Assessment of the Risk due to Storm Surge under Climate Change in the Coastal Zone of Bangladesh

by

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The thesis titled 'Assessment of the risk due to storm surge under climate change in the coastal zone of Bangladesh**'** submitted by Dipankar Kumar Sarkar, Roll No. 1008282004F, Session: October 2008, has been accepted as satisfactory in partial fulfillment of the requirements for the degree of Master of Science in Water Resources Development in February 23, 2011.

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Dedicated to

My family

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ABSTRACT

Coastal areas of the world face a range of risk related to climate change. Cyclone and associated storm surge is the most destructive hazard that frequently occurs in Bangladesh and causes enormous suffering to the people of the coastal area. This study has been carried out to assess the hydrological hazard based risk associated with the storm surge due to increase in Sea Surface Temperature (SST) and Sea Level Rise (SLR) in the coastal area of Bangladesh. Increase in SST and SLR will increase surge height which will enlarge the boundary of the Risk Zone (RZ) and High Risk Area (HRA). The maximum surge height was estimated by using an empirical equation. This study illustrates that surge height will increase by about 13 and 33% for 2 and 4°C increase of SST, respectively, for the entire coastal zone of Bangladesh. Increase in surge height indicates greater intrusion distance and larger RZ and HRA. Intrusion distance of the surge water was calculated by using another empirical equation. Study shows intrusion distance will be increased by 6-10 and 18-23% for 2 and 4°C increase in SST, respectively, in the coastal area of Bangladesh. As RZ depends on the possible extent of inland intrusion, increasing intrusion distance will increase the boundary of the RZ as well as HRA. Study demonstrates that RZ will be increased by approximately 16% and 29% for 2 and 4°C increase in SST, respectively. The study also reveals that the HRA will be increased by approximately 20 and 34% for 2 and 4°C increase in SST, respectively. Within the RZ, the areas where cyclone shelter/safe haven are present partially protect the people from the adverse impact of storm surge. It is also found that at present about 75-99% of the population in the coastal districts of Bangladesh are still vulnerable to storm surge risk due to unavailability of the cyclone shelters. The situation will be even worse for the 2°C increase in SST. Residual risk map of the study area shows that Noakhali Sadar, Lakshmipur, Chakaria, Bhola Sadar, Char Fashion, Ramgati, Patiya and Mirsharai thana will be highly susceptible to storm surge risk for the 2°C increase of SST. Moderately vulnerable thanas are Ramgati, Patiya, Mirsharai, Cox's Bazar Sadar, Sitakundu, Banshkhali, Galachipa, Bauphal, Mehendigonj, Hatiya, Mathbaria, Barguna Sadar, Amtali, Burhanuddin, Lalmohon, Roypur, Companiganj, Sonagaji, Sandwip, Chittagong port, Anwara, Maheskhali Teknaf and Ramu. Hence, the populations of those thanas will be even more vulnerable to cyclones/storm surges as a result of climate change. This information will help in making decision for providing safety to coastal population from the adverse impact of climate change.

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ABBREVIATIONS

AD	Anno Domini
AR4	Assessment Report Four
BBS	Bangladesh Bureau of Statistics
BUET	Bangladesh University of Engineering and Technology
CCP	Chittagong Coastal Plain
CDMP	Comprehensive Disaster Management Programme
CZ	Coastal Zone
DEM	Digital Elevation Model
GTP	Ganges Tidal Plain
HF	Hazard Factor
HRA	High Risk Area
IFCDR	Institute of Flood Control and Drainage Research
IPCC	Intergovernmental Panel on Climate Change
IWM	Institute of Water Modeling
MCSP	Multipurpose Cyclone Shelter Programme
MDP	Meghna Deltaic Plain
MSL	Mean Sea Level
NGOs	Non Governmental Organizations
PDO-ICZMP	Program Development Office for Integrated Coastal Zone Management
PDSCL	Perception of Direct Stakeholder on Coastal Livelihoods
PEDP	Primary Education Development Programme
RCM	Regional Climate Model
RI	Risk Index
RZ	Risk Zone
SLR	Sea Level Rise
SST	Sea Surface Temperature
TD	Tropical Depressions
TS	Tropical Storms
UN	United Nations
UNDP	United Nations Development Programme
UNDRO	United Nations Disaster Relief Organization
VF	Vulnerability Factor
VGD	Vulnerable Group Development
WARPO	Water Resources Planning Organization

