladesh ranks high in the list of most vulnerable countries on earth (Ahmed 2006). Bangladesh's is highly vulnerable to climate change due to a number of hydro-geological and socio-economic factors that include: (a) its geographical location in South Asia; (b) its flat deltaic topography with very low elevation; (c) its extreme climate variability that is governed by monsoon which resulting in acute water distribution over space and time; (d) its high population density and poverty incidence; and (e) its majority of population being dependent on agriculture which is highly influenced by climate variability and change .

The coastal region of Bangladesh is endowed with the largest mangrove forest in the world, a resource that displays a rich biodiversity (WARPO 2005). Agricultural, industrial, commercial, recreational, leisure activities and tourism, marine fishing and associated activities are all carried out in this region. Unplanned use of coastal resources may cause the destruction of ecological balance, pollution and degradation of land and water quality. Recent studies show that frequencies of natural hazards have increased in Bangladesh, affecting especially coastal areas and their communities (BCCSAP 2009). Many areas in Bangladesh are clearly under threat of climate change and people in the coastal region are becoming vulnerable, leading to relatively higher poverty than the other parts of the country (Hossain, Hossain et al. 2012). Scientists predict that, sea level rise will intensify wetland loss, saltwater intrusion in the low laying coasts and the problems caused by waves, storm surges, and shoreline erosion (Gilmer and Ferdaña 2012). The ability to accurately identify low-lying lands is critical for assessing the vulnerability of coastal regions. To do this, coastal managers need to know the height or area elevation and other coastal zone information, but these data and information are not always available with appropriate resolutions for making state and regional governance decisions on climate change and adaptation. According to IPCC fourth assessment report data on disasters and disaster risk reduction are lacking at the local level, which can constrain improvements in local vulnerability reduction (IPCC 2012). As a justification of the above statement we have chosen the coastal belt of Bangladesh, where regular and updated data availability is too difficult due to lack of regular monitoring and management action plan. It is particularly difficult to assess the potential impacts consistently for all coastal regions. The Miami and Perth IPCC coastal workshops suggested that sea-level rise would also threaten Oceanside development in Portugal, Brazil, Nigeria, Thailand and most other nations with tourist beaches. In 1987, for example, flood crests of the Ganges and Brahmaputra rivers coincided in Bangladesh, inundating about one third of the country and forcing tens of millions of people from their homes. In addition, about ten million people live on land that lies within 1 m of mean sea-level near the coast (IPCC 1990).

Bangladesh is one of the most densely populated countries in the world where 28% of the population living in the coastal area (PDO-ICZMP 2004) is victim of frequent natural calamities like tropical cyclones, tornadoes, floods, storm surges and droughts. Sea level rise (SLR) due to climate change has also been included as an additive in these natural calamities. The low-lying topography, funnel shaped coast exposing the land to cyclones and tidal surges, seasonal flooding, widespread poverty, large population base, poor institutional development etc. have particularly made Bangladesh coastal zone vulnerable to climate change. Most of the land area of Bangladesh consists of the deltaic plains of the Ganges, Brahmaputra and Meghna rivers. Accelerated global sea level rise and higher extreme water levels may have acute effects on populations of Bangladesh. Sea-water intrusion due to sea-level rise and declining river runoff is likely to increase the habitat of brackish water fisheries but coastal inundation is likely to seriously affect the aquaculture industry and infrastructure particularly in heavily-populated mega deltas (IPCC 2007). Coastal regions are constantly subject to the action of ocean waves and storms and naturally experience erosion and inundation over various temporal and spatial scales (Westmacott 2001). Faced with a changing climate and a growing intensity of human activities, coastal communities must better understand how modifications of the biological and physical environment (i.e. direct and indirect removal of natural habitats for coastal development) can affect their exposure to storm-induced erosion and flooding (inundation)(Ramieri, Hartley et al. 2011).

A number of previously published studies examined the potential impacts of climate change on Bangladesh assuming certain change in the climate and corresponding SLR. Some of the studies show that following a rise of 1 (one) meter in the sea level, Bangladesh would face a catastrophic situation, including permanent inundation of about 15%-18% of its low-lying coastal areas, loss of Sundarbans (large mangrove forest), displacements of over 10 million people and loss of vulnerable agricultural land and extended Salinity intrusion (Agrawala, Ota et al. 2003). These studies identified critical impacts on drainage congestion problem, reduction in fresh water flow, and disturbance of morphologic processes, increase intensity of disasters.

For designing and implementing effective adaptation and disaster risk management strategies vulnerability reduction is a core common element of adaptation and disaster risk management (IPCC 2012). The target of this research is to develop and validate the methods used in InVEST tool in ArcGIS interface to assess the coastal exposure and vulnerability due to potential sea level rise which will be able to support the future decision making process. The InVEST (Integrated Valuation of Environmental Services and Trade-offs) Coastal Vulnerability model produces a qualitative estimate of such exposure in terms of a Vulnerability Index, which differentiates areas with relatively high or low exposure to erosion and inundation during storms (Project 2012). By coupling these results with regional population information, the model can show areas along a given coastline that are most vulnerable to storm waves and surge. Different types of modelling tools and techniques have been introduced before but most of them are commercial and required expert knowledge. One of the strong foundations of InVEST model is completely open sourced and easily available.

1.5 Study Area at a Glance

The low lying delta Bangladesh (24° 00' North latitude and 90° 00' East longitude) is formed by the interaction of the very large summer discharges of both water and sediment from the Ganges, Brahmaputra (Jamuna) and Meghna Basins with the tides in the Bay of Bengal which could vary in range from 3 m in the west to nearly 6 m in the north-eastern corner of the Bay near Sandwip (sub-district). 147 Thanas (sub-districts) of 19 districts of the southern part of the country and the Exclusive Economic Zone (EEZ) in the Bay of Bengal constitute the coastal zone of Bangladesh. This part of the country are full of natural resources, but unlike most other areas faces vulnerabilities like cyclones, storm surges etc. Figure 1.1 portraits the overview of the study area.

Table 1.1: Bangladesh, Country Profile

Features	Descriptions
Country Total Area:	147,570 km^2 (Land: 81%; Forest: 13.4%, Water body: 5.6%)
Land Area:	119,624 km^2 (Floodplain: 80%; Hill: 12%; Terrace: 8%)
Population:	143.5 million (Average density: 964 persons/sq. km in 2011)
Area of coastal zone:	47,201 km^2 (32% of land area of Bangladesh)
Population in coastal zone:	33.85 million (27% of total population)
Length of the coast:	710 km

Source: Bangladesh Bureau of Statistics (BBS), 2011

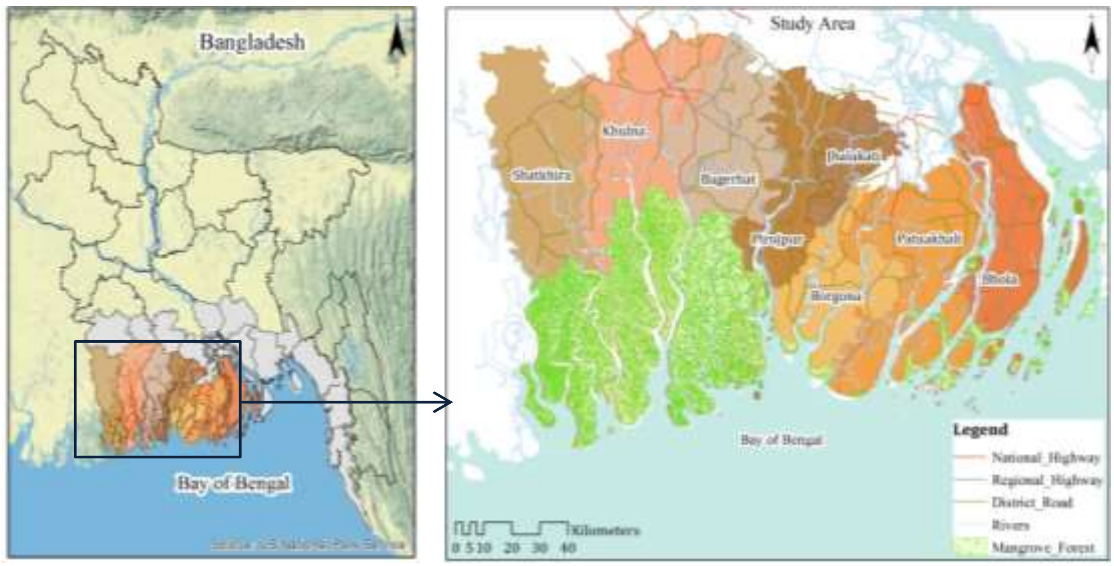

Figure 1.1: Synopsis of the study area with rivers, road networks and forests

Based on emerging insights from some climate model experiments as well as the empirical record, the IPCC third assessment concludes that: "the peak intensity of regional tropical cyclones may increases by 5% to 10% and precipitation rates may increase by 20% to 30%" (IPCC 2001). Even this tentative assessment has several major implications for Bangladesh. First, there is no reason to assume that cyclone tracks will shift under climate change – meaning that Bangladesh is likely to expect to continue to be hit with. The possibility of an increase in peak intensities may increase by 5-10% has potentially serious implications for a country already vulnerable to storm surges driven by strong winds (Agrawala, Ota et al. 2003).

The coastal zone is characterized by a delicately balanced natural morphology of an evolving flat delta subject to very high tides and frequent cyclones coming from the Bay of Bengal with a large volume of sediment inflowing from upstream. The strength of the tides and the flatness of the delta causes the tides to influence river processes a long way upstream in the southern estuaries. This entire area is called the coastal zone. The coastal zone, in its natural state, used to undergo to inundation by high tides, salinity intrusion, cyclonic storms and associated tidal surges.

Depending on the geo-morphological features, the coastal areas of Bangladesh can broadly be divided into three distinct regions namely- western, central, and eastern coastal zones. The western part, also known as the Ganges tidal plain, comprises the very low and flat, semi active delta and is criss-crossed by numerous channels and creeks. The south-western part of the region is covered by the largest mangrove forest of the world. The central region is the most active one, with continuous processes of accretion and erosion. The very active Meghna River estuary lies in the region. This estuarial region has seen the most disastrous effects of tropical cyclones and storm surges in the world. The eastern region, being covered by hilly areas, is more stable, and it has one of the longest beaches in the world (CCC 2009). For the purpose of this study the western and central part of the coastal zone constitutes with 8 (eight) districts such as Jhalokati, Pirojpur, Bhola, Barguna, Patuakhali, Bagerhat, Khulna, Satkhira with 54 Thana's among the 19 (nineteen) district from whole coastal area has been selected. The zone has been selected based on the area which is sea fronting and mostly low lying. A glimpse of the study area briefly described in chapter four (Study Area Profile).

Table 1.2: Characteristics of the coastal region in Bangladesh

Zone	Characteristics
Western Coastal Zone	◆ The entire area is floodplain of the Ganges river (Ganges Tidal Plain) ◆ Contain the famous world largest natural mangrove forest (6017 km^2) ◆ Average land elevation is below 1.5 m MSL ◆ The area suffers from severe salinity intrusion and tidal flooding
Central Coastal Zone	◆ This area is the floodplain of Ganges and Meghna rivers ◆ This area suffers from continuous erosion and accretion ◆ The most dynamic Meghna estuary is located in this region
Eastern Coastal Zone	◆ This area possesses higher land elevation and is covered by hilly region ◆ It is the most stable part of country's coastal zones ◆ The world longest natural beach (120 km) is located in this region

Sources: (Karim and Mimura)

1.6 Structure of the Report

This research report comprised with seven chapters including a list of references and appendixes mentioned in the report. A list of acronyms and abbreviations used in the report has been presented following the abstract. The abstract gives an overall explanation of the study for the populace seeking to have a glimpse of the research work.

Chapter 1 Introduction

Chapter one highlights the overall study background, problem statement, aim and objectives with a brief description of the study area. It also includes overall structure of the report.

Chapter 2 Theoretical Framework

Chapter two contains an extensive review of the reports, journals and research works from the previous studies related with the present research issues.

Chapter 3 Approach and Methodology

Chapter three reflects the overall approach and methodology of the research including data requirement, data collection from various secondary sources such as tidal water level, wind, wave etc., and the information based on population census, Digital Elevation Model, study area land use map. Tools and techniques used to reach the target of the research have been briefly described in this chapter.

Chapter 4 Study Area Profile

Chapter four contains the glimpse of the study area that includes the demography, physiography, climate and meteorology; hydrology and river system; past natural hazards due to climate change etc. The key climatic variables used to simulate the model has also described in this chapter.

Chapter 5 Coastal Vulnerability Model Simulation and Analysis

Chapter five reflect in detail the coastal vulnerability modelling approaches such as fetch calculation, simulation and calculation of Population Vulnerability Index (PVI). It also contains the base data preparation and pre-processing activities such as DEM pre-processing, population grid calculation, selection of AOI etc. This chapter also reflects the process of sensitivity analysis of the PVI model. The area with highly vulnerable people has been illustrated here as the major study findings.

Chapter 6 Discussion and Critical Review

This chapter reflect the discussion on major study findings and critical review based on study approach and method.

Chapter 7 Conclusion and Further Research

This chapter reflects the conclusions based on study findings. Also some recommendations for further research work focused on the study have also been provided in this chapter.

Bibliography and Appendixes

All references and citations used in the whole study have been provided in the bibliographic References section. Some detail descriptions on data and information, maps and methods have been illustrated in the appendix section.

Chapter 2
Theoretical Foundation

2.1 Related Concepts of Vulnerability to Climate Change

2.1.1 Climate change

Climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcing such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in land use (IPCC 2013).

According to the United Nations Framework Convention on Climate Change (UNFCCC), climate change is defined as: “a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods.” The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition, and climate variability attributable to natural causes. Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all spatial and temporal scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability) (IPCC 2012; IPCC 2013).

2.1.2 Exposure and Vulnerability

A potential impact of climate change refers to all impacts that may occur given a projected change in climate, without considering adaptation (IPCC 2007). Exposure and vulnerability are key determinants of disaster risk and of impacts when risk is realized. Generically, vulnerability is a set of conditions and processes resulting from physical, social, economic and environmental factors that increase the susceptibility of a community to the impact of hazards.

The term Exposure means the presence of people; livelihoods; environmental services and resources; infrastructure; or economic, social, or cultural assets in places that could be adversely affected (IPCC 2012).

Vulnerability refers to “the degree to which a system is susceptible to and unable to cope with adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity” (IPCC 2007). Recently IPCC definition of vulnerability is the propensity or predisposition to be adversely affected (IPCC 2012).

Vulnerability assessment is an estimate of the degree of loss or damage that could result from a hazardous event of given severity, including damage to structures, personal injuries, and interruption of economic activities and the normal functions of settlements (Mahendra, Mohanty et al. 2011).

2.1.3 SLR (Sea-level rise)

The height of the ocean surface at any given location, or sea level, is measured either with respect to the surface of the solid Earth RSL (relative sea level) or a geocentric reference such as the reference ellipsoid (geocentric sea level). RSL is the more relevant quantity when considering the coastal impacts of sea level change, and it has been measured using tide gauges during the past few centuries and estimated for longer time spans from geological records Geocentric sea level has been measured over the past two decades using satellite altimetry (IPCC 2013).

Local sea level change differ from the global average because shifting surface winds, the expansion of warming ocean water, and the addition of melting ice can alter ocean currents which, in turn, lead to changes in sea level that vary from place to place. Past and present variations in the distribution of land ice affect the shape and gravitational field of the Earth, which also cause regional fluctuations in sea level. Additional variations in sea level are caused by the influence of more localised processes such as sediment compaction and tectonics (IPCC 2013). Sea-level rise an increase in the mean level of the ocean eustatic sea-level rise is a change in global average sea level brought about by an increase in the volume of the world ocean. Relative sea-level rise occurs where there is a local increase in the level of the ocean relative to the land, which might be due to ocean rise and/or land level subsidence. In areas subject to rapid land-level uplift, relative sea level can fall (IPCC 2007).

2.1.4 GIS

Geographic Information System (GIS) is a set of computer tools designed to efficiently capture, store, update, manipulate, analyse and display all forms of geographically referenced information (ESRI 1992). Now a day GIS and GI Science plays a vital role to understood the spatial distribution pattern of natural phenomenon and climatic variables and analysing them in different perspectives.

2.1.5 InVEST Model

Integrated Valuation of Environmental Services and Trade-offs (InVEST) is a free and open-source software suite to inform and improve natural resource management and investment decisions developed by The Natural Capital Project (NatCap), Stanford University, USA. InVEST quantifies, maps, and values the goods and services from nature that contribute to sustaining and fulfilling human life. The models account for both service supply (e.g. living habitats as buffers for storm waves) and the location and activities of people who benefit from services (e.g. location of people and infrastructure potentially affected by coastal storms). InVEST models can be run independently, or as script tools in the ArcGIS Arc Tool Box environment (NatCap 2007).

The GIS based 'Marine InVEST Coastal Vulnerability Model' produce a population map and a physical exposure map. It used the key physical and biological factors that increase or help to reduce the exposure. Marine InVEST Model is a decision-making tool for mapping and valuing ecosystem services provided by coasts and oceans. Marine InVEST provides diversified outputs such as:

- biophysical outputs (e.g., reduction in height of storm waves by living habitats),
- ecosystem service outputs (e.g., reduction in flooding of property),
- Economic or social outputs (e.g., number of people affected) (NatCap 2013).

Geomorphology or shoreline characteristics such as estuary or delta, natural habitats (mangrove forest, rocky cliff, coastal forest, coral reefs etc.), wind speed and wave direction, SLR are the main factors that have been consider running the model. Rocky cliffs are less prone to erosion than the beaches or deltas. Also the mangrove forest mitigates the vulnerability by reducing the wave induced current speed. If the geomorphology is lower than 1 in ranking the habitat and forcing factor are taken into consideration because geomorphology itself protect the site against erosion and inundation.

The model output try to evaluate how some management action can reduce or increase vulnerability of population in a specific region due to storm surge and sea level rise. The theoretical basis of the model is simple enough to be run by the scientist of various backgrounds.

2.1.6 Adaptation

In human systems, the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate (IPCC 2012).

2.2 Review on Prior Works and Literature

Many researchers have been carried out number of researches to detect the impact of sea level change on marine and coastal ecosystem and coastal community over time and predict the vulnerability and future scenarios of coastal areas. They have introduced and applied different new or existing techniques and methods to achieve the research objectives. Some examples are as follows:

2.2.1 Global level study

IPCC scenarios based on impact of SLR on Marine and Coastal region

An extensive review on recent reports and publications on IPCC (Intergovernmental Panel on Climate Change) has been carried out to know the real scenario of global and regional sea level rise and its impact on coastal area all over the world. In response to growing international concerns about threat to climate change in 1988 the World Meteorological Organization (WMO) and United Nation Environment Programme (UNEP) jointly establish the IPCC.

During the review stage the latest IPCC 5th assessment report on *Climate Change 2013: The Physical Science Basis* contributed by the working group I have been collected. The next Report on "*Climate Change 2014: Impacts, Adaptation and Vulnerability*" of Working Group II (WGII) contribution to the Fifth Assessment Report will be considered in Yokohama, Japan, on 25-29 March 2014.

In IPCC 5th Assessment Report *on* ***"Climate Change 2013: The Physical Science Basis"*** contributed by Working Group I has clearly defined that, the Antarctic Ice Sheet represents the largest potential source of future SLR; the West Antarctic Ice Sheet (WAIS) alone has the potential to raise sea level by ~4.3 m. In fact, such melting results in regional variations in sea level due to a variety of processes, including changes in ocean currents, winds, the Earth's gravity field, and land height. For example, computer models that simulate these latter two processes predict a regional fall in relative sea level around the melting ice sheets, because the gravitational attraction between ice and ocean water is reduced, and the land tends to rise as the ice melts and regional seal level is differs from the global sea level change. In summary, a variety of processes drive height changes of the ocean surface and ocean floor, resulting in distinct spatial patterns of sea level change at local to regional scales (IPCC 2013; IPCC 2013).

According to Boening et al. (2012) the decrease in GMSL over 2010–2011 followed by a rapid increase since 2011 was related to the 2011 La Niña event, whereby changes in land/ocean precipitation patterns caused a temporary increase in water storage on the land (and corresponding decrease in GMSL) especially in Australia, northern South America, and southeast Asia.

According to ***5th Assessment Summary Report of IPCC*** "the mean sea level rise will contribute to upward trends in extreme coastal high water levels in the future". Over the period 1901–2010, global mean sea level rose by 0.19 [0.17 to 0.21] m. For the Fifth Assessment Report of IPCC, the scientific community has defined a set of four new scenarios, denoted RCPs (IPCC 2013).

Global mean sea level rise for 2081−2100 relative to 1986–2005 ranges has been described in table 2.1 according to RCP scenarios.

Table 2.1: RCPs scenarios of Global Mean Sea Level Rise

Global Mean Seal Level Rise (m)	**Scenarios**	**Mean**	**Likely range**	**Mean**	**Likely range**
		2046–2065		**2081–2100**	
	RCP2.6	0.24	0.17 to 0.32	0.40	0.26 to 0.55
	RCP4.5	0.26	0.19 to 0.33	0.47	0.32 to 0.63
	RCP6.0	0.25	0.18 to 0.32	0.48	0.33 to 0.63
	RCP8.5	0.30	0.22 to 0.38	0.63	0.45 to 0.82

Source: IPCC 5th Assessment Report (Summary of Policy Makers), 2013

According to *Working Group II in* ***IPCC 1st assessment report on climate change*** "a sea-level rise of about 0.3 to 0.5 m by 2050 and about 1 m by 2100, together with occur a rise in temperature of the surface ocean layer of between 0.2° and 2.5°". Coastal Natural terrestrial ecosystems i.e., those areas under the influence of tidal or saline water intrusion) will be profoundly influenced by sea level change possible leading to ecosystem disruption through inundation, erosion and saltwater intrusion (Titus 1988). Probably the most important aspects of climate change on the World Ocean and coastal zones will be the impact of sea-level rise on coastal residents and on marine ecosystems. A group of experts convened by the Commonwealth Secretariat (1989) reported that important river deltas that are likely to be seriously affected by climate change include the Nile in Egypt, Ganges in Bangladesh, the Yangtze and Hwang Ho in China, the Mekong in Indo-China, the Irrawaddy in Burma, the Indus in Pakistan, the Niger in Nigeria, the Parana, Magdalena, Orinoco and Amazon in South America, Mississippi in United States and the Po in Europe (IPCC 1990).

In IPCC Technical Report by working group II has prepared Guidelines to assess the impacts of potential climate change and to evaluate appropriate adaptations. According to the Guidelines impact and adaptation assessments involve several steps such as:

- Define of the problem
- Selecting and testing the method
- Selection of scenarios
- Assessment of biophysical and socioeconomic impacts
- Assessment of autonomous adjustment
- Evaluation of adaptation strategies (IPCC 1994)

2.2.2 National and regional scale study

Study on different Modelling approach for coastal zone management

I. Huber and Jameson (1998) and Westmacott, (2001) have described the CORAL model as an integrated coastal zone management technique for decision making process. This model was developed for Curaçao, Maldives and Jamaica. In order to assess the cost-effectiveness of coral reef management strategies, three sub-models such as economic activity model, a water quality and an ecological response model were developed that linked together forming a single integrated model (Huber and Jameson 1998; Westmacott 2001).

II. SimLucia is a micro and macro-level modelling approach described by Engelen et al. (1997), which essentially models three coupled sub-systems, each represented by sets of linked variables: the natural sub-system, the social sub-system and the economic sub-system. The purpose of this study was to describe and analyse the impacts of climate change on their territory, their ecosystems, their social systems and their economic activities, and to provide instruments or tools to design, explore and evaluate policy measures and policy interventions to prevent or alleviate undesirable impacts. This model focuses on the spatial modelling approach and tracks changes in landuse patterns through the use of cellular automata. Identify the impact and change of land use pattern due to climate change issues used the pure hypothesis expressing how the economy could be influenced by climate change (Engelen, Uljee et al. 1997).