CHAPTER ONE: INTRODUCTION

1.1 Background of the Study

The coastal belt of Bangladesh is hit by cyclonic storms and associated storm surges regularly causing loss of human lives and livestock and severe devastation of crops and property. The main cause of loss of lives is storm surge (BUET-BIDS, 1993). Tropical cyclones and associated storm surges strongly affect coastal zones of tropical and temperate Asia. Tropical cyclones and storm surges are one of the most critical factors affecting loss of human lives in India and Bangladesh. Approximately 76% of the total loss of human lives from cyclonic storms has occurred in India and Bangladesh (IPCC, 2007). UNDP has identified Bangladesh to be the most vulnerable country in the world to tropical cyclones (UNDP, 2004). As the climate changes during the 21st century, larger cyclonic storm surges and growing populations may collide in disasters of unprecedented size (Dasgupta et al., 2009).

According to the IPCC AR4, storm surges and related floods are likely to become more severe with increases in intense tropical cyclones in future (IPCC, 2007). For the Bay of Bengal, a study using dynamical models drive by RCM simulations of current and future climates have shown large increases in the frequency of highest storm surges despite no significant change in the frequency of cyclones (Unnikrishnan et al., 2006). Hence, from a practical perspective vulnerability of Bangladesh to cyclones/storm surges may increase even more as a result of climate change (Dasgupta et al., 2010).

There is strong evidence that global sea level gradually rose in the 20th century and is currently rising at an increased rate, after a period of little change between AD 0 and AD 1900. Sea level is projected to rise at an even greater rate in this century. Projected sea-level rise (SLR) could flood the residence of millions of people living in the low lying areas of South, South-East and East Asia such as in Vietnam, Bangladesh, India and China. The two major causes of global SLR are thermal expansion of the oceans (water expands as it warms) and the loss of land-based ice due to increased melting (IPCC, 2007).

As a low-lying country, Bangladesh is considered as one of the most vulnerable countries in the world to climate change and SLR (IPCC, 2007). SLR can also cause the relative decrease of existing shelter heights with respect to mean sea level. Recent climate studies also predicted intensified tropical cyclones and associated storm surges with an increase in Sea Surface Temperature (SST) (Emanuel, 2005). It is very likely that any increase in surge height at the coast will lead to an increase in flooded area and spatial flooding depth (Karim et al. 2005). The consequences of climate change lead to an increase in the cyclone-prone area and put a large number of people at risk (Karim and Mimura, 2008).

Multipurpose Cyclone Shelter Programme (MCSP) (BUET-BIDS, 1993) delineated Risk Zone (RZ) and High Risk Area (HRA). Later on Chowdhury and Rahman (1998) prepared a risk based decision model for optimal allocation of cyclone shelters in the Ganges Tidal Plain. However, the impact of SLR or intensification of cyclonic events under increased SST were not considered in those studies. The socio-economic conditions have also changed since 1993 resulting in change in risk. As climate change continues, it is necessary to re-delineate the risk zone.

1.2 Objectives of the Study

The purpose of the study is to identify the overall risk in case of cyclone associated with the cyclonic storm surge in the coastal region of Bangladesh under climate change. For this reason, the following objectives should be fulfilled-

1. To re-delineate hydrological hazard based high risk area under changing climate.
2. To assess the current vulnerability of the population in the coastal area.
3. Assessment of the residual risk on the basis of current socio-economic condition.

1.3 Justification of the Study

Coastal areas are likely to bear a significant burden from the impacts of climate variability and change. The coastal area of Bangladesh is predominantly vulnerable to cyclone and associated storm surge. It frequently causes enormous suffering to the people of the coastal area of Bangladesh. About 705000 people have been killed by 17 cyclonic storm surges since 1960. The country is likely to be affected by more intense cyclonic events in the foreseeable future due to climate change and SLR. Several studies indicate that the coastal zone vulnerability would be acute due to the combined effects of climate change, SLR, subsidence, and changes of upstream river discharge, cyclone and coastal embankments (BCAS/RA/Approtech, 1994, WB, 2000). The consequences of climate change lead to an increase in the cyclone-prone area and put a large number of people at risk. So, there is a very good reason to carry out a research on storm surge risk due to climate change in the coastal area of Bangladesh.

1.4 Possible Outcome of the Study

Cyclonic storm surge is a frequent threat and possess a wide range of risk to the coastal population of Bangladesh. In Bangladesh Climate Change Strategy and Action Plan (MoEF, 2009) high priority has been given to tropical cyclones and storm surges. The consensus among projections by the global scientific community points to the need for greater disaster preparedness in countries vulnerable to storm surges (Dasgupta et al., 2009). The possible outcome of the study is the mapping of the residual risk (the remaining level of storm surge risk that a community is exposed to after cyclone management measures such as cyclone shelter to reduce risk have been implemented) which will help in making decision for providing safety to coastal population from the adverse impact of climate change.

1.5 Limitations of the Study

- Large numbers of embankment and polders have been constructed in the coastal areas of Bangladesh in order to protect the land from periodic intrusion of saline water during high tide. A benefit of such embankment is that it causes substantial energy dissipation when the surge water crosses it. In this study the effect of embankment was not considered.
- In this study SLR was taken based on IPCC (2007), which predicts SLR of between 0.18 and 0.79 meters in South Asia by the last decade of the 21st century. But no consideration was made on SLR along Bangladesh coast.
- This study is based on secondary information and data. So, no field visit was conducted in order to get actual situation of the study area. In fact, it is quite difficult to visit entire coastal area of Bangladesh by short span of time.

- RZ and HRA in case of storm surge were demarcated by using some empirical equation. Although there are numerical and hydrodynamic models available to demarcate the RZ and HRA.
- Residual risk was computed based on current socio-economic condition. Only demographic change (increase in population) was considered as an indicator of socio-economic condition due to time limitation.

CHAPTER TWO: LITERATURE REVIEW

2.2 Cyclonic and Storm Surge Hazards

2.1.1 Major tropical cyclones around the world

Tropical cyclones are perhaps the most devastating of natural disasters both because of the loss of human life they cause and the large economic losses they induce. Vulnerability to tropical cyclones is becoming more pronounced because the fastest population growth in tropical coastal regions.

The historical evidence highlights the danger associated with cyclones and storm surges. During the past 200 years, 2.6 million people may have drowned during surge events (Nicholls 2003). Although significant adaptation has occurred over time, and many lives have been saved by improved disaster forecasting, evacuation and emergency shelter procedures (Shultz, Russell, and Espinel 2005; Keim 2006).

About 80 tropical storms (tropical cyclones with wind speeds greater than or equal to 17 ms^{-1}) form in the world's waters every year (McBride 1995). Of these, about 6.5% form in the North Indian Ocean (Bay of Bengal and Arabian Sea) (Neumann 1993). Since the frequency of cyclones in the Bay of Bengal is about 5 to 6 times the frequency in the Arabian Sea (IMD 1979), the Bay of Bengal share comes out to be about 5.5%. Bangladesh is hit by about 0.93% (~1%) of the world's total tropical storms, India by 3.34%, Myanmar by 0.51%, Sri Lanka by 0.22%, and 0.50% die in the Bay without hitting any country. These numbers were arrived at by considering the tropical storms that formed in the Bay of Bengal during the period 1877 to 1995. It would seem that Bangladesh is not a high-risk cyclone-prone area. The situation, however, is otherwise. If the world's tropical cyclones with death tolls in excess of 5000 are considered, it is found that 16 out of the 35 such disasters occurred in Bangladesh and 11 in India (Table 2.1). About 53% of the world deaths from these cyclones took place in Bangladesh and about 23% in India, for a combined total of 76% in these 2 countries. Bangladesh and India suffer most, although both of them together are hit by only 4.27% of the world storms (Ali, 1999). It is to be noted that major cyclone disasters are still continuing in Bangladesh and India.