III. Goharnejad, Shamsai et al in their study on 'Vulnerability assessment of southern coastal areas of Iran to sea level rise evaluation of climate change impact', was tried to investigate the impact of climate change on future sea level variability over the southern coastline of Iran. A set of predictors for better representation of the variations in sea level were selected for sea level rise simulation among the GCM outputs using the stepwise method. uses stepwise regression to select the most appropriate predictors and then employs hybrids of artificial neural network (ANN) and artificial neuro-fuzzy inference system (ANFIS) for sea level simulation. This study was tried to investigate the influence of global climate change on sea level changes. (Goharnejad, Shamsai et al. 2013)

IV. In the study on 'Climate change impacts and adaptation assessment in Bangladesh' by Anwar Ali was carried out to identify the possible impact of coastal region due to climate change. He had identified the possible increase in cyclone frequency in the Bay of Bengal, lying south of Bangladesh, due to climate changes by analysing the cyclone data for 119 years. Both qualitative and quantitative discussions were made on cyclone intensity increase for a sea surface temperature rise of 2 and 4°C. Different scenarios of storm surges under different climate change conditions were developed by using a numerical model of storm surges for the Bay of Bengal. Possible loss of land through beach erosion due to sea level rise on the eastern coast of Bangladesh was examined. Some discussions were also made on the impacts of back water effect due to sea level rise on flood situations in the country (Ali 1999).

Geo-spatial technology in coastal hazard and vulnerability analysis

I. Pendleton et al. (2004) was used a coastal vulnerability index (CVI) to map the relative vulnerability of the coast to future sea-level rise within Cape Hatteras National Seashore in North Carolina. They ranked the CVI based on six major geophysical variables in terms of their physical contribution to sea-level rise-related coastal change, such as: geomorphology, regional coastal slope, rate of relative sea-level rise, historical shoreline change rates, mean tidal range, and mean significant wave height. Digital Shoreline Analysis System software was used to derive the rate of shoreline change over time. The CVI scores are divided into low, moderate, high, and very high-vulnerability categories based on the quartile ranges and visual inspection of the data. The CVI was calculated as the square root of the product of the ranked variables divided by the total number of variables. GIS tools has been used for the CVI mapping which highlights those regions where the physical effects of sea-level rise might be the greatest as a technique for evaluation and long-term planning by scientists and park managers (Pendleton, Thieler et al. 2004).

II. Mahendra et al. 2011 have prepared a multi-hazard vulnerability maps (MHVM) for coastal multi-hazard vulnerability assessment. This study was carried out using parameters probability of maximum storm surge height during the return period (mean recurrence interval), future sea level rise, coastal erosion and high resolution coastal topography with the aid of the Remote Sensing and GIS tools (Mahendra, Mohanty et al. 2011).

III. A collaborative study carried out by Bangladesh and the Netherlands to analyse the impact of sea level change on Bangladesh using 2nd IPCC scenarios. To conduct the study GIS and RS technologies with extensive data analysis methods was used. The study concluded that following a rise of one meter in the sea level, Bangladesh would face a catastrophic situation, including permanent inundation of about 15%-18% of its low-lying coastal areas, loss of Sundarbans, displacements of over 10 million people and loss of vulnerable agricultural land (BCAS-R.A-Apportech 1994).

IV. Coto B., Elena in his study on 'Flood hazard, vulnerability and rise assessment in the city of Turrialba, Costa Rica' was proposed a GIS-based method for flood vulnerability assessment. A combination of the cadastral map and flood scenarios for different return periods was generated through the application of loss functions in this study. Vulnerability functions for the different elements at risk or groups of these elements were formulated, which relate floodwater depth and degree of damage to each type of elements at risk. The vulnerability functions were applied to the flood scenarios, obtaining vulnerability values for the whole area. Maps of flood hazard zonation and riverbank erosion hazard of the study area were made based on photo-interpretation and fieldwork observations (Coto 2013).

InVEST model in marine and coastal area management

I. The West Coast Aquatic Management Board (WCA) worked with the Natural Capital Project (NatCap) to apply InVEST as part of a four-year marine spatial planning process in Vancouver Island in Canada. Here the InVEST Tier 0 Coastal Vulnerability model was used to understand the relative vulnerability of the shoreline to erosion and flooding in order to determine the least vulnerable locations for resort development (Bernhardt, Guerry et al. 2012).

II. The Coastal Zone Management Authority and Institute (CZMAI) in Belize have designed several possible coastal zoning to establish guidelines for the sustainable development and ecological integrity of the coastline for the long-term benefit of the Belizean people. They were used InVEST modelling tool (Coastal Vulnerability Model) to identify the impact of these alternative zoning schemes on three ecosystem services – lobster fisheries, tourism and recreation, and coastal protection from storms and inundation – and habitat for culturally important species (Clarke, Rosado et al. 2012).

Most of the modelling techniques described above used proprietary software, and may be complicated and difficult to implement. Also need to consider economic issue as those are not free software and tools. Marine InVEST model is an open source initiative and an integral part of GIS technology.

Table 2.2: Resumes of coastal vulnerability assessment studies in previous years

Researcher	Year and location	Methodology/Approach	Data	Result/findings
Engelen et al.	1997, St. Lucia	SimLucia a spatial modelling approach through the use of cellular automata	population growth, jobs, Road network, infrastructure, land use, SLR, temperature	Identify the tracks changes of landuse patterns
Ali, A.	1999, Bangladesh	Numerical model and GIS	tropical cyclone frequency and intensity, storm surges, coastal erosion, and back water effect	Vulnerability assessment and some adaptive measures
Pendleton, et al.	2004, North Carolina	Filed observation and visual interpretation for ranking and GIS techniques	geomorphology, coastal slope, sea-level rise, historical shoreline change rates, mean tidal range and wave height	Coastal vulnerability index map
Mahendra et al.	2011, Tamil Naddu, India	Remote Sensing and GIS tools	probability of maximum storm surge height during the return period, future sea level rise, coastal erosion and high resolution coastal topography map	Multi Hazard Vulnerability Index Map
Clarke, Rosado et al.	2012, Belize	Coastal Vulnerability Model, InVEST	Strom, flood water level, fisheries data, tourism information	lobster fisheries, tourism and recreation, and coastal protection from storms and inundation
Bernhardt, Guerry et al.	2012, Vancouver Island, Canada	Coastal Vulnerability Model (tire 0), InVEST	Shoreline, erosion and water level	determine the least vulnerable locations for resort development
Goharnejad, Shamsai et al.	2013, Iran	Used climatic variables to evaluate the sea level rise by using Stepwise regression and Artificial Neural Network	Climatic data based on 25 variables simulated by General Circulation Model 3 (CGCM3) under two climate change scenarios A1b and A2 and time series data	Predict the sea level rise for 100 years return period
Coto B., Elena	2013, Costa Rica	GIS and RS technology	Geomorphology, flood depth, river discharge, Satellite imagery	Hazard, vulnerability and risk map

2.3: Conceptual Development of the Study

After reviewing the literature the study has been conceptualised based upon the gaps and laps of the previous research work in the similar field of study.

2.3.1 Research gap aims to be filled

So far all works for coastal modelling used their own technology to simulate and interpret the result and very few of them are integrated with GIS. This research has tried to focus an integration of GIS technology with other coastal modelling tool i.e., Marine InVEST Model aiming to find the people who are vulnerable to climate change. This study has not considered any economic response and costing issues of the area.

Immense studies were carried out using various modelling tools and computer based programming techniques to identify the land use change and spatial distribution of natural phenomenon. But, a few works was focused to know the direct impact of the coastal people and their living environment. This study has tried to find the direct impact on coastal community due to climatic hazard i.e., storm surge and tidal flood. In this research work 1stly four parameters such as relief, wind speed, wave height and surge potential will be used to calculate shoreline exposure index. No historical shoreline change will be calculated. Previous research was used quartile range and visual inspection for ranking, but here InVEST will be used to generate ranking and normalize the value of wind, wave exposure and surge potential. The other parameter will be ranked 1 to 5 through rescaling factor. The CVI will be calculated based on normalized values of seven input parameters through multiplying them with the inverse power of total number of parameters. Both InVEST and GIS tools will be used to generate the desired output.

Flooding and cyclone surge, both situations represent large losses to the community, due to damage of infrastructure and residential areas. Although some research on this topic has been already developed, little has been done to identify the impact on the direct community people for future mitigation of hazard and disasters.

2.3.2 Conceptual Framework

From reviewing literature some key concepts were developed which further encouraged formulating a conceptual framework. The key features that influenced the formulation of the concepts were coastal vulnerability, inundation, shoreline erosion, seal level rise, climate change, natural habitat, InVEST toll and GIS technology. Through integrating these key concepts the theme of the study has been conceptualized. Figure 3.2 depicted the overall conceptual framework of the study.

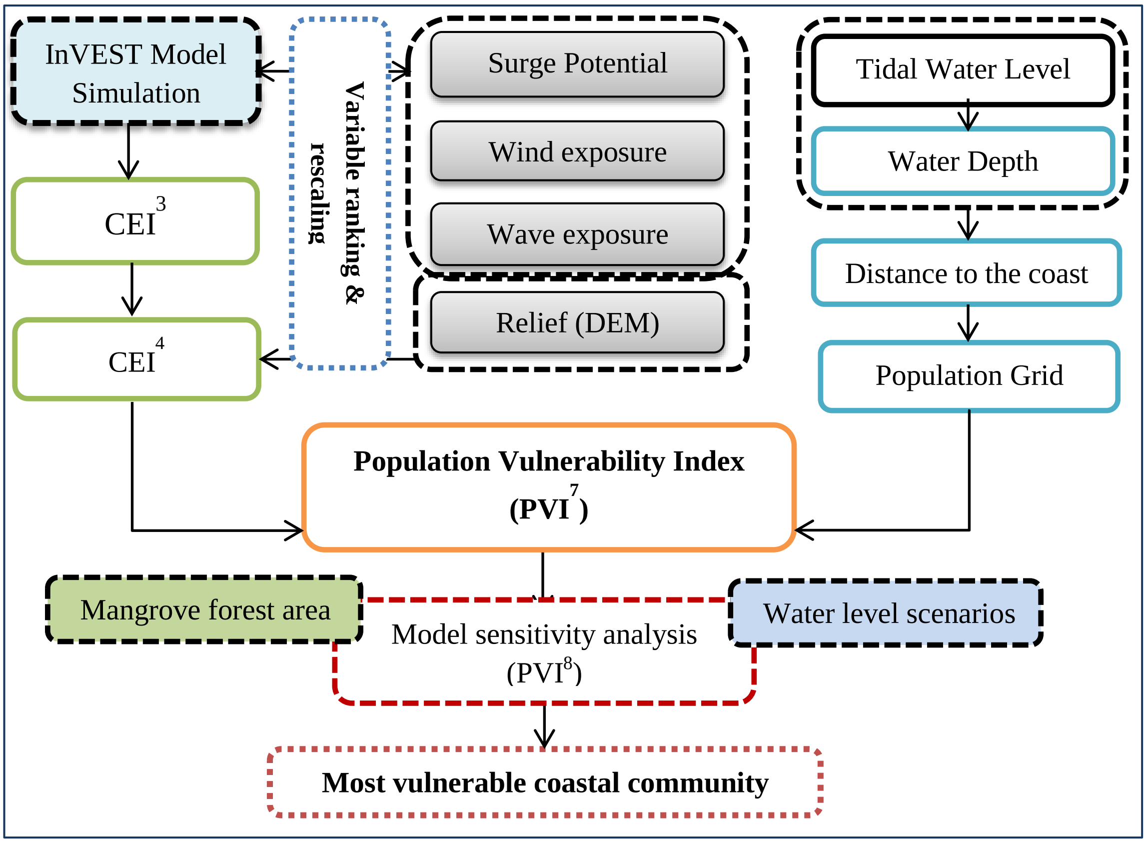

Figure 2.1: conceptual framework of the study

Chapter 3
Research Approach and Methodology

3.1 Research Type

A standard and justifiable methodology of a research could bring the outcomes of real findings (Kothari 1985). The vulnerability of the western coastal area in Bangladesh based on present situation and key climatic parameters such as wind, wave, tidal water level, surge etc. have been identified. The study is carried out following some logical steps through the simulation of Coastal vulnerability Index Model in ArcGIS interface in an integrated way. All the tasks have run through a systematic method. The study outcomes intend to identify the, people of those areas which are highly vulnerable due to climate change issues using geospatial technology. In such a case, it is very important to understand the research type while developing the research method. Research can be classified based on three different perspectives (Kumar 2005) such as, application of the research study, objectives in undertaking the research and inquiry mode employed. The following diagram shows the research classification based on different perspectives:

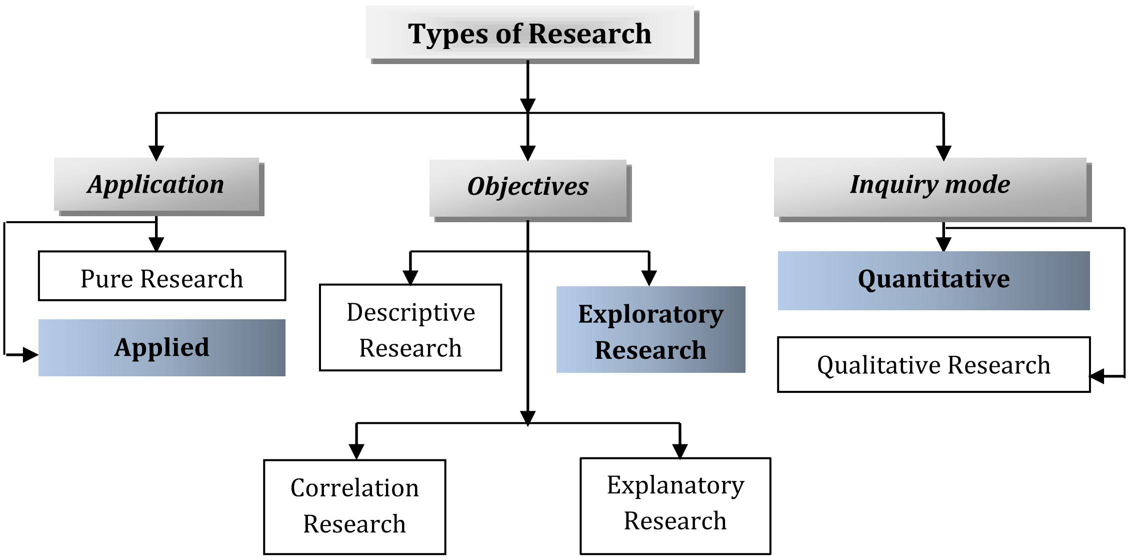

Figure 3.1: types of research (Kumar 2005)

According to the research classification this study covers both the application and inquiry mode. This research work tries to find to out the vulnerable people in the coastal region especially near the shoreline who are at risk due to various issues of climate change. Furthermore the study also conduct a quantitative analysis based on some major key climatic variables to create a vulnerability index of the western part of coastal area of Bangladesh.

3.2 Overall Approach and Methodology

The overall approach and methodology of the study has been described in a sequential way to achieve the target of the research work. To figure out the successful outcome there have been used various tools and techniques, such as Marine InVEST tool, ArcGIS, R Programming which are broadly useable in various international and national scientific studies. Whenever a research work is started we have to consider some sequential steps, such as preliminary thinking about the research, define the problem, setting the goal and objectives etc. The approach and methodology of the study in detail are presented in the subsequent sections.

To give a general idea of this research approach following diagram has been prepared, which gives an idea of expected outputs after successful compilation of this research work. This also provides a hint about the tentative tools and techniques will be used during the whole study. Figure 3.2 depicted the overall concept of the study including tools and techniques.

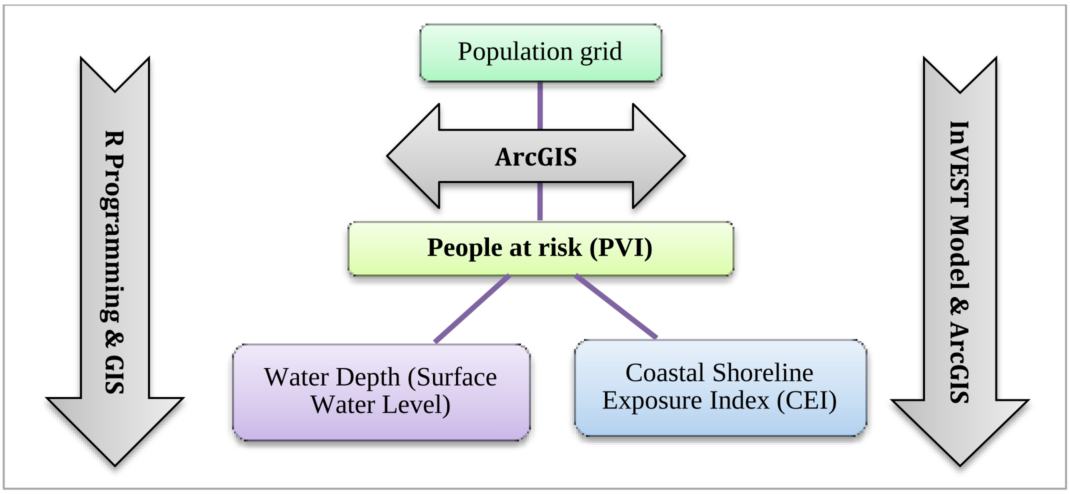

Figure 3.2: Overall study concept based on Tools and Technics

3.2.1 Literature review & brain storming

With the initial conceptual development an extensive literature review has carried out during the study based on coastal vulnerability assessment, flood inundation, sea level rise impact and erosion etc. The review has been conducted through all over the world including regional context. This study helps a lot to conceptualize the study related to identify vulnerability and risk of coastal communities in developing countries due to climate change.

3.2.2 Problem identification & conceptualization

The coastal region is marked by an ever dynamic network of river and estuary system, interaction of huge quantities of fresh water that are discharged by the river systems, and a saline waterfront - penetrating inland from the sea. The study area (western part of coastal zone of Bangladesh) covers by the estuary, delta and coastal deposit. The estuarine zone has ample bio-diversity, vast vegetated land and, above all, an agriculture dependent massive population. As reported the climate change can impart the impacts on the coastal region in respect of drainage, fresh water availability, morphological processes and extreme events (CEGIS 2005). The frequent effects of extreme events surrounding the study area are cyclone, storm surge, tidal flooding etc. During the study it is identified that, in the research area a huge amount of people are highly vulnerable to this frequent hazards. It is important to know the major issues and causes of coastal hazard to mitigate frequent natural disaster or calamities for better future.

From reviewing literature the key concepts were developed that influenced the formulation of the concepts i.e., coastal vulnerability, inundation, shoreline erosion, seal level rise, climate change, natural habitat, InVEST toll and GIS technology. Through integrating these key concepts the theme of the study has been conceptualized.

3.2.3 Topic Selection

It is an important and difficult task to select a consistent topic which must reflect the whole research work. Besides this studying and reviewing an extensive amount of literature review from several sources like books, journals, articles, dissertations and internet sources the study topics has been selected which directly or near about directly reflect the study concept titled as ***"Integrated Approach to Assess Vulnerability of the Coastal Region of Bangladesh due to Climate Change***".

3.2.4 Formulation of objectives

After being conceptualized as well as selection of the title, the purpose of the study was defined clearly. The major aim of this study is to assess vulnerability of the coastal community of western part coastal zone of Bangladesh in an integrated way. Now a day's, the climatic change and adaptation strategies of the coastal area is a burning issue, where the scientists, policymakers, planners and other research communities try to make a bridge between the nature and local people. In context of that, this research objective also set up on facts in a simple scientific perspective to understand the reality of the natural phenomenon and challenges faces by the coastal community people.

3.2.5 Selection of study area

The study area has been selected in such way that is highly vulnerable to climate change and an extreme disaster prone area as the ***western and central part of coastal region of Bangladesh*** is. Being a citizen of Bangladesh the study area has been selected in Bangladesh by considering the following criterion-

- Availability of data and information
- Integrated modeling approach
- Frequent occurrence different natural disasters i.e. cyclone, storm surge, flood, erosion etc.
- Huge area covered by natural habitat (mangrove forest)
- Applicability of selected modeling tools and techniques
- Study outcomes can be applied in the Least Developing Countries (LDCs) for future planning.

3.2.6 Selection of parameters

Some major parameters were identified and considered to simulate and run the model as well as to assess the vulnerability of the study area. For this study, the following parameters were selected to assess the coastal vulnerability and identify the vulnerable coastal community.

Table 3.1: Objective wise parameters

Objectives	Parameters
Simulate and calculate Coastal Vulnerability Index Model of the western part of coastal zone in Bangladesh	Coastal land use
	Total area population
	Climatic variables (wind, wave, surge)
	Relief and bathymetry
	Flood inundation depth
	Distances
Evaluate model sensitivity to different scenarios of SLR and change of natural habitats	Trend of SLR (Tidal water level)
	Natural habitat distance to shoreline
Examine the impact on coastal communities of the study area	No of people at risk
	Vulnerable areas

3.2.7 Data collection

The most important and time consuming part of the research is data collection. It is also important to ensure accuracy of data to get consistent output. Moreover the data and information for this research were collected from some reliable organization. Most of the data collected from the several secondary sources such as-

- Water Resources Planning Organization (WARPO) - National Water Resources Database (NWRD), Dhaka, Bangladesh
- Centre for Environmental and Geographic Information Services (CEGIS), Dhaka, Bangladesh-Landuse information
- Bangladesh Bureau of Statistics (BBS) –Population census, 2011
- U.S. Geological Survey (USGS)-SRTM DEM

Table 3.2: List of collected data and information to conduct the study

Data and Information	Type	Status and time	Data source
Satellite Image	Landsat TM5	2010	CEGIS, Bangladesh
Relief (DEM)	SRTM DEM (.tif file)	2013, 90 m	
Land use	Polygon shape file	2010	
Boundary	Polyline Shape file	2010	
Land elevation	Elevation Points	1997	
Bathymetry	Elevation point data	2010	
Continental shelf	Shape file (contour)	2010	
Natural Habitat	dataset or Shape file	Mangroves forest	
Settlements	Shape file and dataset	2010	
Geo Morphology	Shape file	1990	EGIS, Bangladesh
SLR (Trend)	Shape file and database	1989-2009	NAPA and NWRD
Water level	monthly /m	1989-2009	NWRD, Bangladesh
Wind	monthly /m	1989-2009	
Rainfall	monthly /m	1989-2009	
Temperature	monthly /m	1989-2009	
Population Grid	Spatial representation	Population census, 2011	BBS, Bangladesh
Wave height	Data in meter (hind cast)	WAVEWATCH III	WAVEWATCH III™ © 2009
Wind height			
Storm surge	historical dataset	1960-2013	Published documents

Data sources: (BIWTA 1977-2003), (BWDB 1989-2009), (EGIS 1990), (CEGIS 2010), (BBS 2011),(USGS 2006), (Tolman 2009)

3.2.8 Research tools and techniques

To conduct the research work properly some statistical and spatial analysis tools and technique were used which has been illustrated in table 3.3.

Table 3.3: Tools and techniques for major analysis

Data analysis	Action	Analytical tools	Required
Qualitative data analysis	CVI Model Simulation	Coastal shoreline exposure and erosion (ranking)	Marine InVEST tool, Arc GIS 10.2, Python
	Map presentation	Representation of the study area and model outputs	Arc GIS 10.2
Quantitative data analysis	Descriptive statistics	Frequency distribution, mean, mode, standard deviation	R Programming /MS Excel
	Charts and graphs	Graphical presentation and analysis	,,
	Data recording, encoding and correlation analysis	Measuring relationship of various indicators, trend analysis etc.	,,
	CVI calculation	Final Indexing and ranking	MS Excel/ArcGIS
Others	Report writing	Presenting all the facts & findings	MS Word
	Bibliography	All citations and references	EndNote

3.2.9 Data processing and analysis

After collecting data from different secondary sources these data has been processed and complied with the application of different software. Most of the data has been pre-processed using ArcGIS 10.2, R Programming language and Microsoft Excel. The model has been simulated using Marine InVEST tool in ArcGIS 10.2 interface. From Landsat-TM 5 satellite dataset the study area land use map has been prepared and cross checked with the Google Earth imagery. During the data processing stage all climatic variables (inputs) to run the model were ranked based on quality and quantity following global standard. From the population census data set population grid map has been prepared by following step by step approaches. SRTM DEM has also been pre-processed to fill sink and NoData, then to ignore the canopy height. All the Maps has been digitized and plotted with the help of Arc GIS software.

3.2.10 CVI Model simulation and PVI calculation

In this stage The ***Coastal Vulnerability Index (CVI) Model*** of the study area has simulated using ***Marine InVEST Modelling*** tool in ***ArcGIS*** interface. The model has been simulated by considering the different geophysical and climatic parameters such as relief, wind speed, wave exposure, natural habitats etc. Before running the model all the parameters have normalized and rescaled from low to high vulnerability (1 to 5) rank based on their quality and quantity. The model output is representing the preliminary study output indicating erosion exposure and shoreline exposure. After that, the CVI Model has imitated again with the presence and absence of mangrove forest. From the model exposure index, final coastal Population Vulnerability Index (PVI) has been calculated by incorporation relief, distance from the shore, population density and water depth. Water depth has been calculated from the tidal gauge water level dataset to know the inundated area. Flood inundation map has also been collected for a specific time period prepared from Landsat TM satellite image to compare the inundation result. Finally the impact on coastal population has been identified based on PVI and land use information of the study area.

3.2.11 Model sensitivity analysis

Model has been evaluated by considering different scenario of ***water depth surrounding the study are*** as well as changing the parameters of natural habitat ***(mangrove forest)*** using the proximity analysis tool.

3.2.12 Results and discussion

Final results have been presented in the form of maps, reports, graphs, tables and specific site evaluations. Figure 3.3 shows the methodological flow diagram of the study.

3.2.13 Limitations of the Research

Though this research aims to end up with a fruitful outcome, it has some limitations which were the barrier for attaining most accurate results. The limitations of the study are mentioned below-

- InVEST Model Limitations
- Time constraint
- Data Inconsistency
- Inadequate data and information
- Data Access etc.

The scoring of exposure is the same everywhere in the region of interest; the model does not take into account any interactions between the different variables. Another type of limitations in this model is associated with the computation of the wind and wave exposure. It is necessary to simplify the type of input required to compute wind and wave exposure.

The model outputs only focus near the shore line such as population at risk near the shoreline. It does not take into account the whole study regions population.

To evaluate the result in a perfect way ground truth of data is essential and needs to go to field which has not been done in this study due to lack of adequate time. Also for lack of sufficient time stakeholder analysis to consider the views, ideas and suggestions of different class of community people have not been done in this study.

90 meter resolution SRTM DEM has been collected from USGS Hydro SHEDS (USGS 2006) which was an essential parameter in this study. The major difficulty to use this DEM is that SRTM is surface elevation Model and it includes the canopy height with the surface elevation. Thus, the real elevation of earth surface is somehow ignored which is considered as the inconsistency of data.

3.2.14 Directions for further research

On the basis of the analysis and findings, some management strategies for future management action plan of coastal areas to mitigate vulnerability could be provided to ensure a sustainable living environment and breathing place for the people. In future this result could be applied to other part of the countries with limited data and information. Also the method could be applied to other developing countries with similar climatic characteristics.

3.2.15 Formulation & submission of draft

Finally, after completing the modelling, analysis and discussion phase a draft dissertation paper has been prepared containing all the study findings.

3.2.16 Final dissertation paper

After the final defence there may have some feedback from the externals. By performing necessary corrections and rearrangements of the draft the final report has been produced as per the instructions, is given. This report has contained with all the facts and findings of the study "***Integrated Approach to Assess Vulnerability of the Coastal Region of Bangladesh due to Climate Change***".

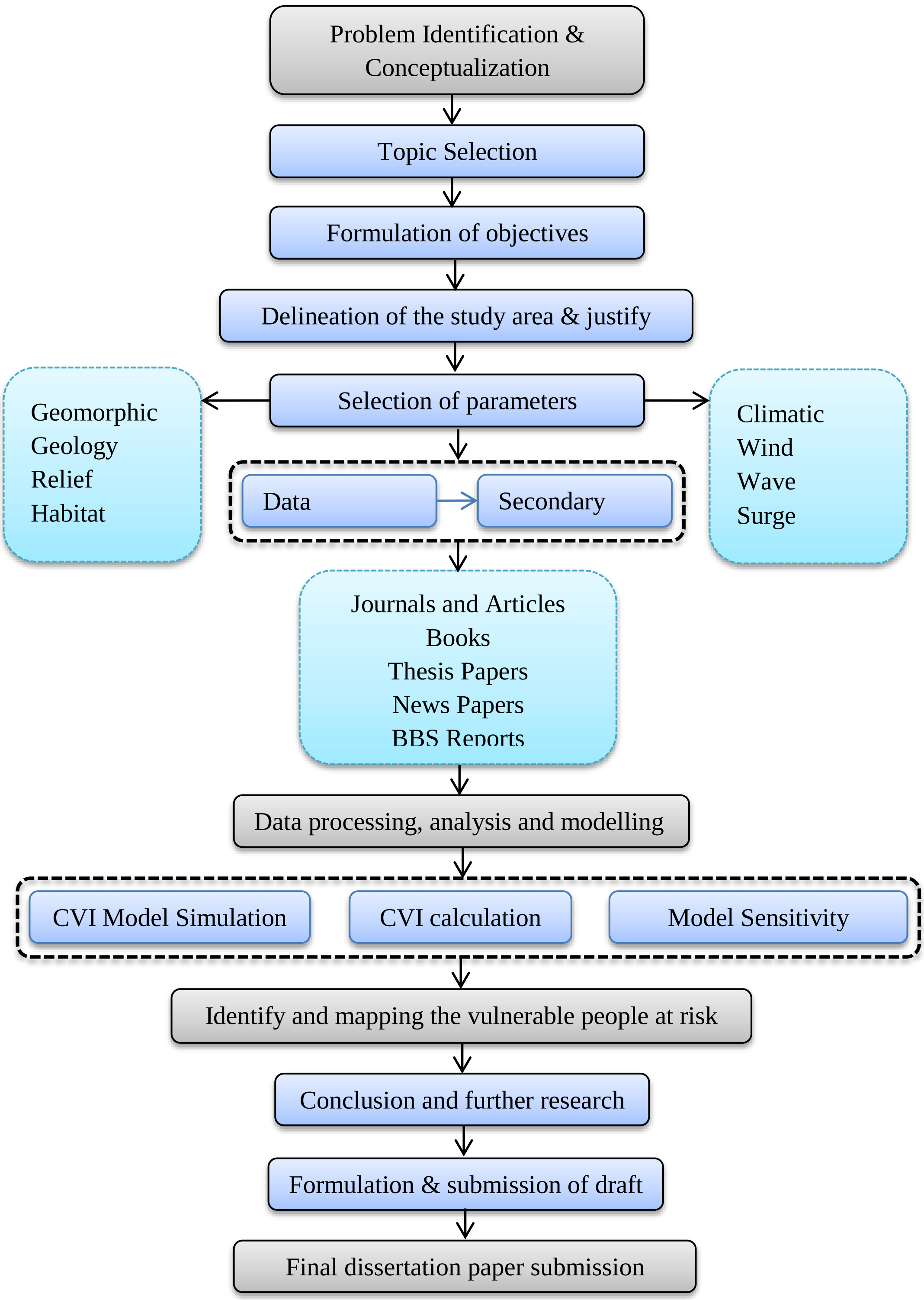

Figure 3.3: Graphical representation of the Research Methodology

Chapter 4

Study Area Profile

4.1 Demographic Profile

Bangladesh lies between 20°34″ and 26°38″ North, between 88°01″, and 92°41″ East. Its climate is tropic and humid. It has mainly four seasons, e.g. Pre-monsoon (March to May), Monsoon (June to September), Post-monsoon (October to November), Dry (December to February). 80% of the rainfall occurs during the monsoon from June to September, when the tidal water level reached at the peak (Hossain, Hossain et al. 2012). The major demographic features of the study area include area and boundary, Population distribution, income and occupation, Literacy rates etc. The parameters which are directly linked with this study analysis have been described in the subsequent sections. The other demographic features which are not directly linked with the analyses have been depicted in Appendixes A.

4.1.1 Area and boundary

The study area is covers around 45.28% (21,830 sq.km approximately) of the total coastal region of Bangladesh. District wise area coverage in the study area has depicted in Appendix A1. The land area coverage of the study area is around 17,946.13 sq.km, excluded the water body along the coast line.

4.1.2 Population distribution

Population density in the coastal district is slightly higher than the national average. The total population of the whole country is around 143.5 million, whereas the total population of the study area is approximately 11.34 million (BBS 2011). The Urban-rural population ratio of the area is 0.17 and the male-female population ratio is about 0.99. The average population density of the study area is about 243.5/sq.km, estimated from Thana2 (sub district) wise population census, 2011. District wise population distribution under the study area has represented in Appendix A2.

[2] The country administrative boundary at level four is defined by Thana, which is equivalent to sub-district.

4.2 Study Area Physiography

The country consists of low and flat land formed mainly by the sediments carried by the Ganges and the Brahmaputra River systems except the hilly regions in the north-eastern and south-eastern parts. From physiographic point of view, about 80 % of the land is floodplains with very low elevation above the MSL with the rest made up of hills and elevated lands. Topography of the country is characterised by very low differences in the elevation between adjoining ridge tops and depression centres, which range from less than 1 meter on tidal floodplains, 1 to 3 meters on the main river and estuarine floodplains, and up to 5 to 6 meters in the Sylhet Basin in the north-east (Ahmed 2006). A brief overview of the physiographic units such as geology, land type climatic condition, weather and meteorology etc., of the study area has been descried in the following sections.

4.2.1 Landuse Pattern

The coastal area is mostly low lying with varied land use pattern. Around 35% land area is covered by agricultural activity and 24% is settlement (figure 4.1). Also a large extent of area (app.40%) is covered with mangrove vegetation and water body such as rivers, lakes and seasonal water logging. The land use map of the study area has been depicted in Appendix B1.

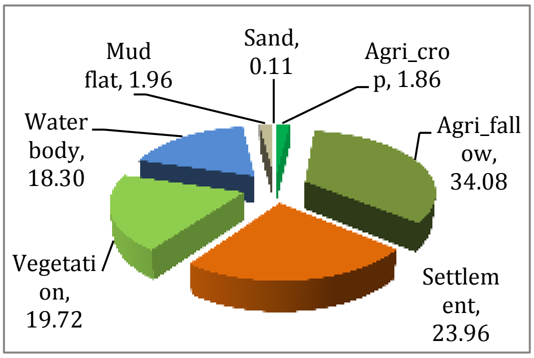

Figure 4.1: Percentage of area based on land use category

4.2.2 Mangrove forest (The Sundarbans)

Sundarbans[3] is the world largest mangrove forest and internationally recognized protected areas. Protected areas are important in terms of providing vital ecosystem services, such as water purification and retention, erosion control and reduced flooding etc. They buffer human communities against different environmental risks and hazards. A large number of

[3] The Sundarbans Reserved Forest is one of the world heritage sites. It was listed as the one of the important wet lands in the Ramsar Convention, RAMSAR (2014). The List of Wetlands of International Importance.

communities live in the proximity of the forest (to its North and East), an area called Sundarban Impact Zone (SIZ). Most of these communities rely largely on the resources of the Sundarban for their livelihood (Islam 2011).

Table 4.1: District wise area coverage of mangrove forest

Zone wise mangrove	Location (District)	Area in sq. km
Sundarbans (East) Wildlife Sanctuary	Bagerhat	312.26
Sundarbans (West) Wildlife Sanctuary	Satkhira	715.02
Sundarbans (South) Wildlife Sanctuary	Khulna	369.70

Source: Islam 2011 & CEGIS, 2010

4.2.3 Study Area geology and geomorphology

Bangladesh is mainly underlain by sedimentary deposits accumulated between 1.6 million years to recent times covering more than 85% of the land that are mostly flat and in some places slightly undulating in character. The whole area of the country categorized by several geological classes based on land and soil characteristics such as Coastal Deposits, Deltaic Deposits, Paludal Deposits, Alluvial Deposits, Sylhet Limestone etc., (EGIS 1990). Among the entire category only the deltaic deposits and daludal deposits are concentrated on the study area. Deltaic deposits has subcategorize by deltaic silt, estuarine deposit, mangrove swamp deposit, tidal deltaic deposit, tidal mud and deltaic sand. Coastal deposits lay on the eastern part (Cox's Bazar near the sea) of coastal area. The detail characteristics of the geological classes in study area include subcategories has been described in Appendix B2.

The coastal morphology of Bangladesh is dominated by: (a) a vast network of rivers, (b) an enormous discharge of river water with sediment, (c) large number of off-shore islands and sand bars, (d) a funnel shaped, shallow and wide estuary, (e) gently sloping wide continental shelf, (f) a narrow strip of coastal landforms fronting hill ranges, (g) strong tidal actions, and (h) frequent landfall of tropical cyclones (CEGIS 2003). The geomorphology of the coastal areas plays a vital role in storm surge propagation from the coastline towards inland. Storm surges travel longer distances on the plain land with low surface slopes compared to plain land with moderate to steeper slopes. Coastal flooding from the surges is directly influenced by the variation in elevation and surface form. Therefore, there is a clear relation between geomorphology and surge propagation or, in other words, between geomorphology and storm surge height. The higher the elevation of the surface form and steeper the slope, the lower the penetration of surge waters inland and vice versa. The soil distribution on the land based on geological characteristics of the study area has denoted the map in Appendix B3.

4.2.4 Major River system

A network of rivers originated in the Himalayas flow over the country that carries sediments (the building blocks of the landmass of the delta). The major river systems of the eastern Himalaya - the Ganges, the Brahmaputra, and the Meghna (GBM) - their tributaries and distributaries crisscross the floodplains. The map in Appendix C1 represents the major river system of Bangladesh.

4.2.5 Climate change key variables

Key variable are those variables for which a general assessment of the anticipated effects due to climate change can be made. The key variables of climate change defined by the National Committee on Coastal and Ocean Engineering, NCCOE (1999) are mean sea level, ocean currents and temperature, wind climate, wave climate, rainfall/runoff and air temperature. For the present study key variables affected by climate change in the coastal region have been specified as mean sea level, tidal water level, wind, wave and storm surge potential or height have been described in the subsequent sections.

The other climatic variables i.e., rainfall and temperature that are not directly used in the analysis have been illustrated in Appendix C2.

Tidal water level

The tidal wave from the Indian Ocean travels through the deep Bay of Bengal and approaches the coast of Bangladesh approximately from the south. It arrives at Hiron Point and at Cox's Bazar at about the same time. The extensive shallow area in front of the large delta causes some refraction and distortion. The water level variation is dominated by a semi-diurnal tide with a considerable variation from neap to spring tides.

In the study area the average tidal range is approximately 2.89 m during monsoon. In the area around Sandwip, the tidal range is significantly higher with an average range of over 4 m. The maximum high-tide water level is about 7.0 m and more during cyclone surges. Figure 4.2 illustrates the water level changing trend from year 1980 to 2009 based on tidal gauges water level.

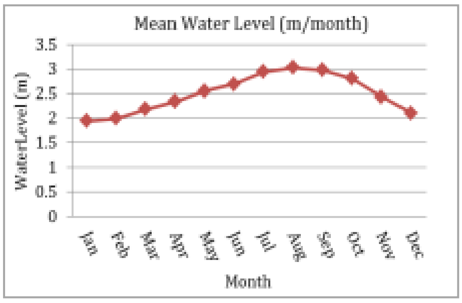

Figure 4.2: mean maximum water level during high tide

Wind and Wave

Meghna Estuary Study (MES) shows that under the prevailing S-SE winds (with an average wind speed of about 8 m/s), the average significant wave height varies between 0.6-1.5 m in the near shore zone to 0.1-0.6 m in the landward part of the Meghna Estuary area (MES June 2001). In the dry season the waves are generally less than 0.6 m with peak periods of 3 - 4 seconds. During the monsoon wave heights exceed 2 m with periods greater than 6 seconds. Wave heights in the landward part of the Meghna Estuary area don't exceed 0.4 m due to the moderate wind conditions (BWDB 1999).

Mean Sea Level (MSL)

The importance of mean sea level (MSL) as a key variable has been long recognized due to its direct linkage to coastal flooding of large populations. The 3rd IPCC (2001) predictions of the global sea level rise for the full range of SRES scenarios is 0.09m to 0.88m for 1990 to 2100. Major difficulties in determining regional sea-level trends for Tropical Asia relate to the limited amount of historical tide-gauge data and the region's high decadal and inter-annual variability. Sea level rise scenarios adopted from NAPA recommendations are 14, 32 and 88 cm for the projected year 2030, 2050 and 2100 respectively, which are based on the IPCC Third Assessment Report and SMRC studies for Bangladesh.

Table 4.2: Climate change scenarios for Bangladesh

Year	**Temperature change (0C) Mean**		**Precipitation change (%) Mean**		**Sea Level Rise Scenario (cm)**			**Cyclone (%)**
	Monsoon Season	Dry Season	Monsoon Season	Dry Season	3rd IPCC (High range)	SMRC	NAPA	
2030	0.8	1.1	+6.0	-2.0	14	18	14	5
2050	1.1	1.6	+8.0	-5.0	32	30	32	10
2100	1.9	2.7	+12.0	-10.0	88	60	88	10

Source: National Adaptation Programme of Action (NAPA), (GOB 2005)

A study carried out by the SAARC Meteorological Research Council (SMRC) revealed that the rate of SLR during the last 22 years is many fold higher than the mean rate of global sea level rise (Karim and Mimura).

Table 4.3: Trend of SLR along the coast of Bangladesh

Station Name	Region	Latitude	Longitude	Trend (mm/year)
Hiron Point	Western	$21^0$48'	$89^0$28'	4.0
Char Changa	Central	$22^0$08'	$91^0$06'	6.0
Cox's Bazar	Eastern	$21^0$26'	$91^0$59'	7.8

Source: Adapted from SMRC, no.3, cited from (Karim and Mimura)

4.3 Natural Vulnerabilities due to Climate Change

Coastal livelihood are often affected and threatened by a host of incidents and process. These together define the vulnerability context of the coastal households followed by cyclone, storm surge, flood, coastal erosion, salinity intrusion etc. A brief description of major natural vulnerabilities in coastal area of Bangladesh have illustrated in the following sections.

4.3.1 Storm surge and cyclone

Tropical cyclones are a major threat to the coastal areas, causing loss of human lives and livestock and severe damage to crops and fisheries. In the last 125 years, more than 42 cyclones have hit the coastal areas. The historical information on cyclonic storm surge in the coastal belt (western and central coast) of Bangladesh has given in Appendix C3. Recently, the most devastating cyclones hit the Southwest coast under Bagerhat district in 2007 (Sidr) and 2009 (Aila). Surge record from 1960 to 2013 indicate that Bangladesh coast is highly prone to destructive tropical cyclones associated with tidal surge (CEGIS 2005). The storms usually form in the south-east portion of the Bay of Bengal, move in a north-westerly direction and often turn north-easterly towards the east coast of Bangladesh.

Two different types of cyclone form in the bay- one is the tropical cyclone (forms during the pre and post monsoon season) and the other is the monsoonal depression, which develops during the south-east monsoon season (CEGIS 2005). Figure 4.3 illustrate that number of storm surge occurred during may is very high and also high in November to December.

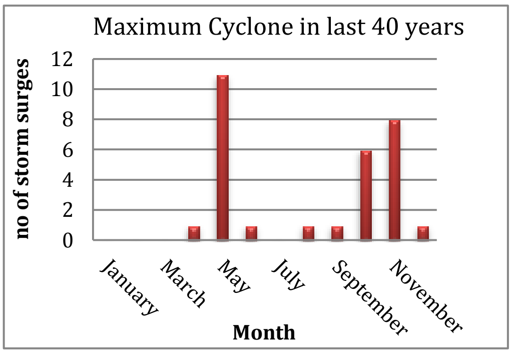

Figure 4.3: Breakdown of cyclones by month in the last 40 years

In the last 40 years, 30 cyclones have affected the western and central coast in Bay of Bengal region. Maximum numbers of people were died during the devastating storm surge in 1970 and 1991. A severe cyclone occurs almost once every three years. Although the frequency of cyclones is not unusual compared to other cyclone hotspot countries, the impact it causes stands out: 53 % of the cyclones that claimed more than 5,000 lives took place in Bangladesh (GOB 2008).

Because of frequent storm surges, the low lying coastal areas are predominantly vulnerable, where the population, infrastructure, agriculture, livestock and economic development are at high risk. Figure 4.4 illustrate the maximum wind speed during storm surge which was very high in 2007 during Cyclone Sidr[4].

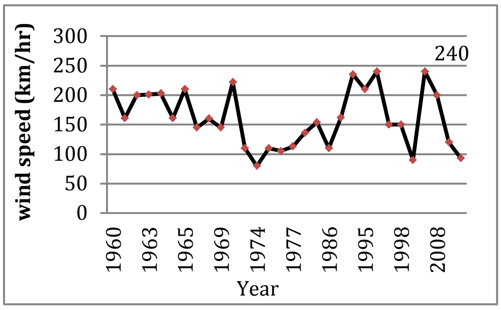

Figure 4.4: Maximum wind speed during storm surge from year 1960 to 2008

4.3.2 Coastal erosion

Erosion and accretion were found prominent in the coastal area of Bangladesh when major changes of river courses took place either by natural phenomena such as geological activities of subsidence or upliftment or by human interference, such as cross-dam, embankment, sluices etc. (Islam, 2004). The study area covers with 12 number of embankment or polders, most of them are in vulnerable condition according to the environmental impact assessment study of CEGIS, 2012. Both erosion and accretion in the Meghna estuary region (i.e. northern part of Bhola district, Lakshimpur, Noakhali and Feni coastal belt, Hatiya and Sandwip area) were found to be prominent. Major threat of erosion in the next 25 years found in the region of northern part of Bhola, Lakshimpur coastline, north and north eastern parts of Hatiya, north and western part of Sandwip. Slow accretion may take place in the southern parts of Hatiya and Noakhali mainland (CEGIS 2007).

4.3.3 Salinity intrusion

Water and soil salinity is a common natural problem in many parts of the coastal zone affecting agricultural and industrial activities. Detail description has been illustrated in Appendix C4.

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[4] Cyclone Sidr, 2007 was a severe tropical cyclone that resulting in one of the worst natural disasters in Bangladesh. Sidr formed in the central Bay of Bengal, and quickly strengthened to reach peak 1 minute sustained winds of 260 km/h (160 mph), a tropical. Around 3,447 deaths were blamed on the storm, Source: www.wikipedia.ogr.