Table 2.1: Death associated with noteworthy tropical cyclone disasters in the world (data upto 1991 from Ali and Chowdhury, 1997 and data after 1991 from Wikipedia, 2008)

Year	Location	Deaths
1584	Bangladesh	200000
1737	India	300000
1779	India	20000
1780	Antilles	20000
1822	Bangladesh	40000
1833	India	50000
1839	India	20000
1854	India	50000
1864	India	50000
1876	Bangladesh	100000
1881	China	300000
1895	India	5000
1897	Bangladesh	175000
1900	Texas, USA	6000
1906	Hong Kong	10000
1912	Bangladesh	40000
1919	Bangladesh	40000
1923	Japan	250000
1937	Hong Kong	11000
1941	Bangladesh	7500
1942	India	40000
1960	Bangladesh	5149
1960	Japan	5000
1961	Bangladesh	11468
1963	Bangladesh	11520
1963	Cuba-Haiti	7196
1965 (11 May)	Bangladesh	19279
1965 (31 May)	Bangladesh	12000
1970	Bangladesh	500000
1971	India	10000
1977	India	10000
1985	Bangladesh	11069
1988	Bangladesh	5708
1989	India	20000
1991	Bangladesh	138000
2008	Myanmar	138366

2.1.2 Previous tropical cyclones and storm surges in Bangladesh

Tropical cyclones generally occur over some parts of tropical oceans in latitudes between 10 and 30 both sides of the equator, and they become severe when they are located between 20 and 30 latitude (Holmes 2001). Bangladesh lies between 20° 34′ N and 26° 38′ N latitude and with a 440-mile long coastline is highly vulnerable to tropical cyclones and associated storm surges. A total of 119 tropical cyclones hit the coast of Bangladesh from 1877 to 2003 of which 39 are tropical depressions (TD), 54 are tropical storms (TS), and 26 reach hurricane intensity (after Islam and Peterson, 2009). Decade wise distribution of tropical cyclones which made landfall on Bangladesh coast during the period 1880 to 2009 is shown in Figure 2.1. It shows that in the past century (1901-2000), the rate of tropical storms striking the coast is 10 storms/decade or one storm per year. Since 1950, the rate of landfalling tropical storms in this area has increased, 1.18 per year for 1950-2000. Monthly distribution of tropical cyclonic storms which hit Bangladesh coast during the period 1877 to 2009 is given in Figure 2.2. It shows that cyclonic disturbances are absent from January through March but frequently occur during May to June (called pre-monsoon cyclonic storm) and October to November (called post-monsoon cyclonic storm). The reason is that in the pre- and post-monsoon season, the average sea surface temperature in the Bay of Bengal region and associated weather conditions are ideal for the formation of tropical cyclones (Islam and Peterson, 2009). Tracks of some severe cyclonic storm during the period 1960 to 2009 are shown in figure 2.3.

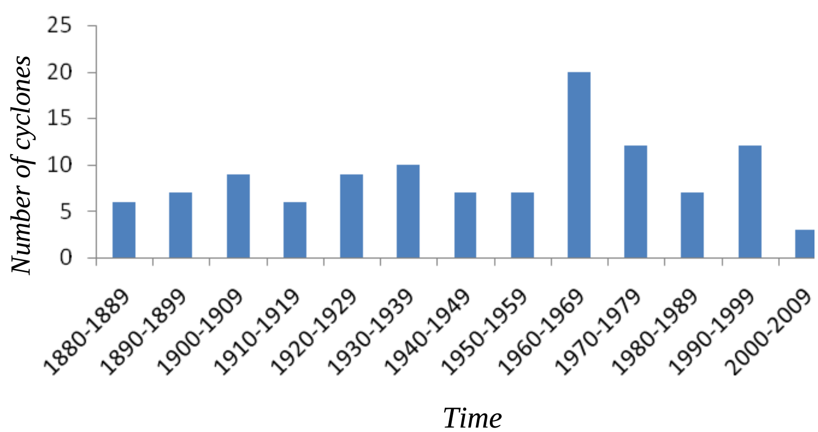


Figure 2.1: Decade wise distribution of cyclonic storms in Bangladesh from 1880 to 2009 (data upto 2003 from Islam and Peterson, 2009 and after that from Dasgupta et al., 2010)

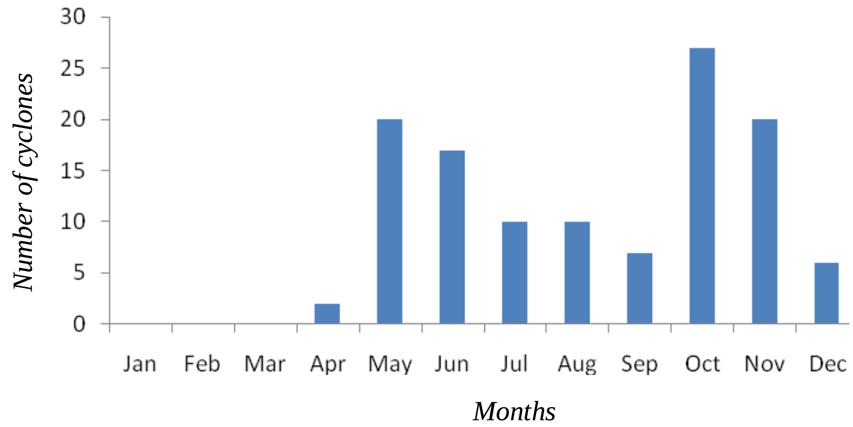


Figure 2.2: Monthly distribution of landfalling tropical cyclones in Bangladesh from 1877 to 2009 (data upto 2003 after Islam and Peterson, 2009 and after that from Dasgupta et al., 2010)

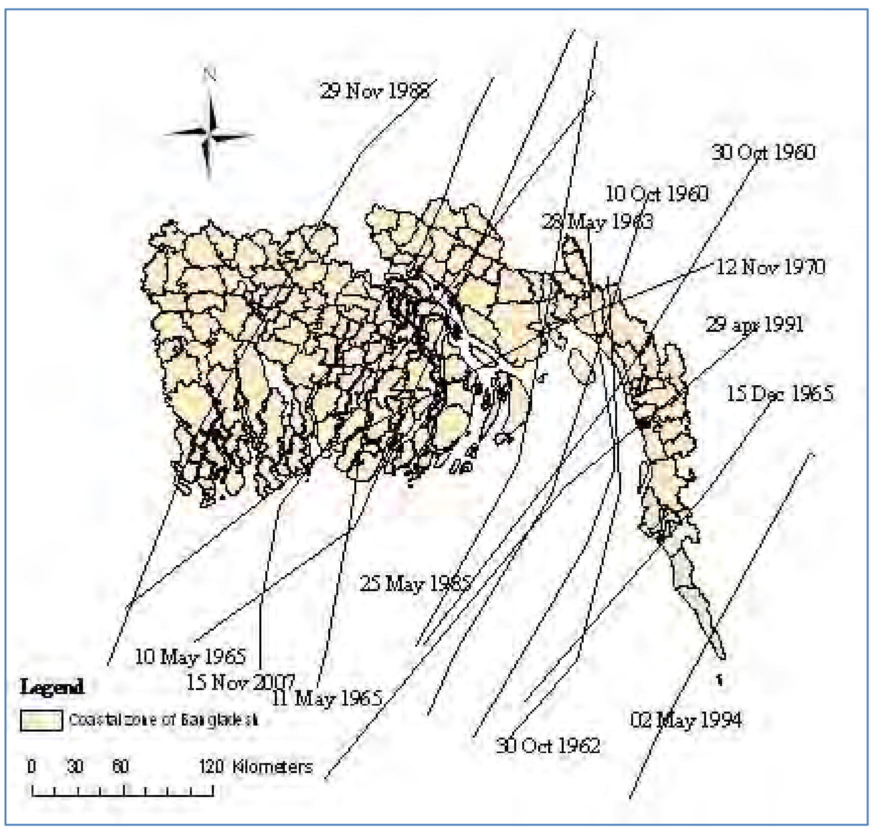


Figure 2.3: Tracks of some severe cyclones that crossed the coast of Bangladesh during the period 1960-2009 (tracks are plotted after Islam and Peterson, 2009; track data upto 2003 (ibid) and track data after 2003 is from Dasgupta et al., 2010).