4.3.4 Flood Inundation

The most common water-related natural hazard in Bangladesh is flood. Flooding in Bangladesh is the result of a complex series of factors. These include a huge inflow of water from upstream catchment areas coinciding with heavy monsoon rainfall in the country, a low floodplain gradient, congested drainage channels, the major rivers converging inside Bangladesh, tides and storm surges in coastal areas, and polders that increase the intensity of floodwater outside protected areas. Different combinations of these various factors give rise to different types of flooding (Ahmed 2006).

In Coastal areas there are various types of floods such as monsoon or fluvial flood, flash flood and tidal floods. Tidal flood is mostly typical for the coastal zone. High tide regularly inundate large tract of these area. During extreme monsoon storms fresh water runoff from big rivers, combined wind and wave set up caused by strong southern winds and raise the sea surface in the Bay of Bengal (PDO-ICZMP 2004).

Chapter 5
Coastal Vulnerability Model Simulation and Analysis

The main target of this study is to create a coastal vulnerability model for identifying the vulnerable community in the western coastal zone of Bangladesh. For this, some specific objectives have also been defined at the beginning of the study. Seven biophysical and climatic parameters have been selected for the calculation of population vulnerability index (PVI), which are Relief, wind, wave, surge potential, distance from the shoreline, water depth and population density. Another parameter, distance based on mangrove forest coverage has been taken into consideration to analysis the sensitivity of the final model output. This chapter is explaining the detail description of all modelling activities carried out to reach the target point. Five major tasks have been carried out based on aim and objectives, that are-

- Preparation of population grid map
- Simulate Marine InVEST model to generate Coastal Exposure Index (CEI)
- Calculate the Population Vulnerability Index (PVI) as the major study findings
- Model Sensitivity analysis
- Identify the people at risk and vulnerable coastal community

5.1 Preparation of Population Grid

A grid also known as a raster data set is a type of tessellation (mosaic) that divides a surface into uniform cells or pixels. The raster data model is common for representing phenomenon that varies continuously over a surface. From the population census 2011 (BBS 2011) population grid for the study area has been calculated. The baseline gridding has done using a proportional allocation algorithm on the Thana (sub-district) wise spatially distributed population census. For preparing the spatially distributed population grid of study area was followed the basic method developed for Gridded Population of the World (GPW) (Deichmann, Balk et al. October 2001; Balk, Yetman et al. October, 2010). The steps used to develop gridded population of the study area include the following sections.

5.1.1 Preliminary gridding approach

The total population of the study area is about 11.34 million (BBS 2011). Firstly the collected population census 2011 data (tabular format) was joined with the geographic boundaries (administrative unit, Level three-Thana or sub-district).

The joined administrative unit (Thana population) has transformed directly to the 500 meter spatial resolution raster grid format in map scale of 1:1,137,169. It has done based on population density, where the average population density per sq.km was 1133 with the maximum and minimum of 16702 and 96 respectively. This process does not consider different land use pattern of the study area.

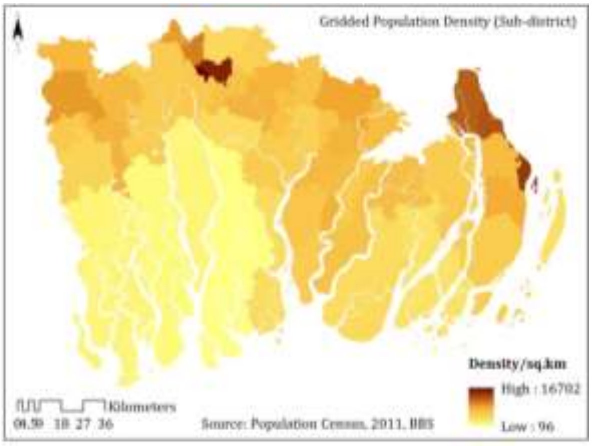


Figure 5.1: Gridded population distribution per Thana

5.1.2 Precise gridding approach

The 1st gridded population of the study area (Figure 5.1) seems inconsistent because of its distribution pattern. The whole areas of Thana (each administrative unit) consider the same amount of population for each grid. The amount of population in a settlement area and in an agricultural land could not be same. Thus to make a reliable population grid some basic steps were considered based on GPW method adapted from the Proceedings of European Forum for Geo-statistics Conference on 'Construction of Gridded Population and Poverty Data Sets from Different Data Sources', (Balk, Yetman et al. October, 2010).

The proportion of population (in percentage) was estimated based on land use category (e.g. settlement, agriculture, vegetation etc.). The land use map prepared from satellite image (LandSAT TM August, 2010) has collected from CEGIS a public trust under the Ministry of Water Resources, Bangladesh (CEGIS 2010) and was used to estimate and distribute (percentage wise estimated) population. The detail about the land use category of the study area has described in the Physiographic profile of the study area section. The proportion of population was estimated in such a way that the overall population density of the study area remains unchanged to ensure data consistency. It was also cross checked with the global population grid dataset 2005 to know the population distribution pattern in the study area. Among the total population for the settlement 82.5 % was distributed. The rest of population was distributed to agriculture and vegetation, 16% and 1.5% respectively. Then fixed the population estimates for the water body, mud flat and sand area to zero. Next the population densities as pop/km^2, for each land use component (polygon) were computed.

To distribute the population uniformly a regular grid in vector GIS format (“fishnet”) with a resolution of 1km was created and overlay with the each land use category (estimated population) boundaries. Also overlay with the total administrative unit boundary. The grid extend was assigned as the Thana population (sub-district) boundary.

The area was calculated in km^2 for each resulting polygon (grid) of overlap. This area was multiplied with the corresponding land use categories population density to get a population estimate for each polygon cell of overlap (proportional allocation algorithm), shown in figure 5.2.

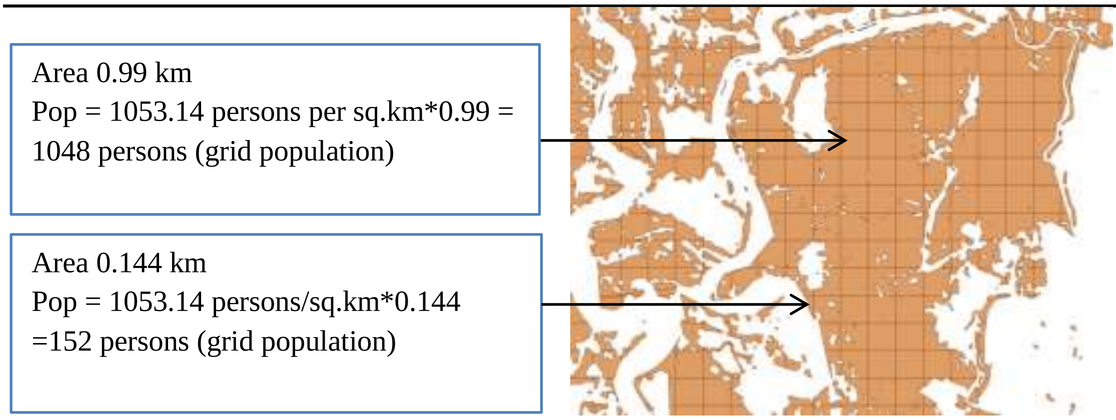


Figure 5.2: Proportional allocation algorithm for population in settlement

For each of the population estimated area in km^2 (Figure 5.3, 5.4 and 5.5) based on the land use category, all polygons of overlap has aggregated that belong to a given grid cell. Then, link these grid cell totals back to the original regular grid (“fishnet”) shown in Figure 5.6.

The aggregated grid was then converted to raster GIS data format or transform to grids with 90 m spatial resolution. The grid wise calculated population was considered during grid transformation, so the raster represents the total number of persons in each grid cell.

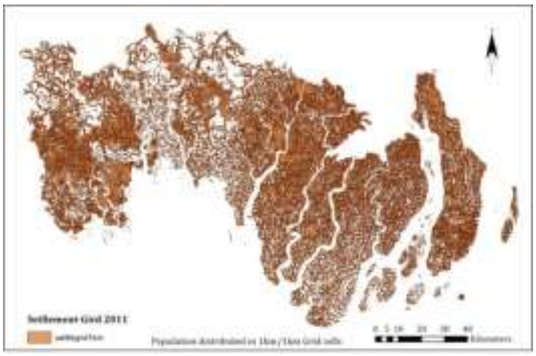


Figure 5.3: Population estimated (85.2%) area in km2 for settlement

Figure 5.4 Population estimated (16%) area in km2 for agricultural land

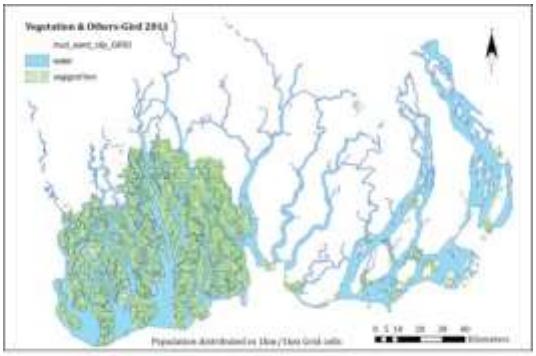


Figure 5.5: Estimated population 0.15% area for vegetation and 0% for others

Figure 5.6: Aggregated and linked grid with all estimated population

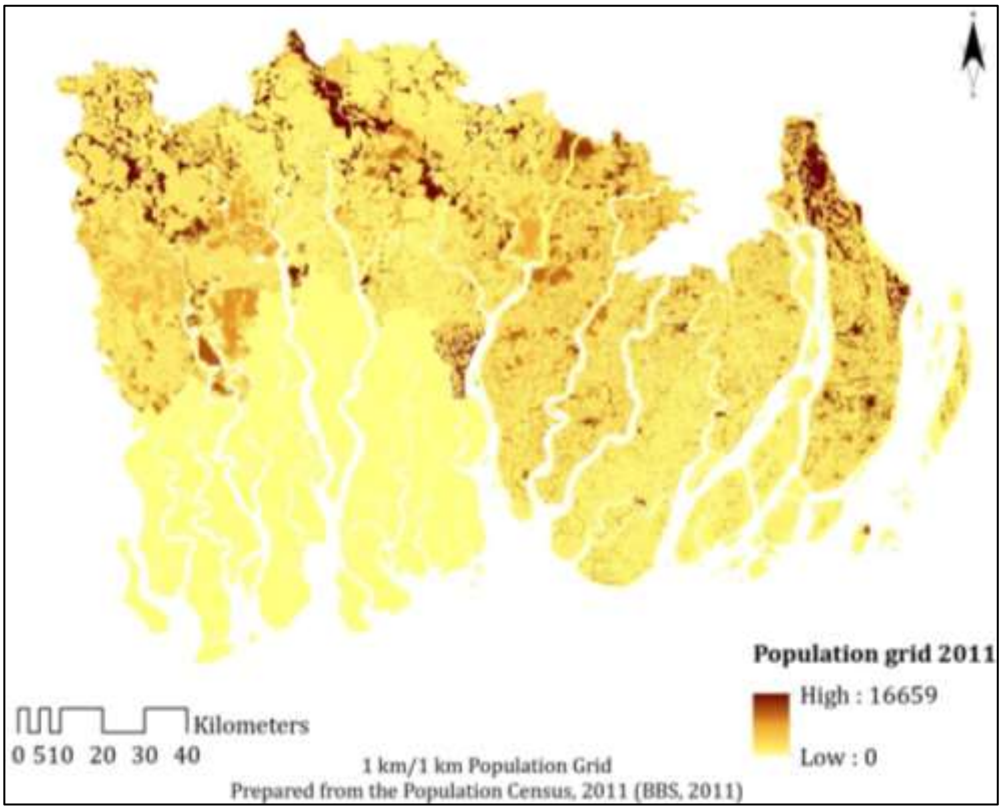


Figure 5.7: Final Gridded Population, 2011 (Raster format) of the study area

Figure 5.7 represents the resultant population grid where maximum 16659 numbers of persons are living each 1 km grid area and a minimum of zero in some area of vegetation (mangrove forest) near the sea shore. And the average number of persons per 1km grid area is about 1187.45, which is near about the Thana wise population density (1133/sq.km). The light yellow color represents high population density area and the dark brown color indicates the low densely populated area. Now the overall population density for settlement are is about 1908 and for the agriculture and mangrove forest area are around 288 and 79 per sq. km.

To assess the population residing near any segment of coastline, this population grid has used 1st to simulate the Marine InVEST Model. Later it has been used to assess the vulnerability to people of whole study area.

5.2 Simulation of Marine InVEST Model

The model has created the population and exposure index maps using a spatial representation (raster) of population and spatial representations (shape files and raster) of four bio-geophysical variables based upon the study area:

- Relief
- Wind exposure
- Wave exposure
- Potential surge height

The Exposure Index (EI) output contain a number of indices and rankings of input variables i.e., relief, wind, wave and surge potential. The model simulation steps in detail have been described in the subsequent sections. The outputs of the model are raster files (grids) of population and exposure index along the shoreline in the coastal region of Bangladesh, which have a spatial resolution 90 meters. The population raster just contain the information near the shore line, not the whole area of interest. That's why the model generated population raster has not been considered for further analysis.

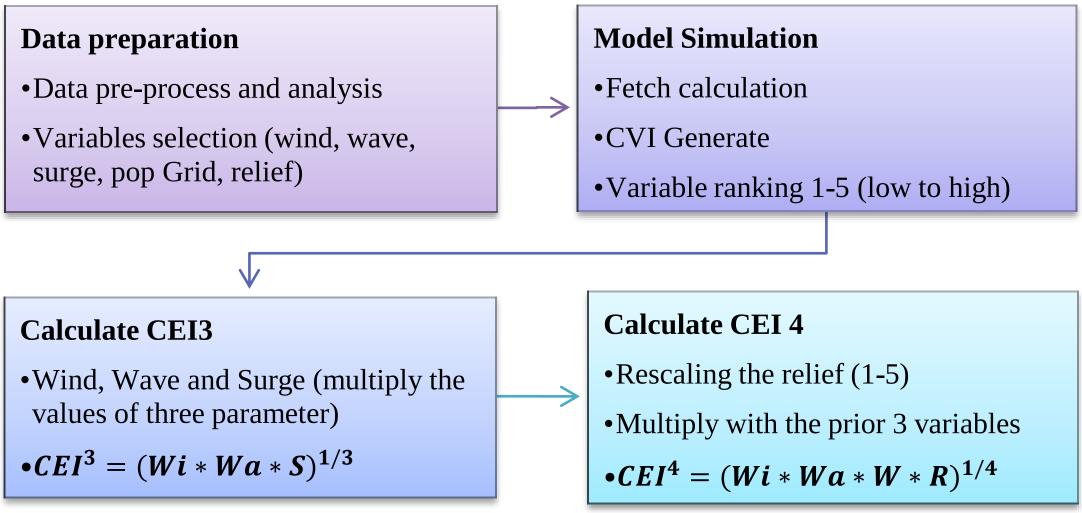


Figure 5.8: Analitical framework of Coastal vulnerability Index Model Simulation

5.2.1 Data Processing and Analysis

Pre-processing and preparation of base data along with essential information is one of the major tasks of this study. Also to simulate the coastal vulnerability model a number of input parameters has been identified, pre-processed and prepared, so that the model would run without any hamper. Study area boundary delineation. The preparation process of base data and information to fulfil the study and to simulate the Coastal Vulnerability Index Model has described in the subsequent sections.

Boundary Delineation

The 1st consideration of any modeling techniques is to delineate the boundary. For this study the boundary has delineated based on the western part of coastal region of Bangladesh which include 8 (eight) Districts.

To simulate the Marine InVEST Model it was necessary to define the area of interest (AOI) based on the study site. An AOI instructs the model where to clip the Land Polygon input data in order to define the spatial extent of the analysis. The AOI's has projected using the WGS 1984_UTM_Zone_45 projected coordinate system to set the projection for the sequential intermediate and output data layers with the WGS1984 datum.

In order to allocate wind and wave information from the Wave Watch III data (WWIII), this AOI created in such way that must overlap one or more of the provided WWIII points. During the AOI selection it was also taken into consideration that, the western part of study area minimizes the boundary near the coast or river line. Around ten (10) Wave watch data found that fall on the study AOI layer which has been used for the calculation of wind and wave exposure through the simulation of model.

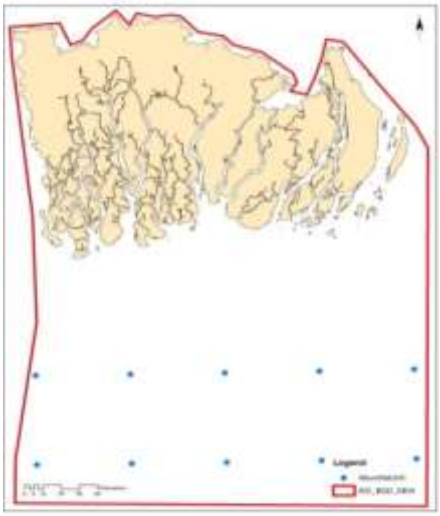


Figure 5.9: AOI with study bounary and WWIII point location

Relief or DEM

The SRTM-DEM (Shuttle Radar Topography Mission-Digital Elevation Model) for the study area has collected from the USGS Hydro shade (USGS 2006). The 90 meter spatial resolution surface elevation model has prepared for the hydrological analysis for various global level studies. Places that are, on average, at greater elevations above Mean Seal Level (MSL) are at a lower risk of being inundated than areas at lower elevations. Relief is defined in the model as the average elevation of the coastal land area from each shore segment of the discretized shoreline (Tallis, Ricketts et al. 2013).

The collected DEM has been pre-processed before simulation of the Marine InVEST model and other calculations. The main tricky matter of SRTM DEM for hydrological analysis and modeling approaches is to ignore the canopy (forest) height, which has not been ignored during the preparation of SRTM DEM. Thus the elevation of the area does not represent the actual height because of the canopy height. In order to solve this issue the average height (6 or 7) of the mangrove forest area has been subtracted from the actual SRTM DEM. The polygon feature of mangrove forest has been used to assign the subtracted values. The values has prepared based on the maximum standard (tolerable) height of mangrove area, shown in table 5.1. Then the forest area polygon has joined with other polygon which covers the rest of the study area with 0 meter height value. Then the joined polygon has converted to raster with same spatial resolution as the SRTM DEM and subtracted from the DEM. So, now the elevation of the area has changed and canopy height has nearly ignored.

Table 5.1: Values assigned to subtract the height of canopy (forest)

Number	Feature class	Value in meter (condition)	Subtracted value (m)
1	Mangrove forest	If ≥24	13
2	"	If ≥20	10
3	"	If ≥14<20	9
4	"	If ≥10<14	6
5	"	If ≥7<10	4
6	Planted forest	If ≥5<7	2
7	"	If <5	0
8	For rest of the area		0

Afterward the DEM has been filled in order to ignore the sink value and fill the empty cells inside the study boundary by using the *focal statistics* algorithm in ArcGIS. The NoData value has assigned as -32678 based on SRTM DEM data processing method to overlook confusion in ArcGIS. Thus for the sink area and empty cells the neighboring cell values was assigned according to (3*3) rectangular neighboring cells.

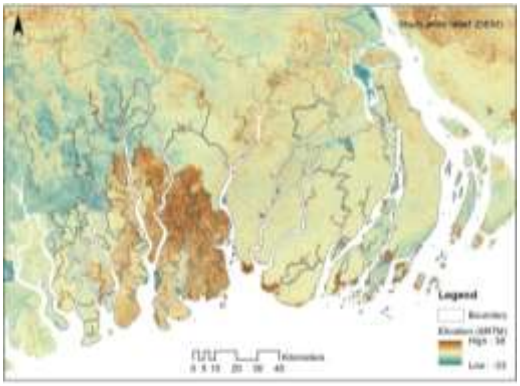


Figure 5.10: Before preprocessing of SRTM DEM

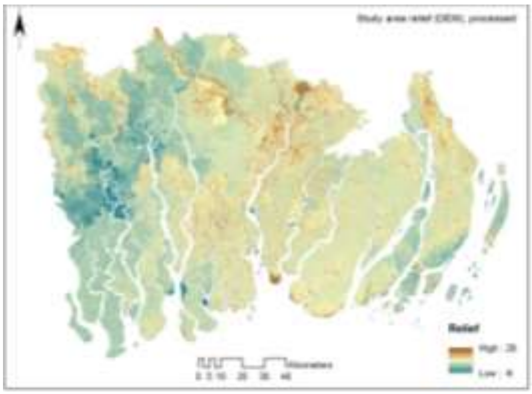


Figure 5.11: Relief after processing of SRTM DEM

Figure 5.10 and figure 5.11 portrait the study area elevation information before and after preprocessing of SRTM-DEM.

Bathymetry and Continental shelf

Bathymetry is the measurement of the depth of the water bodies including oceans, seas, rivers and lakes etc. Bay of Bengal, the largest bay of the world, covers a watery of 2.2 million km² and reaches a depth of up to of 5,258 meters (Kader, Chowdhury et al. 2013). It is located between latitudes 5°N and 22°N and longitudes 80°E and 95°E, and bordered by Sri Lanka, India, Bangladesh, Myanmar, and the northern Malay Peninsula. A continental shelf is the part of the edge of a continent between the shoreline and the continental slope (continental shelf. (n.d.). Retrieved January 19th). It is covered by shallow ocean waters and has a very gentle slope.

For the purpose of this study bathymetric elevation point dataset was collected provided by the Bangladesh Navy (BN) and interpolated to identify the continental shelf near the coast of study area. From the elevation point data the raster bathymetry layer has created using Kriging interpolation with 250 meter spatial resolution and then generated contour line in 20 meter interval. This contour then converted to vector polygon layer which has used as the continental shelf of Bay of Bengal near the study area. This continental shelf layer has been used as the input of InVEST model to compute the average depth along the fetch layers to determine the exposure of each shoreline segment and in the computation of surge potential.

The maximum depth of the bathymetry found around 970 meter on the south-western part in Bay of Bengal near Indian Ocean, shown in figure 5.12. The continental shelf of central part of the bay has found to be comparatively flat and continental shelf was found to be extended around 150 to 200 m (Kader, Chowdhury et al. 2013).

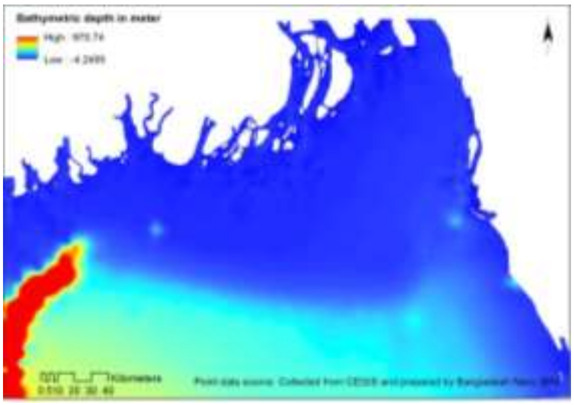


Figure 5.12: Depth of Sea bathymetry

Natural Habitat

Natural habitats (sea grass beds, mangroves, coastal dunes etc.) play a vital role in decreasing coastal hazards that harm shorelines and coastal community (Tallis, Ricketts et al. 2013). A large portion of the study area is covers by mangrove forest which is one of prominent natural habitat. Mangroves and coastal forests dramatically reduce wave height in shallow waters and decrease the strength of wave and wind generated currents.

At the initial stage of CVI model simulation the habitat layer has not used as an input in order to keep that for model sensitivity analysis. The approach of processing on habitat layer based on fact has described in later on the model sensitivity analysis section.

Climatic Variables

Three climatic variables such as wind, wave and surge height have been considers during simulate the Coastal Vulnerability Index model in InVEST tool framework. Surface water elevation was calculated using the tidal gauge water level time series (from 1980 to 2009) dataset.

Wind and Wave Exposure

To estimate the importance of wind exposure and wind-generated waves, a shape file with default wind and wave data compiled from 6 years of WAVEWATCH III (WW3) (Tolman 2009) model hind cast reanalysis results collected from InVEST model website. The relative exposure of a reach of coastline to storm waves is a qualitative indicator of the potential for shoreline erosion. For each of the 16 equiangular wind sectors, the average of the highest 10% wind speed, wave height and wave power have been computed from the WAVEWATCH III dataset. The model estimates the relative exposure of a shoreline segment to waves by assigning it the maximum of the weighted average power of oceanic waves. If there is no record of time series in a particular sector because only weak winds blow from that direction, then average wind speed in that sector is assigned a value of zero (0). It should be noted that, in the model, wind direction is the direction winds are blowing FROM, and not TOWARDS (Tallis, Ricketts et al. 2013).

Surge potential

Storm surge elevation is a function of wind speed and direction, but also of the amount of time wind blows over relatively shallow areas. In general, the longer the distance between the coastline and the edge of the continental shelf at a given area during a given storm, the higher the storm surge. The model estimates the relative exposure to storm surges by computing the distance between the shoreline and the continental shelf contour created from the bathymetry information.

The model assigns a distance to all segments within the area of interest, even to segments that seem sheltered because they are too far inland, protected by a significant land mass, or on a side of an island that is not exposed to the open sea water.

5.2.2 Fetch calculation

The fetch (fetch length), is the length of water over which a given wind has blown. When it reaches shore it is the main factor that creates storm surge which leads to coastal erosion and flooding. Fetch length along with the wind speed (wind strength) determines the size (sea state) of waves produced, the longer the fetch and the faster the wind speed (Wikipedia 2014).

The 1st stage of the model (tire 0) was to calculate the fetch distance with the threshold distance value of 12500 meters to determine if the current segment is enclosed by land or not. For a given coastline segment, the model has estimated fetch distances over each of the 16 equiangular sectors. The maximum fetch distance (51069 meter) is in southern part of the coast which is adjacent to the sea shore. And the minimum length is 1on the north-west part. Thus the maximum wind speed should be higher near the shore line of south coast. The calculated fetch distance grid has plotted in Appendix D1.

5.2.3 Coastal Exposure Index

The model computes the physical exposure index by combining the ranks of the four biological and physical variables at each shoreline segment. Ranks vary from very low exposure (rank=1) to very high exposure (rank=5), based on model-defined criteria (Table 5.2). This ranking system is based on methods proposed by Gornitz et al. (1990) cited from InVEST online user manual (Tallis, Ricketts et al. 2013).

Table 5.2: List of bio-geophysical variables and ranking system

Rank	Very Low	Low	Moderate	High	Very High
Variable	1	2	3	4	5
Relief	0 to 20 %	21 to 40 %	41 to 60 %	61 to 80 %	81 to 100 %
Wind Exposure	0 to 20 %	21 to 40 %	41 to 60 %	61 to 80 %	81 to 100 %
Wave Exposure	0 to 20 %	21 to 40 %	41 to 60 %	61 to 80 %	81 to 100 %
Surge Potential	0 to 20 %	21 to 40 %	41 to 60 %	61 to 80 %	81 to 100 %
Natural Habitats	Mangrove	-	-	Sea grass	No habitat
The color code and values indicate the ranking factors for assessing vulnerability. Red color with ranking value 5 indicates high vulnerability and dark green with value 1 very low vulnerability.					

Source: Adapted from Gornitz et al. (1990) and cited from (Tallis, Ricketts et al. 2013)

Calculate Coastal Exposure index (CEI^3)

After simulation of the Marine InvEST model, the exposure index (CEI^3) has calculated in relation to the three ranking parameters i.e., wind and exposure and potential surge height. The variables were ranked by the physical process based model itself during the simulation periods. The formula to calculate Exposure index (EI) for each shoreline segment as the geometric mean of all the variable ranks, shown in equation 1.1:

$$\boldsymbol{CEI^3} = (\boldsymbol{Wi} * \boldsymbol{Wa} * \boldsymbol{S})^{\frac{1}{3}} \ldots \ldots \ldots (\mathbf{1.1})$$

Where, CEI^3 = Coastal Exposure Index based on four parameter

Wi = wind rank

Wa=wave rank

S=surge potential rank

During the calculation all the values was multiplied in each grid by grid cell basis. Thus the maximum value of CEI^3 was found 125 and minimum 1. After calculating the exposure index (CEI^3), the raster grid has converted to point vector data format and interpolated using the Natural Neighbor Interpolation algorithm in ArcGIS. The algorithm computes the closest subset of input samples to a query point and applies weights to them based on proportionate areas to interpolate a value (ESRI 2013). The interpolated raster layer calculates the value of exposure index based on its nearest grid of shoreline segment. This output has extracted by the study area mask and to get the accurate area specific exposure index (CEI^3).

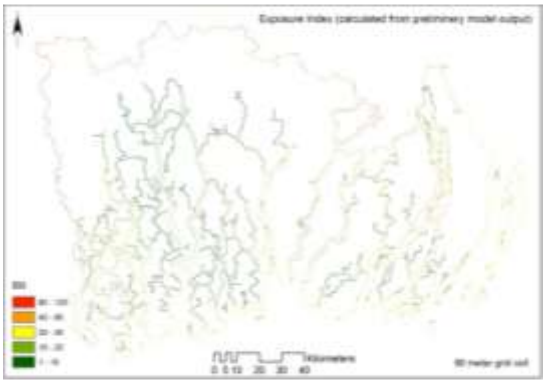


Figure 5.13: Exposure Index 3 (EI3) (model simulated)

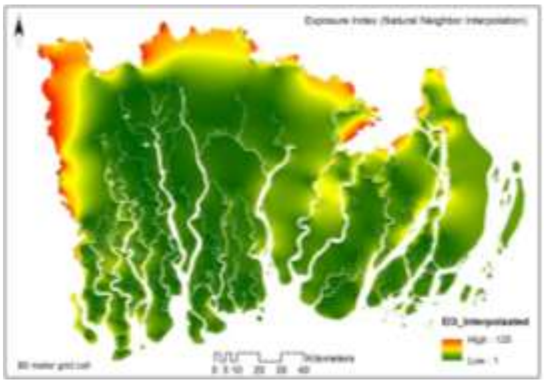


Figure 5.14: Coastal Exposure Index 3 (CEI3) using natural neghbour interpolation

DEM rescaling

In order to ignore the biasness of weighted values (error) of parameter DEM has rescaled in reverse order where 1 for high elevation and 5 for low elevation area, shown in figure 5.15. All variables have been normalized and rescaled using same equations.

Formula 2.1 was used for general normalization and formula 2.2 has used to normalize the data in reverse word after word in necessary cases. As for the rescaling equation has been specified regarding the relief (DEM) of the study area where both equation was used to normalized the data reverse order in the scale of 1 to 5, 1 for high elevation and 5 for low elevation area.

Formula to rescaling of SRTM DEM-

$$\boldsymbol{R' = 1 + \left[\frac{(R - Min(R)}{(Max(R) - Min(R))}\right] * 4} \dots\dots\dots\dots (\mathbf{2.1})$$

The reverse order assigned to rescale DEM through the following equation-

$$\boldsymbol{R = 5 + 1 - R'} \dots \dots \dots \dots (\mathbf{2.2})$$

Calculate Coastal Exposure Index (CEI4)

To calculate the Coastal Exposure Index (CEI^4) following formula has to be applied, where all the parameter has been multiplied with the inverse power of total number of parameters.

$$\boldsymbol{CEI^4 = (CEI^3 * R)^{1/4}} \dots \dots \dots \dots \dots (\mathbf{1.2})$$

Where, CEI^3 = multiplied value of wind, wave and surge potential.
And R indicates rescaled relief (elevation) value of the study area.

But for the continuation of work flow and to reach at the target point smoothly here the multiplied values of all four parameters has kept unchanged and has not assigned the power factor (0.25) to get the exact value of EI4 scaled in 1 to 5.

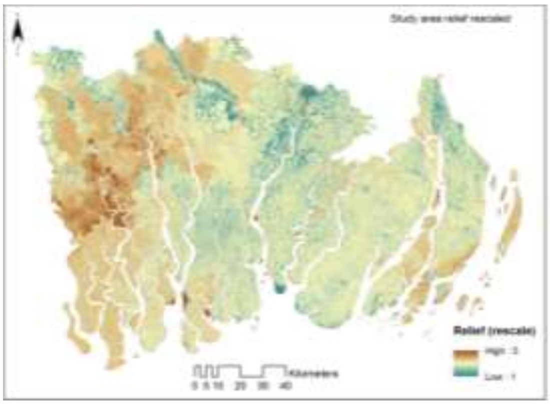


Figure 5.15: Rescaled relief for calculation of CEI4

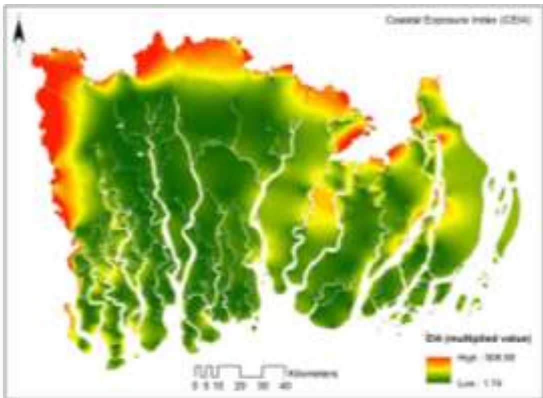


Figure 5.16: Coastal Exposure Index (CEI4)

Figure 5.16 represent the calculated CEI 4 with wind exposure, wave exposure, surge potential and relief of the whole study area. Here the multiplied value output has considered the final CEI4 covering the study area, where the maximum value is 506.58 and the minimum value is 1.74.

5.3 Population Vulnerability Index (PVI)

The aim of this research was to analyse the vulnerability of coastal area population due to various natural calamities due to Sea level rise such as wind, wave, storm surge, tidal flooding etc. To model the Population vulnerability Index result seven parameters have considered, which are-

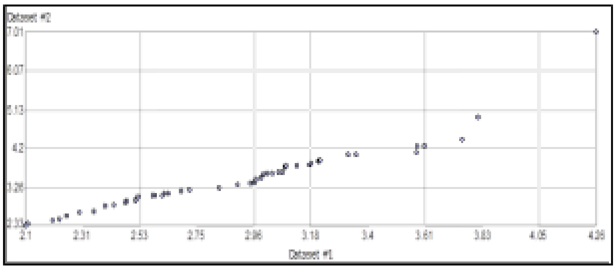
- Wind exposure,
- Wave exposure,
- Potential surge height,
- Relief (DEM),
- Distance from the shoreline for each population grid,
- Water Level (Depth) and
- Population density (gridded population)

All the parameters have rescaled in 1 to 5 according to the vulnerability index rank using the similar equation 2.1 for same order and then equation 2.2 for reverse order in the case of distance. The calculated PVI is the geometric mean of all the variable ranks and rescaled.

5.3.1 Water depth (flood inundation) calculation

Water depth has been calculated from the time series water level (WL) data (1980 to 2009) of 48 tidal and river gauge stations. Each station is introduced by the river name and ID (example shown in Appendix E1). The time series data was normalized to identify outliers and missing data. For the case of all missing data -9999 values has assigned. The mean and maximum water level has calculated from the normalized dataset. The maximum high water level has identified from the calculated mean values through the iteration process by changing the number and name of months.

Finally it was found that from month of June to September the WL reached at the pick, where the maximum WL is 7 m at station Chapra (station ID 25) which is the south western part in district Satkhira. The maximum mean water level is 4.26 m.



Dataset#1: Tidal WL, Attribute: Mean WL
Dataset#2: Tidal WL, Attribute: Max_ WL

Figure 5.17: Distribution pattern of mean vs maximum water level

The Predicted WL for the next 10 years (2020) has been calculated by considering the 29 years observed value of 48 river stations (gauge data). The *'predict function'* in R package has been used to calculate the predicted WL. Each station wise predicted value has generated from the previous 29 years observed data of that station. The calculated mean and maximum WL, existing end year water level in 2009 and the predicted values of WL in 2020 has presented tabular format in Appendix E2. The R script to calculate mean and predicted water level has been demonstrated in Appendix F.

Table 5.3: Exploratory analysis of four water level scenarios

Descriptive statistics	Mean_WL	Max_WL	WL_2009	Pred_WL_2020
Mean	2.898	3.454	3.034	3.117
Standard Error	0.069	0.113	0.087	0.108
Standard Deviation	0.480	0.780	0.600	0.750
Skewness	0.469	2.038	0.081	0.037
Minimum	2.095	2.325	1.827	1.504
Maximum	4.262	7.008	4.367	4.544
Confidence Level (95.0%)	0.139	0.226	0.174	0.218

After calculation of the mean, maximum and predicted values of WL, the attribute dataset was joined with the station point vector data to get the latitude and longitude of all station point. To calculate water depth, values have categories in four levels based on mean, maximum, WL in 2009 and predicted WL in 2020. The Universal Kriging Interpolation (*Exponential covariance model*) technique was used to interpolate the water surface area in ArcGIS through an iteration process by changing the parameter values of model to minimize the prediction error. From previous studies it was appraised that, in geo-statistical interpolation problems, the exponential covariance model are well defined for interpolation of continuous surfaces, particularly in case of weather related variables (EPA 2004). The performance of the interpolation was assessed using cross validation. In order to get best option of low error rates we use two criterions: mean error (ME) and root mean squared error (RMSE). If the ME of Kriging interpolation is smaller or (closer to zero) and the RMSE is closer to one (1) then the interpolated output is being considered as the best fit. Several tries were done to reduce the mean error. After fixing the error issues same model with similar values of all parameter were tried to assign during the interpolation of four type of measure water level. Thus, the outputs will not be biased due to method properties.

Table 5.4: Method properties of Universal Kriging Interpolation

Variable	Model type	Neighbors		Cross validation results			
		Type	Factor	Mean	RMSE	RMSS	Regression Function (R^2)
Mean_WL	Exponential	Smooth	0.2	-0.027	0.35	2.99	0.524
Max_WL	“	“	“	-0.030	0.70	2.15	0.452
2009_WL	“	“	“	-0.029	0.50	3.44	0.337
Pred_WL	“	“	“	-0.031	0.68	3.16	0.274

Table 5.4 represents the method properties for each interpolation which indicates that the water depth has predicted near about right way where all the mean error is closer to zero. And the Root Mean Square Error (RMSE) mostly closer to one (0.7).

Table 5.5: Correlation matrix of different water level scenarios

Water Level (WL)	Mean_WL	Max_WL	WL_2009	Pred_WL_2020
Mean_WL	1.000			
Max_WL	0.747	1.000		
WL_2009	0.831	0.718	1.000	
WL_2020	0.686	0.640	0.974	1.000

Table 5.5 shows that the correlation between the mean and maximum water depth is 0.747, which indicates that both are distributed properly and in similar pattern.

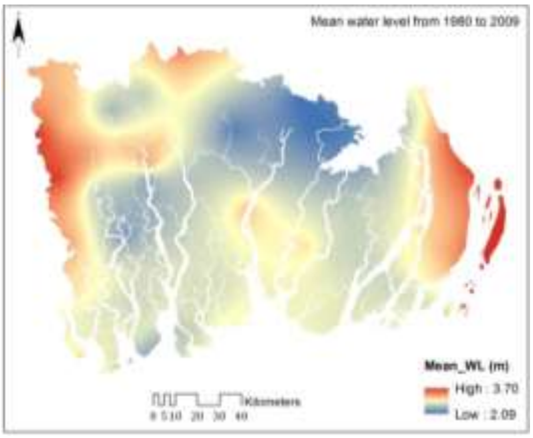


Figure 5.18: Interpolated mean water level during high tide

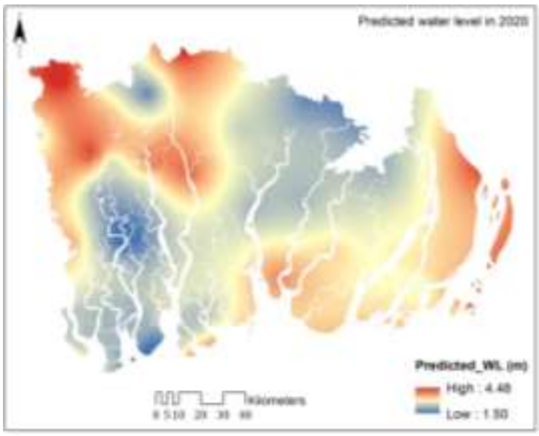


Figure 5.19: Predicted water level in 2020 from previous 29 years data

Figure (5.18) and figure (5.19) demonstrate the interpolated water depth based on mean and predicted (2020) values of water level. After calculation the depth of water each (4) category has rescaled according to the highest maximum value and lowest minimum values among four categories. The maximum water level was found **7.00** m on the interpolated output of maximum water level (Shown in Appendix D2) and the minimum water level was **1.54** m on the calculated water depth based upon the predicted year 2020. Here during the normalization of water depth variables similar maximum and minimum value has assigned for all four water level categories to minimize the error of weight factor, which means after rescaling the maximum value will remain maximum in (1 to 5) scale and the minimum value will be minimum. Otherwise, if individual maximum and minimum values has assigned for rescaling the output value will be biased which has checked during the rescaling process.

5.3.2 Distance calculation

Another parameter was identified for calculating the PVI that is the distance from the coastline of each population grid cell. Vulnerability to coastal area is considered to depend directly on the distance between the element and the coastline. The distance for each population grid from the shoreline was calculated using the Euclidian Distance function in ArcGIS, where the calculated distance value for each grid cell is the distance from the nearest coast line grid of exposure index.

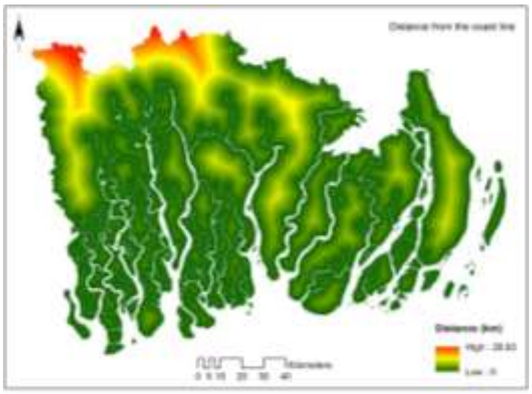


Figure 5.20: Distacne from the nearest pint of shore line

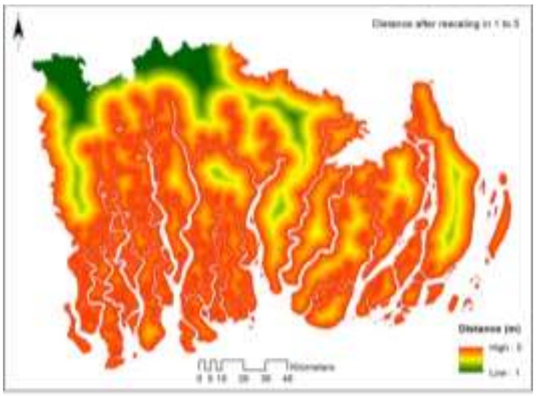


Figure 5.21: rescaling of distnace 1 to 5 based on long to short order

Figure 5.20 shows that the maximum distance from coastline to each population grid was 28.93 km, which is on the north-west part of the study area. And the minimum zero distance found near the coast which is rational. The calculated distance was rescaled in reverse order shown in figure 5.21, where 1(very low vulnerability) for long distance and 5 (very high) for short distance from the coast line.

5.3.3 Calculate Population Vulnerability Index (PVI)

Finlay the population Vulnerability Index (PVI[7]) has calculated by multiplying the values of CEI4, Water Depth and Distance with the inverse power of total number (7) of parameters. The formula is as follows-

$$\boldsymbol{PVI^n = (CEI^4 * Wd_n * D * P)^{\frac{1}{7}}} \ldots\ldots\ldots\ldots (\mathbf{1.3})$$

Where, PVI = population Vulnerability Index

CEI^4 = Coastal Exposure Index based on four parameters (wind exposure, wave exposure, surge potential and relief)

n = Water level in mean/ maximum/2009/ predicted 2020 category

Wd_n = calculated water depth in certain category (n)

D = Distance from the shoreline of each population grid points

P = Rescaling of calculated population grid

The Population vulnerability Index (PVI) has calculated by considering the water level or depth in 2009 as the base year and in year 2020 as the year of predicted water level. Figure 5.22 and figure 5.23 are the two major study outcomes through analyses and calculations of all variables. From the model outcome high exposure rate was found 3.62 and 3.59 in year 2009 and 2020, where the low rank was 1.51 and 1.53 correspondingly.

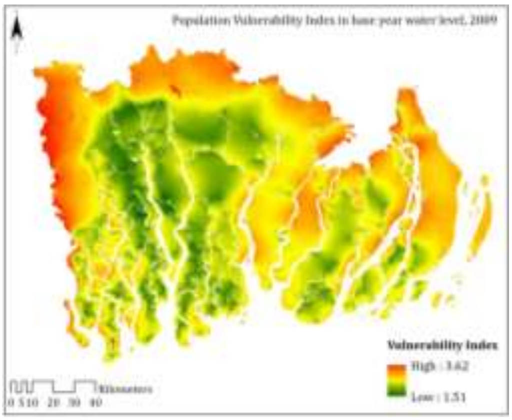


Figure 5.22: Population Vulnerabilty Index Model (PVI) in year 2009

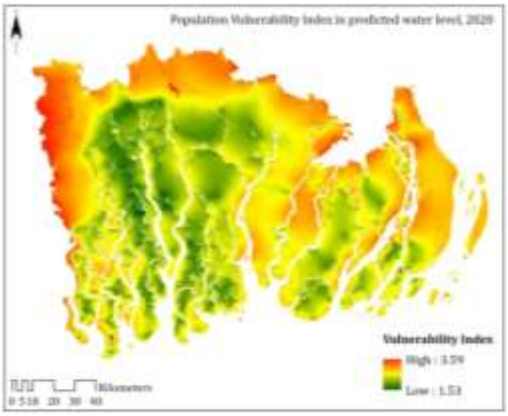


Figure 5.23: Population Vulnerabilty Index Model (PVI) in predicted year 2020

Some further analyses of these results are presented in section 5.5 , but prior to that the model sensitivity analyses have examined.The detailed discussion based on the study findings has been illustrated in chapter six.

Table 5.6: Statistics of individual PVI[7] in different water level scenarios

PVI	Statistics of individual PVI[7] in different water level scenarios			
	MIN	MAX	MEAN	STD
ei7_09w1	1.5165	3.6207	2.4834	0.3491
ei7_20w1	1.5311	3.5941	2.4936	0.3497
ei7_mxw1	1.5257	3.7725	2.5249	0.3560
ei7_mnw1	1.4938	3.6640	2.4661	0.3496

The PVI for the mean and maximum mean water level of 29 years observed data (1980-2009) has been used during the model evaluation (sensitivity analysis) process. Thus the PVI regarding these two calculated water depth will be explained in the next discussion chapter.

5.4 Model Sensitivity Analysis

It is to mention here that, to identify a definite evaluation criterion, it requires more review on similar studies and time. But due to time constraint the model just considers two influential factors, i.e., mangrove distance and water level scenarios. Firstly the model result evaluated based on different water level scenarios i.e., maximum observed value for 29-year period and predicted value in 2020. And the other one was the distance factor indicates the value of each grid cell of population as the nearest distance value of mangrove grid cell based on the mangrove area coverage.

5.4.1 Based on different water level Scenarios

To evaluate the model result two water level scenario have been used and calculated the Population Vulnerability Index (PVI[7]) to see how the model result stimulated by new value of same parameter.

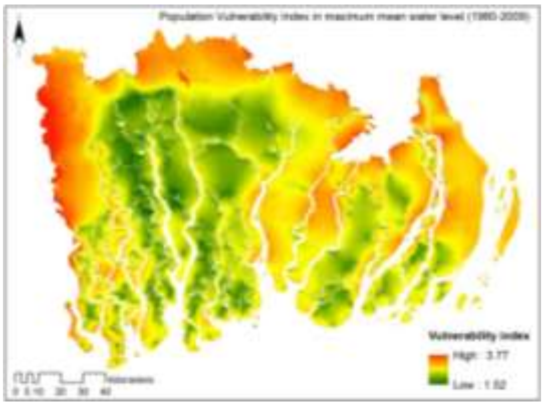


Figure 5.24: PVI calculated for maximum water level of 29 years observed data

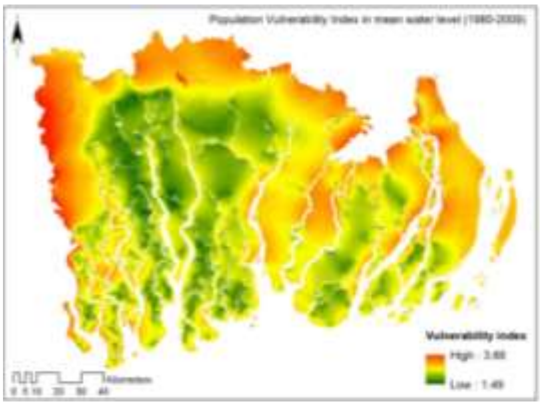


Figure 5.25: PVI calculated for mean water level of 29 years observed data

Figure 5.24 and figure 5.25 shows that for maximum mean water level of 29 years period of observed data, where the vulnerability ranges from 3.77 to 1.52 and from 3.66 to 1.49 correspondingly, although the visual appearance of both of them are almost similar.

5.4.2 Based on natural habitat

Based on previous study findings and ecological knowledge portal mangrove forest plays an important role to mitigate disaster and climatic hazard in the coastal area of Bangladesh. By considering its importance, the population vulnerability index (PVI) model has intended to evaluate based on the presence and absence of mangrove forest by changing the proportion of mangrove forest area. Due to presence of mangrove the near shore area became more protected.

About 25% of the study area is covers by the mangrove forest (4271 sq.km), is an important natural habitats for the coastal community and the ecology as a whole. Around 3604 sq.km forest area covered by the exterior coast on the west to southern part of the study area and rest of the area (667 sq.km.) encloses the interior coast.

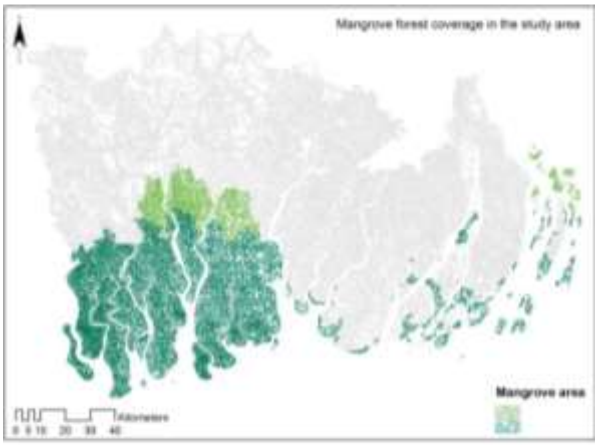


Figure 5.26: Mangrove forest in the study area

Firstly the mangrove area shape file (vector format) (collected from CEGIS, Bangladesh) has converted to raster grid format. Then the distance has calculated from the mangrove area to each population grid point by using Euclidian distance tools in ArcGIS.

After that, the distance has been rescaled in equivalent order where 1 (very low) for short distance and 5 (very high) for long distance from the shoreline. Mangrove forest could play a vital role to mitigate coastal hazard, as considered the 2nd hypothesis. Thus, the area with mangrove has assigned as low vulnerable zone in ranking.

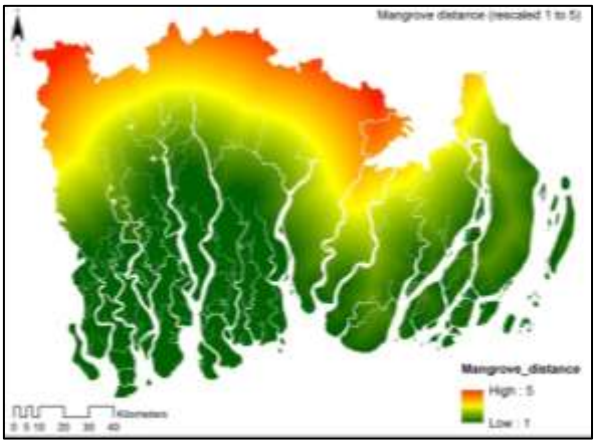


Figure 5.27: Rescaling of mangrove area based on distance

The Population Vulnerability Index (PVI[7]) has been multiplied with the distance of mangrove forest to see the impact of mangrove in the study area. The distance has calculated according to the presence of mangrove forest. Near to the forest area the distance has ranked as the low vulnerable and longer distance as the high vulnerable range. It is to be noted that, if the mangrove could be considered based on the proportion of area directly to assign the vulnerability ranking factor (1 to 5), then the research findings would be more precise. This issue needs to consider for further study.

PVI^8 (with the presence of mangrove forest) has been calculated and the result shows that the amount of vulnerable area has decreased, which indicate the importance of conservation of natural habitat to mitigate disaster. The correlation between with and without mangrove forest is about 0.93, where the significance difference is about 7%.

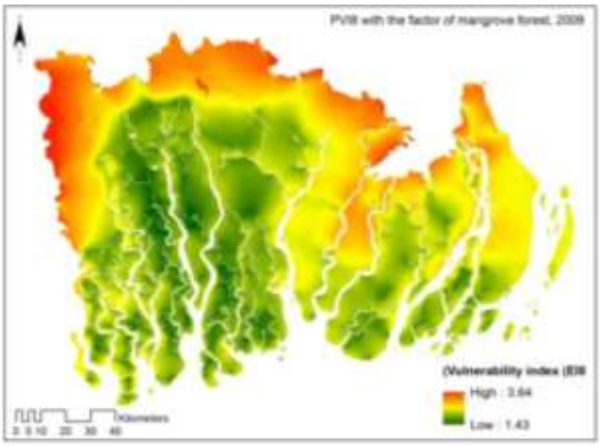


Figure 5.28: PVI^8 with considering mangrove influence to mitigate vulnerability

5.5 Major Study Findings

To interpret the result from the Population Vulnerability Index Models (PVI^7s), the main study outcomes several analyses have carried out. All analysis have carried out by considering the PVI^7 model in 2009 (water level) and some outcomes after the sensitivity analysis with the presence of mangrove forest. This section has been separated based on people, area and land use category to identify the resultant vulnerability impact in each sector. All the graphs and tables displayed here has generated based upon the outcome of PVI^8, PVI^7 and PVI^6 (excluding population) models. The research hypothetical questions has been tried to answer at this point.

5.5.1 Correlation matrix

Table 5.7: Correlation matrix of PVI's based on different water level scenarios

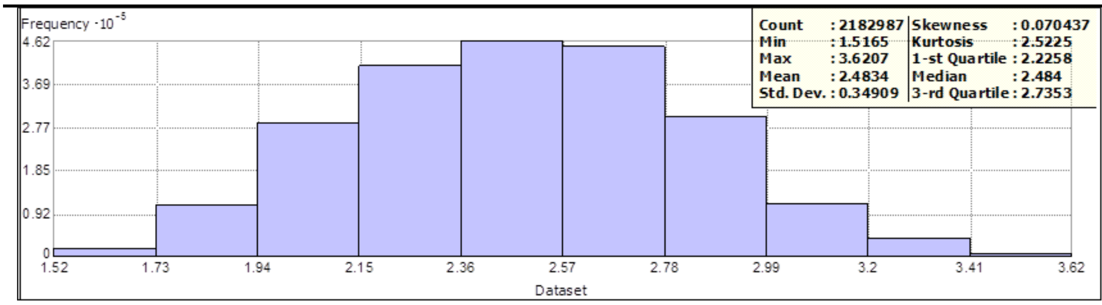
PVI	Correlation matrix of PVIs in different water level scenarios			
	ei7_2009wl	ei7_2020wl	ei7_maxwl	ei7_meanwl
ei7_2009wl	1.000	0.999	0.995	0.997
ei7_2020wl	0.999	1.000	0.992	0.994
ei7_maxwl	0.995	0.992	1.000	0.997
ei7_meanwl	0.997	0.994	0.997	1.000

Table 5.7 illustrates that, the PVI^7 in 2009 (water level) and the PVI^7 in 2020 (predicted water level) has the difference is about 0.001, whereas it differs from 0.008 to 0.003

compared to mean and maximum water level scenarios. The major study findings in detail have been described in the subsequent sections.

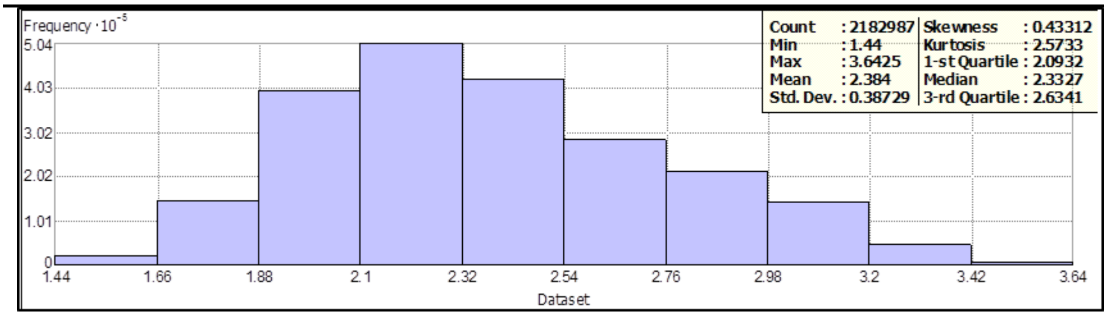
5.5.2 Analytical findings and mapping

The Final study output PVI[7] model calculated in 2009 and 2020 (predicted water level) has been compared by computing the histogram plot with PVI[8] (vulnerability range with mangrove forest). Three histograms were plotted; those are PVI in 2009 with and without mangrove and PVI[7] in 2020.



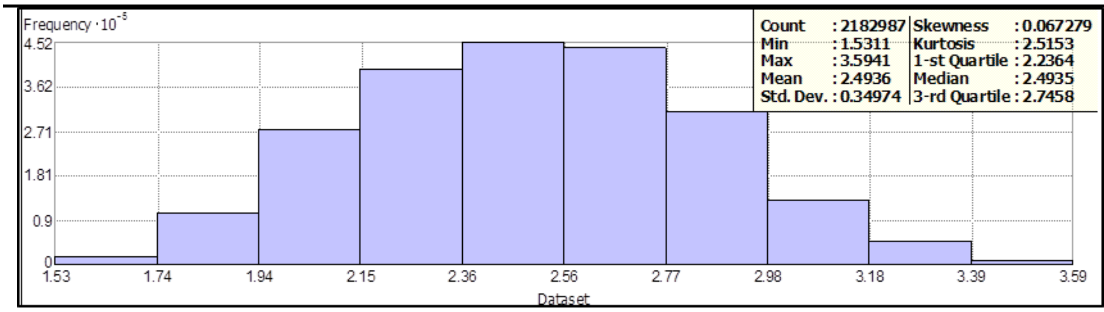
Dataset: PVI in 2009 without mangrove, Attribute: grid_code (vulnerability)

Figure 5.29: Histogram of PVI[7] without mangrove forest



Dataset: PVI in 2009 with mangrove, Attribute: grid_code (vulnerability)

Figure 5.30: Histogram of PVI[8] with the presene of mangrove forest



Dataset: PVI in 2020 (Predicted), Attribute: grid_code (vulnerability)

Figure 5.31: Histogram of PVI7 in 2020 with predicted water level

Figure 5.29 and figure 5.30 are the comparison between the calculated PVI models with and without mangrove forest. PVI with mangrove is more positively skewed (0.43) than the presence of mangrove where the skewness is 0.7. The distribution and skewedness of PVI model in 2020 has been plotted in figure 5.31. Here the mostly the vulnerability range 2.36 to 2.77 and normally distributed (positive skeweness only 0.06) which is moderate to high vulnerable group.

Mapping the study area based on number of people affected by various vulnerable categories due to hazard, area specific vulnerable zoning, histogram of landuse category in different vulnerability ranges etc., have prepared to understand the model results and make that easily understandable and interpretable.

Areas in different vulnerable range

Area has been calculated according to the range of vulnerability in the year of 2009. High (3.16-3.62) vulnerable area was found near the west coast in Satkhira district and some part of Bhola and Jhalokhathi district near the middle and eastern coast. Red colour is the high vulnerable group and green is less.

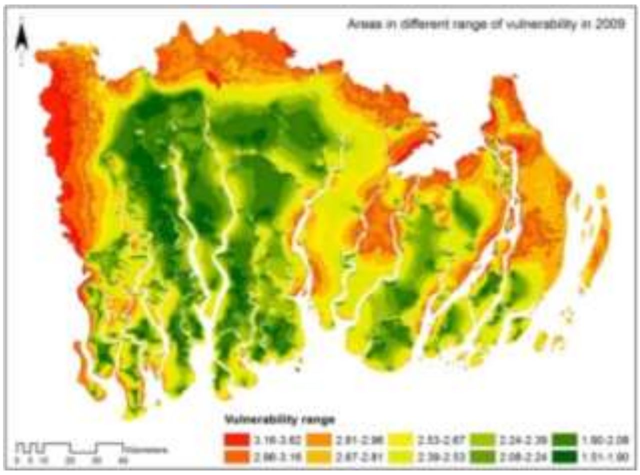


Figure 5.32: Vulnerable zone in different category

Most Vulnerable community

The most vulnerable community has been identified from the model output ranges from 3.05 to 3.64. Figure 5.33 represents the most vulnerable community in the north western part of the study area. Dark red is the high vulnerable community and the rest of area is moderate to less vulnerable mark as white.

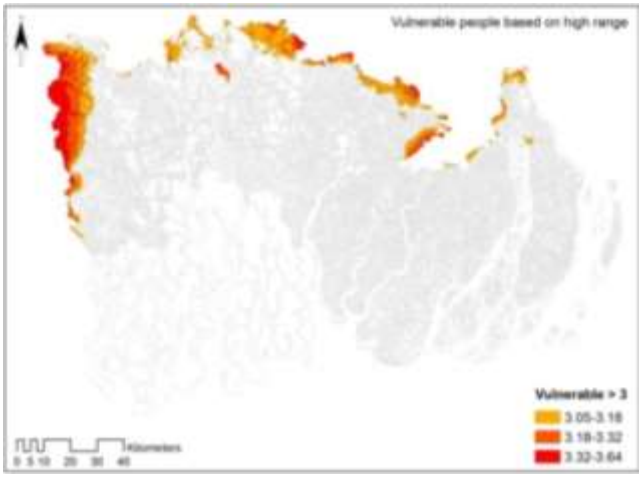


Figure 5.33: Most vulnerable community

Moderate Vulnerable community

To identify the people at moderate vulnerable group, a range between 2.08 to 2.93 has been plotted from the Population Vulnerable Index (PVI), shown in figure 5.34. Red indicates the maximum value and green indicate the minimum value. Near the mangrove forest area the people are less prone to disasters.

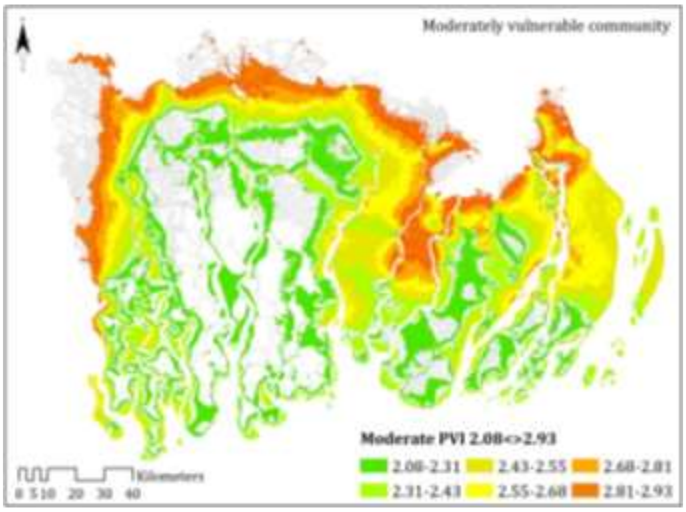
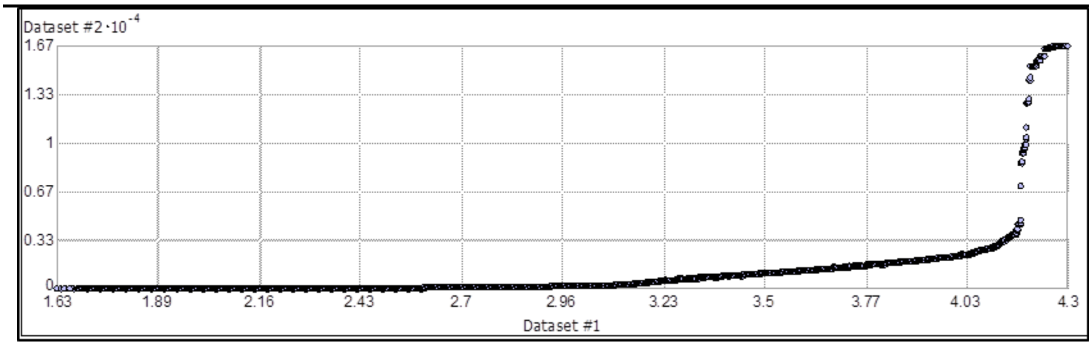


Figure 5.34: Moderate vulnerable community

Vulnerability vs. Population density

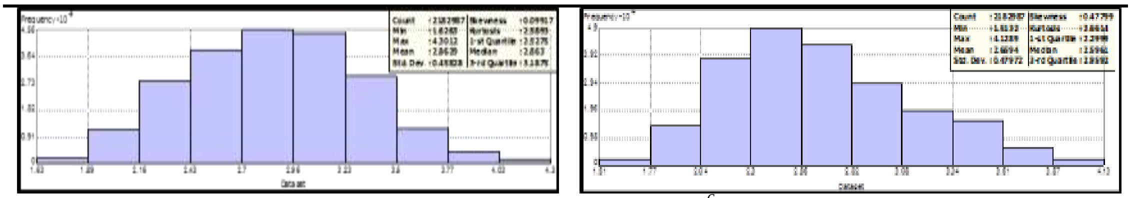
To know the exact number of people at risk due to climate change an attempt was taken to calculate the risk based on population distribution. The main hypothesis of this study was that high densely populated area is more vulnerable to climatic hazard than the less populated area. To verify that assumption a general QQ plot has calculated between the PVI^6 (vulnerability calculated from six biophysical parameters except population density) and gridded population density, shown in figure 6.8. It can be accomplished that the research hypothesis was factual, which is very clear from the following figure.



Dataset#1: PVI^6 in 2009 Water Level, Attribute: grid_code (vulnerability)
Dataset#2: Gridded Population Density, 2011, Attribute: grid_code (Population)

Figure 5.35: Relation between population density and vulnerability index

The QQ Plot (figure 5.35) shows that there is a positive correlation between the PVI6 and population density. Correlation between PVI^6 and Population density is about 0.131.



Dataset: PVI6 in 2009 WL (without mangrove), Attribute: grid_code (vulnerability)

Dataset: PVI[6] in 2009 WL (with mangrove), Attribute: grid_code (vulnerability)

Figure 5.36: Comparison between two PVI[7] (with and without mangrove)

Figure 5.36 portrayed that, PVI[7] (without mangrove) is more normally distributed than PVI7 (with mangrove), where the variation of skewness is 0.09 and 0.47 respectively.

Area coverage

The maximum areas in the study region shelter the vulnerable range of 2.08 to 2.96 which is low to moderate vulnerable zone. 434.88 sq.km areas are highly vulnerable. This analysis also indicates that the model result is consistent, as the settlement should be more or less liveable for the coastal community. Similar analysis could be done for the other PVIs.

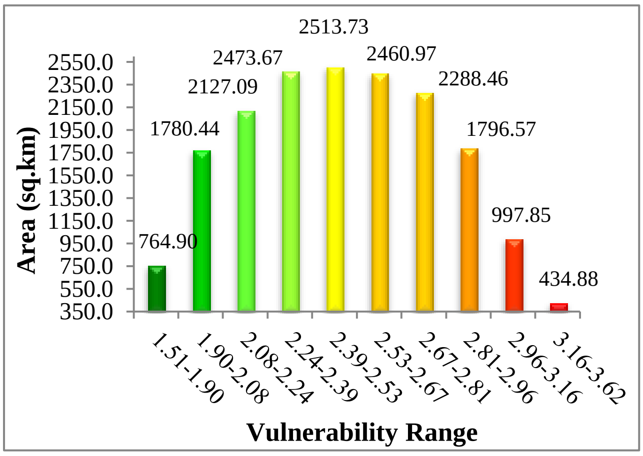


Figure 5.37: Area coverage in different vulnrable category

District wise vulnerable group

Figure 5.38 is the graphical representation of district wise vulnerable level, area in % for all vulnerable groups. The exposure range has been divided in 10 classes. The detail description based upon all the facts and findings have been illustrated in chapter six.

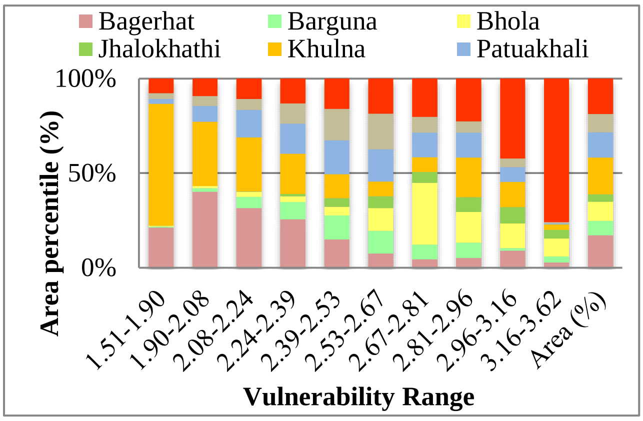


Figure 5.38: District wise vulnerable zone (area in %)

Vulnerable land use category with and without mangrove

An attempt was taken to identify the ratio of land use pattern in different vulnerable range. As for instance two histograms were plotted by considering the presence (figure 5.39) and absence (figure 5.40) of mangrove habitat.

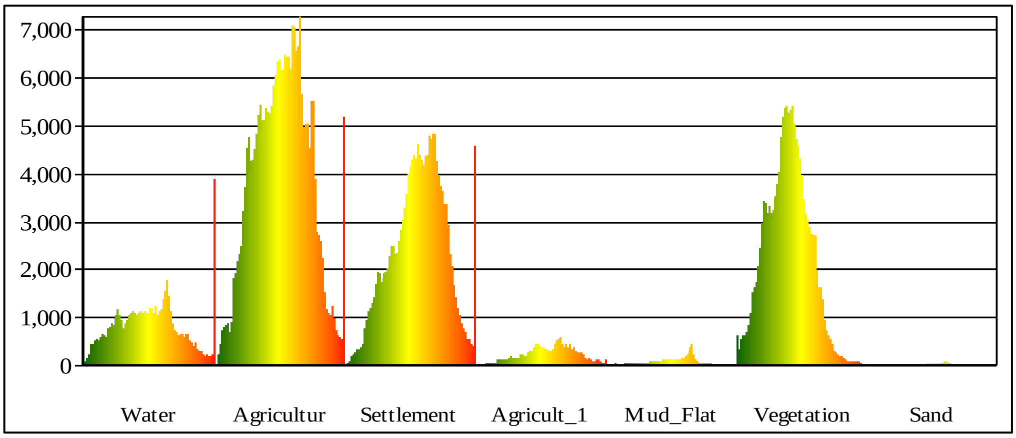


Figure 5.39: Histogram of landuse on different vunerabilty range without mangrove

Most of the land use category was almost similar percentage of high vulnerable and low vulnerable class. At that time the mangrove forest area was considered as empty and has no positive impact to mitigate hazard. Maximum area of settlement, water body, agricultural land and mud land were in moderate to high exposed category.

Afterward, another histogram has designed using the exposure index 8 (PVI[8]) where proportion of the mangrove forest area included modelling the PVI.

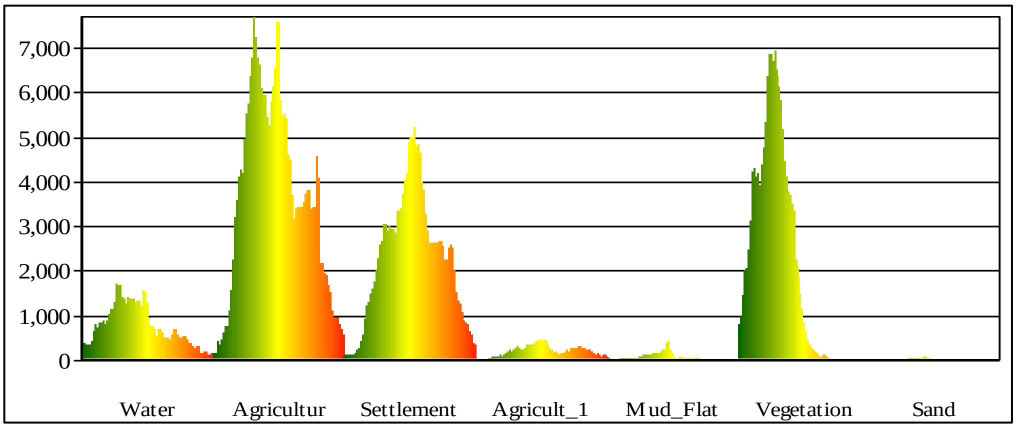


Figure 5.40: Histogram of landuse on different vulnerabilty range with mangrove

From the two histogram plots the influence of mangrove forest to protect coastal area has recognized. Figure 5.39 shows that, vegetation area is positively skewed towards high vulnerable range in absence of mangrove forest. The same land use area in figure 5.40 has dramatically changed and normally distributed after considering the presence of mangrove in the study area, in figure 5.40 where most of the area falls in low vulnerable category. For the settlement area green colour in figure 5.40 indicate that after considering the mangrove the area become more greener which is also the indication less vulnerable group. Agricultural crop land has the similar changing pattern with the presence and absence of mangrove forest.

Table 5.8: Comparison on vulnerable landuse classes with and without mangrove

CLASS_NAME	PVI^7 without mangrove (2009)				PVI^8 with mangrove (2009)			
	MIN	MAX	MEAN	STD	MIN	MAX	MEAN	STD
Water	1.52	3.54	2.47	0.40	1.44	3.56	2.34	0.40
Agricultural Land (Fallow)	1.55	3.50	2.51	0.34	1.47	3.51	2.46	0.37
Settlement	1.57	3.62	2.60	0.33	1.49	3.64	2.56	0.35
Agricultural Land (Crop)	1.66	3.44	2.62	0.32	1.59	3.51	2.59	0.38
Mud Flat	1.57	3.46	2.54	0.30	1.49	3.22	2.31	0.25
Vegetation	1.53	3.35	2.29	0.27	1.45	2.88	2.06	0.21
Sand	1.61	2.96	2.54	0.20	1.51	2.59	2.26	0.15

Source: Author, 2014

The comparison and change of land use category with the presence and absence of mangrove forest has been depicted in table 5.8. In both cases of PVIs the maximum vulnerability ranges from 3.62 and 3.64 are lies on settlement. Also it has found that the minimum rate vulnerability for the settlement has reduced to 1.49 from 1.57, though the overall vulnerability rate in PVI^8 (with mangrove) seems bit higher than the previous PVI^7 (without mangrove).

Chapter 6
Discussion and Critical Review

6.1 Discussion of Model Outcomes

All analysis fact ad findings have described by considering the PVI models in 2009 (water level) and in 2020 predicted water level and some outcomes after the sensitivity analysis. From the correlation matrix among all four PVIs it is found that the variable of different water level scenarios has more or less similar impact in coastal area, as maximum water level during high tide has been identified prior to the water level interpolation. But the presence of eighth variable distance based on mangrove forests area coverage has more influence to change the rate of vulnerability negative to positive direction.

Most Vulnerable community

From the model outcome based on all scenarios most vulnerable community has found on the north-western part of the study area situated in Satkhira district ranges from 3.32 to 3.64. A very small part of Khulna and Khulna and Bagerhat district also found to be highly vulnerable due to storm surge, cyclone and flood inundation. Middle part of the study area found to be less vulnerable to climatic hazards. The western border is enclosed by Ganges River basin and where high velocity of wind and wave generated during storm surge.

The most vulnerable zone has found far from the southern coast but which is near the Ganges basin and Meghna Estuary. A huge amount of water comes during monsoon because of high tidal flow and hit the area where the rivers ended. Thus the areas near the shore line less vulnerable (Mangrove forest protected area) then the area near the Ganges basin and Meghna Estuary.

Moderate Vulnerable community

Mostly Pirojpur and Barguna District on the eastern and central part of the study area near the Meghna Estuary are moderately exposed to tidal surge and inundation. Also the eastern part of Bhola district sifts on this vulnerable category. Most of the areas enclosed by the mangrove forest are less vulnerable ranges from 2 to 2.5 in the moderate level.

Thus around 40% of the people lie on the moderate vulnerable group. If some remedial measures have taken this area and community people could be safe from devastating disasters.

Vulnerability vs. Population density

The average population density of the study was 1031.89 per sq.km with the maximum and minimum of 1582 and 705 per sq.km correspondingly. From the population vs. vulnerability range it is found that, the maximum population density area reached at the peak of venerable range, 3.16 to 3.62 which is nearly covers 1600 people per square kilometre. The correlation between the population density and PVI[6] (without mangrove) is 0.13 whereas with mangrove is 0.21.

Table 6.1: Correlation matrix of population density and PVI[6]s

Layer 1-Gridded Population, Layer 2- PVI[6] (without mangrove), Layer 3- PVI[6] (with mangrove)								
Descriptive Statistics of PVI's					Correlation MATRIX			
Layer	MIN	MAX	MEAN	STD	**Layer**	1	2	3
1	0.000	16659.00	329.669	617.565	1	1.000	0.131	0.211
2	1.626	4.301	2.8629	0.4583	2	0.130	1.000	0.932
3	1.513	4.129	2.659	0.479	3	0.211	0.932	1.000

Source: Author, 2014

Thus it can be accomplished that, high densely settlement are severely prone to natural disasters. So, in future land use plan in a uniform pattern has to be planned to mitigate the vulnerable community from upcoming disaster. Future resettlement action plan needs to be proposed for the densely populated community.

Area coverage

Only 434.88 sq.km area indicates the vulnerable array greater than 3 which is moderate to high vulnerable group. Table 6.2 demonstrates the whole study area in different vulnerable group disjointed by district. Again it was found that, most vulnerable district is Satkhira and Khulna where peoples are at risk due to cyclone, storm surge and tidal flooding.

Table 6.2: District wise area distribution based on vulnerability range

Vulnerability Range	**District wise area (sq. km)**								**Tot. Area (sq.km)**
	Bagerhat	Borguna	Bhola	Jhalokhathi	Khulna	Patuakhali	Pirojpur	Satkhira	
1.51-1.90	161.4	4.5	3.1	0.0	492.9	19.5	24.2	59.2	764.9
1.90-2.08	714.3	32.7	20.6	1.1	603.9	149.0	92.2	166.7	1780.4
2.08-2.24	670.0	123.9	58.1	3.9	608.8	309.8	119.8	232.8	2127.1
2.24-2.39	630.9	224.6	76.6	28.3	527.4	394.7	263.1	328.0	2473.7

2.39-2.53	374.1	318.1	114.4	117.3	319.3	450.1	414.9	405.5	2513.7
2.53-2.67	180.8	299.3	291.8	157.0	188.8	423.2	461.2	459.0	2461.0
2.67-2.81	101.7	174.8	748.7	132.8	178.1	298.9	188.3	465.1	2288.5
2.81-2.96	89.8	146.1	292.1	141.8	376.6	236.9	104.2	409.1	1796.6
2.96-3.16	89.2	13.3	129.7	86.5	132.8	79.0	44.7	422.6	997.9
3.16-3.62	12.9	15.8	45.1	22.1	13.4	2.8	3.2	364.7	480.0
Total Area	**3025.2**	**1353.1**	**1780.1**	**690.9**	**3441.9**	**2364**	**1715.8**	**3312.7**	**17683.7**

Source: Author, 2014

From the level of vulnerability Jhalokhathi district can be consider as the safer place than the other seven districts, where very few, 3.90 % of people are in vulnerable to disaster. This analysis also indicates that the model result is consistent, as the settlement should be more or less liveable for the coastal community.

Vulnerable land use category with and without mangrove

Most of the land use category was almost similar percentage of high vulnerable and low vulnerable class. At that time the mangrove forest area was considered as empty and has no positive impact to mitigate hazard. Maximum area of settlement, water body, agricultural land and mud land were in moderate to high exposed category.

The exposure index 8 (PVI^8) with the proportion of the mangrove forest area to modelling the Population Vulnerability Index justify the influence of mangrove forest to mitigate vulnerability. Dramatically the vegetation turn into green (low vulnerable), mud are became yellowish to greenish, water body absorbed more green area than the red and also the agricultural land increased to be green. That indicates the influence of mangrove in coastal hazard mitigation.

6.2 Critical Reasoning and Limitations

Though this research work identifies the most vulnerable community in the coastal zone through some modelling and analytical mechanisms, it needs to be evaluated in a proper way. This research hypothetical outcome was based on the simulated model findings. And need to think about suitable evaluation technique to establish that assumption was decent.

The model developed in this study are based on a limited length time series of water level, wind and wave data, so supplying more data would increase the reliability of the models and results. However, just 10 years perdition of future water level changes is given here; for real case applications, further studies will be needed, especially on data and model uncertainty. The flood inundation or flood depth calculation has not carried out by following proper hydrological modelling approach, because there is no data available related to the river discharges and cross section of river network.

One of the major criticism has been recognized during the study regarding the Marine InVEST Model is that the model consider outside of AOI as water body, which is not always precise. For that reason sometimes the result cannot be considered as definitive. Another matter of InVEST model is only to focus the shore line boundary as an output.

The uncertainties in the selection of different climate change scenarios are not considered. The models employed do not incorporate uncertainties which could play an important role in the evaluation of climate change impacts. Furthermore, the application of different methods involving data sharing and overlapping in different series of data can provide useful information for future research.

Due to lack of time during the research work, no information has considered related to vulnerability of structures to flood water and costs of content items, structures or land. Consequently, even though the proposed methodologies for vulnerability and risk assessment are totally valid and applicable in other parts of Bangladesh and elsewhere, the results obtained from the application cannot be taken as definitive, because some of them were derived from some model generated hypothetical values.

6.3 Concluding Remarks

From the study findings (histogram plots) it is clear that the mangrove forest plays a vital role to mitigate vulnerability and helps the coastal community from various climatic hazards. Our aspiration was to raise awareness of the coastal community about the importance of mangrove forest and keep them liveable and away from destruction. A huge amount of study had been carried out before to analysis the vulnerability of coastal area specially the coastal shore line. A wide ranging tools and technics were used which were mostly challenging and difficult to understand for the common people. This research has tried to establish simple method to calculate vulnerability of people in a specific area by using simple mathematical equation and GIS technology.

Chapter 7
Conclusion and Further Research

7.1 Conclusion

Impact of climate change especially the sea level rise on the western and central coastal zone of Bangladesh has been assessed by modelling and calculating the Coastal Vulnerability Index (CVI) and Population Vulnerability Index (PVI) using Marine InVEST Model and ArcGIS. Seven major key climatic variables have been considered to simulate CVI model and to calculate PVI. All the parameters has been normalized and finally multiplied to calculate PVI, so that the calculated values of PVIs can generate unbiased results. The potential effects of climate change have been studied for different water level (WL) scenarios during high tide. The study has analysed the 29 years (1980-2010) water level time series data to establish base condition of flood level during high tide. The study mainly assessed the impacts based upon the a) changes in water levels and induced inundations, b) Increase in surge height; and c) presence and absence of mangrove forest coverage.

The first objective of the research was to simulate and calculate PVI of the coastal zone of Bangladesh to answer the question -How exposed is the coast to the effects of climate change?

- North-western parts in the Ganges basin area are highly exposed to natural calamities.

Second objective was to evaluate model sensitivity to different scenarios of inundation and change of natural habitats, in response to - What will happen with and without mangrove?

- Mangrove forest plays vital role to cope with the vulnerability for climatic issues, (7% change of land from the study findings).

Finally to identify the most vulnerable coastal communities due to natural calamities to answer the question- Where are people highly vulnerable to coastal cyclones and flood inundation?

- The north-western part of the study is more vulnerable to climate change, which is about 364.7 sq. km. The research outcomes show that, most vulnerable district is

Satkhira and Khulna where peoples are at high risk due to storm surge and tidal flooding, where the population density is highest around 16659 numbers of people per grid.

Knowledge gained from the study some remedial measures has been suggested as the strategies of future action plan to mitigate disasters, as follows-

a) Preservation of mangrove forest as a strategy of future action plan to mitigate climate hazard near the shore line in coastal region.

b) More detailed assessment of Climate change impacts on people and land resources and formulation of adaptation scenarios are needed in coping with Climate change.

c) Development of guidelines to incorporate the research on climate change effect in planning and design.

d) Increase the method's applicability in other coastal areas at the regional scale to identify the climatic impact on the coastal community in a simple way.

7.2 Perspective of Further Studies

This study has carried out with a very limited time frame which hampers the study collect more information for conducting more analysis. More time has to be considered in future for the similar type of study.

Proper flood modelling tools has to be identifying to know the impact of differ water level scenario as the key issue of flood inundation. Also try to develop own database for the wind and wave height information to simulate the CVI model.

Further study needed to develop better evaluation mechanism during model sensitivity analysis. For more accuracy, try to identify pathway to consider direct influence of the proportion mangrove forest coverage to assign the vulnerability ranking. This issue needs to consider for further study.

This method could be applied in other parts of the world with similar geographical characteristics to evaluate the methods applicability. The interpretation of depicting the population density in different vulnerable group, as demonstrated in this research, will be of great value to the urban planners and decision makers, for the future planning of the coastal region of Bangladesh to mitigate disasters.

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Appendix A: Demographic Features of the study area

Appendix A1: District wise area coverage of the study area

DISTRICT	Area (sq.km)	BBS Area (sq.km)	% Share of Total Country Area
Jhalokati	706.87	706.78	0.5
Pirojpur	1,753.04	1,527.45	0.9
Bhola	1,786.62	3,403.48	2.3
Barguna	1,355.96	1,831.31	1.2
Patuakhali	2,406.41	3,128.89	2.2
Bagerhat	3,064.34	3,202.53	4.1
Khulna	3,494.07	4,332.04	4.2
Satkhira	3,378.82	3,698.13	4.2
Total	**17,946.13**	**21,830.61**	**19.6%**

Source: BBS 2011, CEGIS 2010

Appendix A2: Districts wise population distribution in the study area

District	No of HH*	Male	Female	Urban	Rural	Total Population (U+R)	Density/ sq.km
Jhalokati	157231	329,147	353,522	112,003	570,666	682,669	964.5
Pirojpur	254421	639,126	659,755	205,413	1,093,468	1,298,881	806.7
Bhola	370560	884,069	892,726	243,317	1,533,478	1,776,795	1,183.7
Barguna	214594	437,413	455,368	103,094	789,687	892,781	739.8
Patuakhal i	343963	719,639	745,560	189,682	1,275,517	1,465,199	683.3
Bagerhat	348200	677,738	679,268	168,360	1,188,646	1,357,006	696.0
Khulna	538801	961,457	925,805	432,832	1,454,430	1,887,262	2,442.8
Satkhira	467486	979,934	996,412	226,183	1,750,163	1,976,346	802.8
Total	**2,695,256**	**5,628,523**	**5,708,416**	**1,680,884**	**9,656,055**	**11,336,939**	**Average 1,039.9**
*** No of HH= Number of total House Hold**							

Source: Bangladesh Bureau of Statistics (BBS 2011)

Appendix A3: Income, occupation and literacy pattern of the study area

Major livelihood groups and activities in coastal areas of Bangladesh

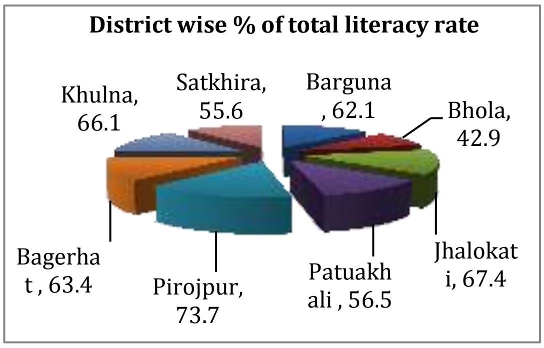
Livelihood Group	Main Economic Activity	Livelihood Group	Main Economic Activity
Farmer	Agriculture	Wage Labour	Agriculture/ Vegetable farming
	Fish/ Shrimp / river fishing		Rickshaw/ van puller
	Poultry & Livestock		Labour in shrimp farm/ Small industry/ Salt farm/ Fishing boat/ Construction works/ forest/ mechanic
	Small business		Small business/ Dry fish Business
	Salt fanning		Fishing in Sea
Fisher	Shrimp/ Fishing in river or Sea	Woman	Domestic work
	Small business		Poultry & Livestock
	Agriculture		Homestead Gardening
	Drying fish		Day Labour
	Net servicing/ preparation		Cottage industry
	Boat preparation/ servicing		Private tutor

Livelihood Group	Main Economic Activity	Livelihood Group	Main Economic Activity
	Rickshaw/ van rent		Small business
	Salt Farming		Service
	House rent		Nursery/Fish farming

Source: CEGIS, Bangladesh, 2007

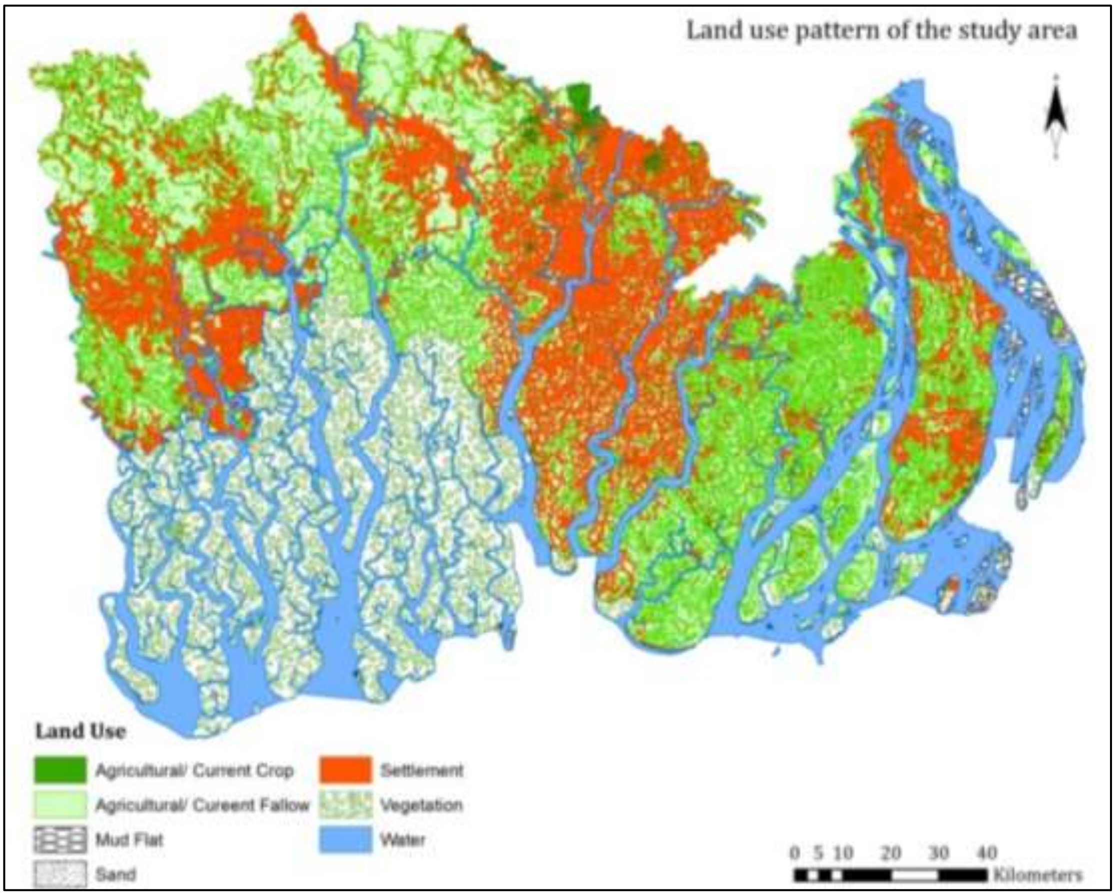
Literacy rates

In the year of 2011 the average literacy rate of the coastal area is 60.96% whereas the country overall rate is 56.1% for all ages (BBS 2001). The average illiteracy rate of the study area is about 29.31% (BBS 2011). Figure bellow represents the district wise total literacy rate in the study area.



Appendix B: Physiography of the Study area

Appendix B1: Study area land use pattern and mangrove forest coverage



[Source: Landsat TM 5, August 2010, CEGIS 2010]

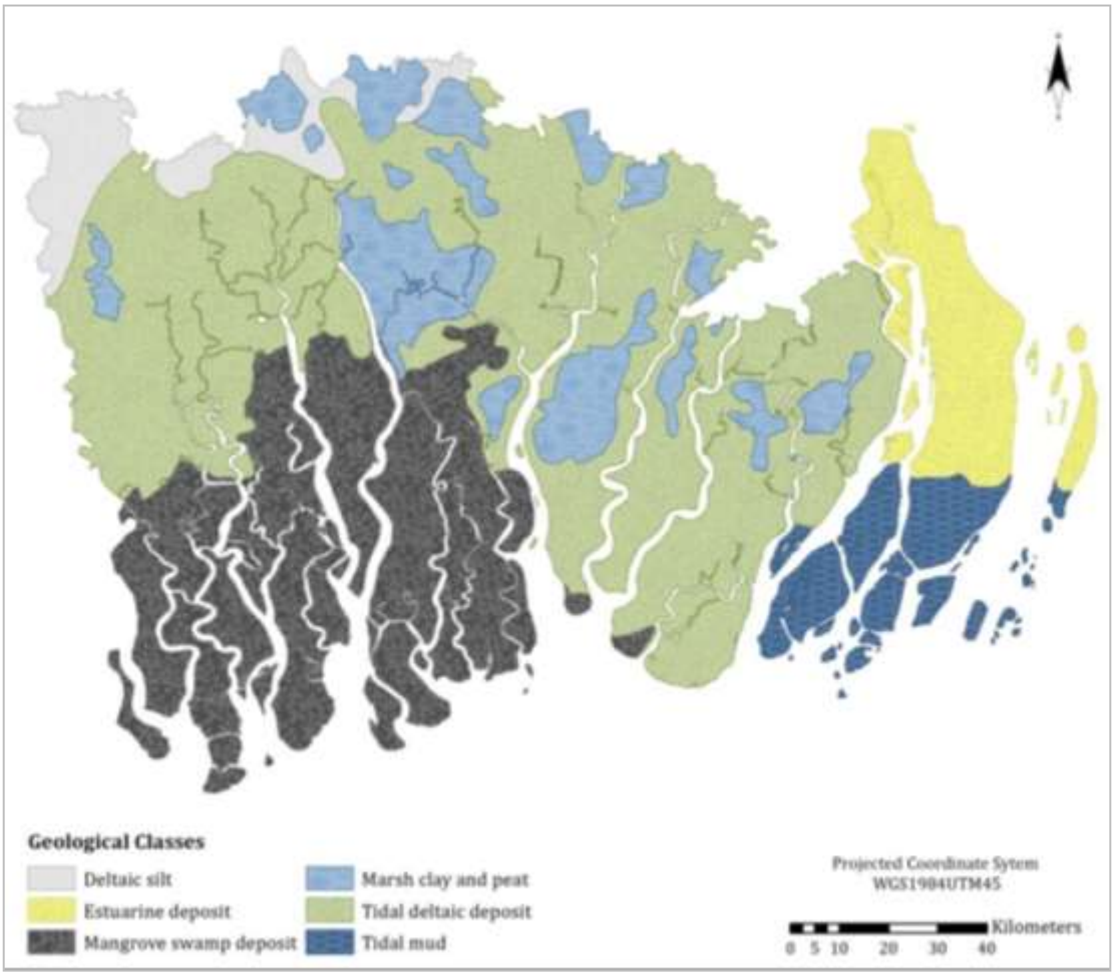
Appendix B2: Geomorphological characteristics of the study area

Major geological type	**Geomorphology class**	**Soil type and land characteristics**
Deltaic Deposits	Deltaic silt	• Light-grey to grey, fine sandy silt to clay silt. • Fine overbank sediments deposited by distributaries in flood basins.
	Estuarine deposit	• Light grey to brownish and yellowish grey silt to clay silt • Thin lenticular deposits of yellowish-brown, fine to very fine sand are present along the channels, edge of the islands • Most estuarine islands are actively eroding on the upstream side and aggrading on the downstream end.
	Mangrove swamp deposit	• Dark-grey to black silt and clay deposited in the active tidal zone • Dominated by woody, organic-rich, mangrove swamps. • The area is uncultivated and is covered by natural mangrove forest.
	Tidal deltaic deposit	• Light to greenish grey, weathering to yellowish grey, silt to clay silt • Very fine to fine sand along active and abandoned stream channels including crevasse slopes. Contains some

Major geological type	Geomorphology class	Soil type and land characteristics
		brackish water deposits. ✦ Numerous tidal creeks are present in the area. ✦ Large tracts are submerged during spring tides.
	Tidal mud	✦ Dark to bluish grey saturated silt with clay containing shell fragments ✦ Contains scattered lenses of beach sand ✦ The zone is defined by high and low tides and areas of active deposition
Paludal Deposits	Marsh clay and peat	✦ Grey or bluish grey clay, black herbaceous peat, and yellowish grey silt. ✦ Alternating beds of peat and peaty clay common in bils and large structurally controlled depressions. ✦ In the deepest parts peat is thickest. ✦ Thin beds of peat and clay are interbedded with alluvial silt in the north central Sylhet depression.
Coastal Deposits	Beach and dune sand	✦ Light to whitish-grey sand. ✦ Medium to fine, well sorted, sub rounded, contains concretions, shell fragments, heavy minerals. ✦ Includes small mud flat deposits.

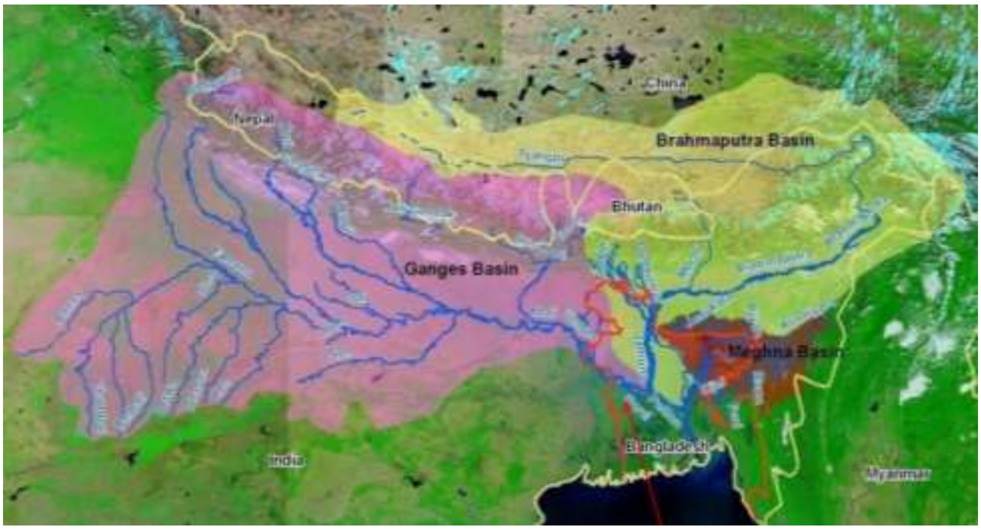
Source: GIS unit, EGIS, 1990

Appendix B3: Soil and land type based on geological categories of the study area



Appendix C: Climatology and Natural Hazards

Appendix C1: Major River System



Sources: CEGIS, Bangladesh, 2010

Appendix C2: Rainfall and Temperature

Rainfall

The mean annual rainfall is about 2300mm, but there exists a wide spatial and temporal distribution. Annual rainfall ranges from 1200mm in the extreme west to over 5000mm in the east and north-east (MPO, 1991). Generally, the eastern parts of the country occupied higher rainfall than the western parts.

Temperature

Bangladesh has a humid, warm, tropical climate is influenced primarily by monsoon and partly by pre-monsoon and post-monsoon circulations. Winter is relatively cooler and drier, with the average temperature ranging from a minimum of 7.2 to 12.8°C to a maximum of 23.9 to 31.1°C. The minimum falls below 5^{o}C in the north though frost is extremely rare. There is a south to north thermal gradient in winter mean temperature: generally the southern districts are 5^{o}C warmer than the northern districts. Pre-monsoon is hot with an average maximum of 36.7°C, very high rate of evaporation, but occasional heavy rainfall from March to June. In some places the temperature occasionally rises up to 40.6°C or more. The maximum temperatures are observed in April, the beginning of pre-monsoon season. The mean monsoon temperatures are higher in the western districts compared to that for the eastern districts (Agrawala, Ota et al. 2003).

Appendix C3: Historical info of storm surge in the coastal belt of Bangladesh

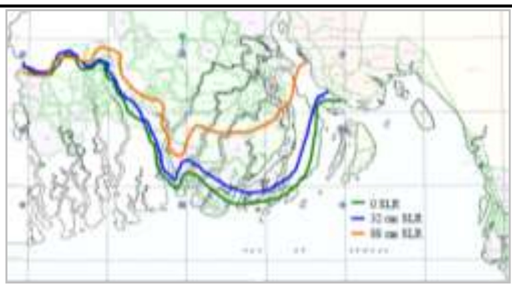
Cyclone No	Year	Month	Average wind speed (km/hr.)	Surge height (m)	Tidal Height	Deaths (people)
1	1960	October	210	4.8	1.8	5,149
2	1961	May	161	2.75	-	11,466
3	1962	October	200	5.8	-	-
4	1963	May	201	5	0.3	11,520
5	1965	May	161	4	1.2	19,279
6	1965	December	210	5.4	-	873
7	1966	October	145	6.5	-	850
8	1967	October	160	3	-	-
9	1969	October	145	-	-	-
10	1970	November	222	10.6	2.1	5,00,000
11	1971	November	110	1	0	-
12	1974	August	80	2.5	1.7	-
13	1975	May	110	-	-	-
14	1976	October	105	3.5	-	-
15	1977	May	113	0.6	0.7	-
16	1983	November	136	2.5	-	-
17	1985	May	154	3.2	1.8	11,069
18	1986	November	110	-	1.5	14
19	1988	November	162	3.5	-	2,000
20	1991	April	235	5.8	1.7	1,38,000
21	1995	November	210	-	-	650
22	1997	May	240	3.05	-	126
23	1997	September	150	2.44	-	-
24	1998	May	150	2.135	-	-
25	1998	November	90	1.83	-	-
26	2007	November	240	3.05	-	3,406
27	2008	May	200	1.85	-	
28	2009	May	120	3	-	115
29	2013	May	93	0.4	-	-

Source: (Fritz and Blount 2007), Wikipedia, Newspapers

Appendix C4: Previous Scenario on Salinity intrusion of the study area

The salinity level becomes minimum during the monsoon (June to September) when the main rivers discharge about 80% of the annual fresh water flow. During monsoon season, the saline water is fully flushed out of the Meghna Estuary, but in the western part of the lower delta it is not fully flushed due to the scarcity of fresh water flow from upstream.

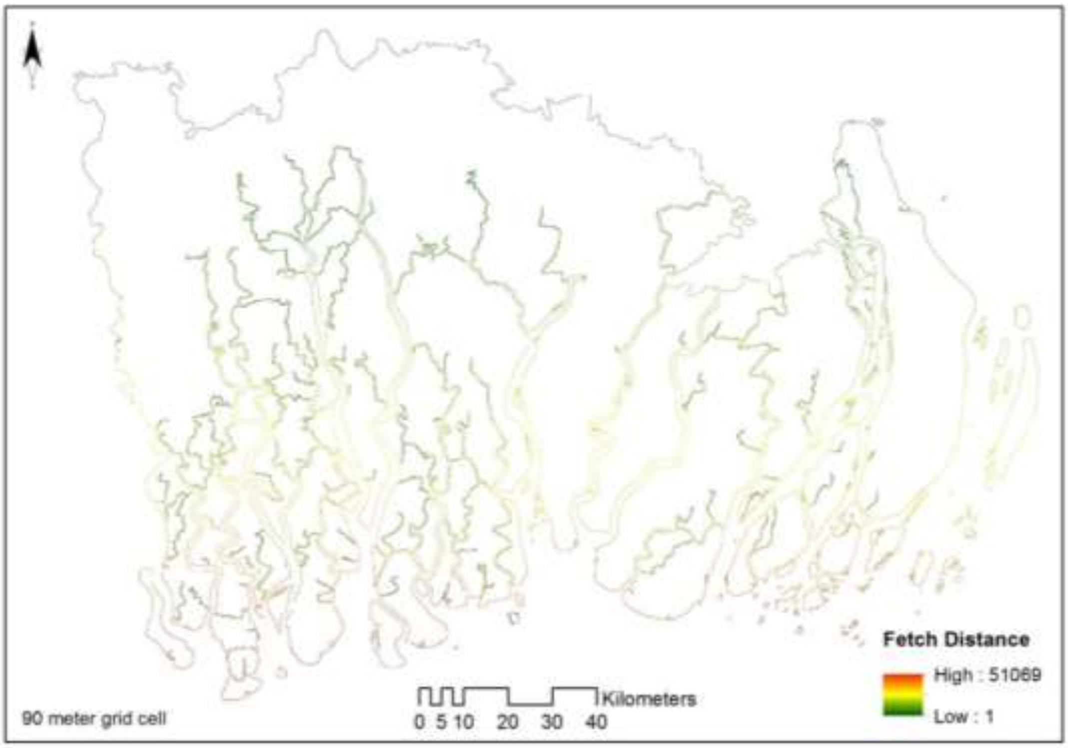
High salinities both in monsoon and dry season in the southwest corner and along Pussur-Sibsa (river) system of the area are associated with the decreasing upstream freshwater flow as well as silting of the major channels.



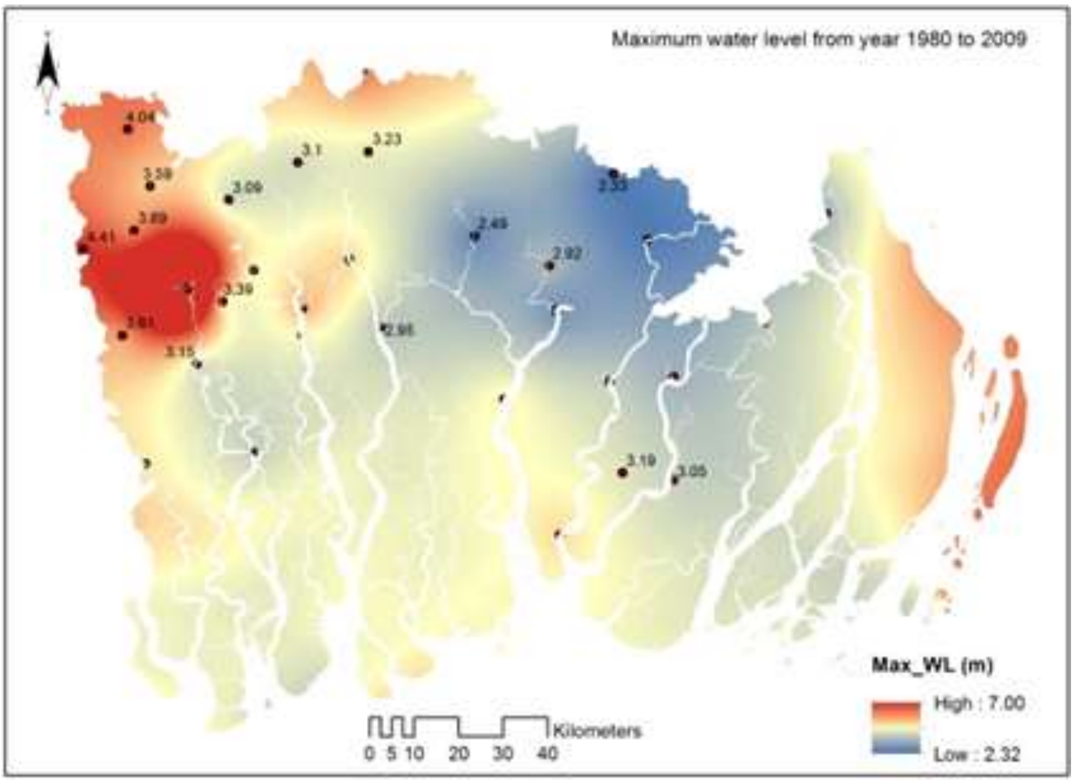
Line of equal salinity (5 ppt) for different SLR during dry season

Appendix D: Fetch Distance and Water Depth Plots

Appendix D1: Fetch distance in meter (m) of the coastal shore line



Appendix D2: Interpolated Water level scenario (maximum) of 48 stations



Appendix E: Station wise tidal gauge water level data info

Appendix E1: Example of time series data in station 288.4 in River Tentulia at Bhola

Station_ID	Stn_name	Long_dd	Lat_dd	Year	JUN_MAX	JUL_MAX	AUG_MAX	SEP_MAX
288.4	Bhola Kheyaghat (River-Tentulia)	90.574	22.674	1990	2.44	2.79	2.8	2.47
				1991	2.47	2.58	2.63	2.73
				1992	2.51	2.54	2.6	2.61
				1993	2.61	2.51	2.84	2.59
				1994	2.33	2.27	2.28	2.31
				1995	2.66	3.17	2.6	2.47
				1996	2.3	2.62	2.78	2.46
				1997	2.32	2.16	2.12	2.08
				1998	2.58	2.83	2.82	3.15
				1999	2.56	2.57	2.68	2.5
				2000	2.51	2.63	2.72	2.57

Source: Time series Data, NWRD, 2010, CEGIS, Bangladesh

Appendix E2: Station wise tidal gauge water level in meter (m) data in 48 stations

Sl. no.	Stn ID	Stnname	LONG DD	LATDD	Slopes	Mean_ WL	Max_ WL	2009_WL	Pred_W L_2020
1	107	Pirojpur	89.9660	22.5820	0.01	2.40	2.92	2.59	2.73
2	318	Babuganj	90.3260	22.8240	-0.03	2.48	2.89	2.11	1.78
3	107.2	Rayanda	89.8620	22.3130	-0.02	3.08	3.44	2.71	2.49
4	128	Shakra	88.9490	22.6310	-0.03	3.61	4.41	3.13	2.83
5	20	Amtali	90.2280	22.1420	0.02	2.72	3.05	3.06	3.27
6	19	Mirjaganj	90.2330	22.3520	0.01	2.61	2.81	2.68	2.75
7	38	Bamna	90.0930	22.3440	-0.01	2.69	3.06	2.58	2.51
8	244	Mongla	89.5980	22.4640	0.04	2.58	2.95	3.46	3.95
9	253	Sarupkati	90.1110	22.7650	0.00	2.10	2.33	2.10	2.09
10	1	Bagerhat	89.8050	22.6450	0.02	2.20	2.49	2.53	2.73
11	27	Keshabpur	89.2160	22.9060	-0.02	3.00	3.78	2.70	2.52
12	258	Paikgacha	89.3210	22.5830	0.01	3.06	3.37	3.29	3.43
13	18	Barisal	90.3790	22.6960	-0.01	2.25	2.47	2.05	1.92
14	136.1	Umedpur	89.9780	22.4900	0.01	2.48	2.57	2.57	2.66
15	38.1	Barguna	90.1170	22.1600	0.01	2.97	3.19	3.05	3.12
16	129	Basantapur	89.0320	22.4550	0.00	3.58	3.81	3.58	3.57
17	130	Kaikhali	89.0800	22.1940	0.01	3.21	3.47	3.44	3.57
18	163	Tala Magura	89.2700	22.7260	0.03	2.52	3.09	3.04	3.35
19	164	Chandkhali	89.2540	22.5210	-0.01	2.95	3.39	2.84	2.78
20	25	Chapra	89.1770	22.5480	0.03	3.21	7.01	3.77	4.13
21	165	Kobadak ForestOffice	89.3120	22.2160	-0.03	2.35	3.05	1.83	1.50
22	288.4	Bhola Kheyaghat	90.5740	22.6740	0.01	2.59	2.85	2.69	2.77
23	183	Kaitpara	90.4370	22.4560	0.00	2.51	3.01	2.46	2.43
24	18.1	Bakerganj	90.3420	22.5440	0.01	2.22	2.64	2.40	2.51
25	198	Haridaspur	89.8200	23.0520	0.00	3.17	3.78	3.24	3.29

Sl. no.	Stn ID	Stnname	LONG DD	LATDD	Slopes	Mean_ WL	Max_ WL	2009_WL	Pred_W L_2020
26	30	Afraghat	89.3930	23.1050	0.01	2.97	3.62	3.13	3.24
27	219	Gazirhat	89.5650	22.9840	0.04	3.35	4.03	4.03	4.42
28	23	Kalaroa	89.0500	22.8720	0.05	3.08	4.04	3.97	4.49
29	320	Hizla	90.4450	23.0540	-0.01	2.90	3.32	2.80	2.70
30	277.3	Nilkamal	90.5860	23.0660	0.01	4.26	4.94	4.37	4.44
31	240	Bhawanigan j	90.7710	22.8680	0.00	3.02	3.61	3.01	3.01
32	239	Lakshmipur	90.8250	22.9230	-0.01	3.32	3.82	3.18	3.09
33	24	Benarpota	89.0980	22.7570	0.02	3.07	3.59	3.48	3.76
34	241	Khulna	89.5760	22.8190	0.02	2.97	3.23	3.28	3.49
35	243	Chalna	89.5300	22.6020	0.02	2.99	3.58	3.39	3.62
36	253A	Uzirpur	90.2540	22.8090	-0.01	2.30	2.67	2.18	2.04
37	254.5	Elarchar	89.0610	22.6680	0.02	3.13	3.89	3.48	3.70
38	29	Sutarkhali F.O.	89.4280	22.5060	0.02	3.21	3.74	3.57	3.79
39	259	Nalianala (Hadda	89.4250	22.4520	0.02	2.43	3.35	2.83	3.06
40	26	Protapnagar	89.1940	22.3950	-0.01	2.62	3.16	2.50	2.41
41	278	Daulatkhan	90.8300	22.6100	0.00	3.75	4.09	3.78	3.80
42	279	Tajumuddin	90.8540	22.4690	0.02	3.58	3.89	3.91	4.14
43	28	Dumuria	89.4220	22.8000	-0.02	2.64	3.10	2.32	2.10
44	300	Gournadi	90.2350	22.9760	0.00	3.03	3.91	3.10	3.14
45	321	Hatiya	91.1120	22.4240	-0.01	3.81	4.25	3.70	3.61
46	37	Jhalakati	90.1830	22.6300	0.02	2.10	2.38	2.38	2.55
47	39	Patharghata	89.9790	22.0370	0.03	2.83	3.55	3.37	3.74
48	162	Jhikargacha	89.1000	23.1010	0.05	3.18	4.26	3.98	4.54

Source: National Water Resources Data base (NWRD), WARPO, Dhaka, Bangladesh

Appendix F: R script to calculate and predict water Depth

```
> setwd("C: \\MSc_THESIS_2013\\DATABASE\\THESIS_dATA_iNFO\\R\")
> dat <- read.csv ("waterlevels.csv", header=TRUE)
> stns <- sort (unique (dat$STATIONID))
> naval <- min (dat [,3:ncol (dat)]) # = -99999
> dat [dat == naval] <- NA

> #SLR MEAN, TREND, END YEAR, PREDICTION - MAXIMUL HIGH TIDE
>
> y1 <- rowMeans (cbind(dat$JUN_MAXOFTSVALHIGH_UPDATED,
+                       dat$JUL_MAXOFTSVALHIGH_UPDATED,
+                       dat$AUG_MAXOFTSVALHIGH_UPDATED,
+                       dat$SEP_MAXOFTSVALHIGH_UPDATED))

> min.num.years <- 12
> plot.stns <- c(1, 2, 3, 5, 6, 7)#TO PLOT MORE THAN ONE STATIONS
> plot.stns <- 162 #TO PLOT ONE STATION
> # or to include all stations
> plot.stns <- stns
> allyears <- 1980:2009
> new <- data.frame (years=allyears)
> flowvals <- data.frame (array (NA, dim=c(length (allyears), length (plot.stns))))
> flowvals.pred <- flowvals
> slopes <- mean.flows <- max.flows <- flow2009 <- flow2020 <- rep (NA, length (plot.stn))
> for (i in 1:length (plot.stns)) {
+   indx <- which (dat$STATIONID == stns [plot.stns [i] ])
+   years <- dat$YEAR [indx]
+   yi <- y1 [indx] # y1 means that it's the JAS data only
+   indx2 <- which (!is.na (yi) & yi > naval)
+   years <- years [indx2]
+   yi <- yi [indx2] # then it's in metres / year
+   if (length (indx2) >= min.num.years) {
+     indx3 <- which (allyears %in% years)
+     flowvals [indx3, i] <- yi

+     mod <- lm (yi ~ years)
+     flowvals.pred [, i] <- predict (mod, new)
+     coeffs <- summary (mod)$coefficients
+     slopes [i] <- coeffs [2]
+     mean.flows [i] <- mean (yi)
+     max.flows [i] <- max (yi)
+     flow2009 [i] <- coeffs [1] + 2009 * coeffs [2]
+     flow2020 [i] <- coeffs [1] + 2020 * coeffs [2]
+   }
+ }
> names (flowvals) <- paste (plot.stns)
> results_Max<- data.frame (cbind (stns, slopes, mean.flows, max.flows, flow2009, flow20))
> row.names (results_Max) <- plot.stns
> write.table (results_Max, file="flow_MaxHT.csv", row.names=TRUE, sep=",")
```

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