Large tropical cyclones create storm surges that can strike crowded coastal regions with devastating force. In the coastal region of Bangladesh, it is frequently found that storm surge is the key factor in the cyclonic disasters, especially since the coast line is low lying (Chowdhury and Rahman, 1998).

Bangladesh is on the receiving end of about 40% of the impact of total storm surges in the world (Murty and El Sabh, 1992). The reasons for this disproportional large impact of storm surges on the coast of Bangladesh were reported (Ali, 1999) to be the following.

- The phenomenon of recurvature of tropical cyclones in the Bay of Bengal,
- Shallow continental shelf, especially in the eastern part of Bangladesh,
- High tidal range,
- Triangular shape at the head of the Bay of Bengal,
- Almost sea level geography of the Bangladesh coastal land,
- High density of population and coastal protection system.

All the factors for a major cyclone disaster are present and such disasters have occurred several times in the past and claimed hundreds of thousands of lives notably in 1970 and 1991.

Storm surges are generated by the winds and the atmospheric pressure changes associated with cyclones. Wind is the main contributing factor (~90%). It exerts stress on the water underneath, and surge is generated. In Bangladesh, storm surge heights in excess of 10 m are not uncommon. A few examples of storm surge heights are given in Table 2.2 in the column under 'business as usual'-meaning normal conditions (that is, no climate change). Only those cyclones are included in which there was a death toll of at least 1000.

Table 2.2: Storm surge scenarios for cyclones affecting Bangladesh from1960 to 1995, each of which caused at least 1000 human deaths (adopted from Ali, 1999)

Cyclone date	Deaths	Storm surge height (m)		
		Business as usual	2°C	4°C
Oct 9, 1960	3000	3.05	3.69	4.55
Oct 30, 1960	5149	4.57-6.10	5.53-7.38	6.80-11.00
May 9, 1961	11468	2.44-3.05	2.95-3.69	3.64-4.55
May 28, 1963	11520	4.27-5.18	5.17-6.27	6.36-7.72
May 11, 1965	19279	3.66	4.43	5.45
May 31, 1965	12000	6.10-7.62	5.53-9.22	11.00-11.35
Nov 12, 1970	500000	6.10-9.14	5.53-11.06	11.00-13.62
May 25, 1985	11069	3.05-4.57	3.69-5.50	4.55-6.80
Nov 29, 1988	5708	1.52-3.05	1.84-3.69	2.27-4.55
Apr 29, 1991	138000	6.10-7.62	5.53-9.22	11.00-11.35

Business as usual: no climate change; 2 and 4°C: lower and upper bounds of the rise in temperature by 2100, as given by the IPCC.

2.1.3 Recent cyclonic storms in Bangladesh

The coastal regions of Bangladesh are subject to damaging cyclones almost every year. Since 1995, five severe cyclones (Table 2.3) hit coast of Bangladesh coast in May 1997, September 1997, May 1998, November 2007 and May 2009 (GoB, 2009). Among the recent cyclones two of the latest cyclones are cyclone Sidr and cyclone Aila. Cyclone Sidr struck Bangladesh in November 2007, killing over 3,000 people, injuring over 50,000, damaging or destroying over 1.5 million homes, and affecting the livelihoods of over 7 million people (UN 2007; BDMIC 2007). Cyclone Aila hit the south-western coast of Bangladesh on 25 May, 2009 leaving over 190 people dead and causing widespread devastation. Initially, the impact of the disaster was not so severe. However, as time has gone by, the situation in the affected areas has worsened. Much land has remained severely water-logged and more and more houses, often made of mud, have collapsed. It is now estimated that four million people are affected, over 240,000 homes have been completely destroyed and over 370,000 homes partly destroyed (IFRCRCS, 2009).

Present increase of cyclone intensity in the Bay of Bengal is partly attributed by climate change. In recent years, general cyclonic activity in the Bay of Bengal has become more frequent, causing rougher seas that can make it difficult for fishermen and small craft to put to sea (MoEF, 2009). For the Bay of Bengal, a study using dynamical models driven by RCM20 simulations of current and future climates have shown large increases in the frequency of highest storm surges despite no significant change in the frequency of cyclones (Unnikrishnan et al, 2006). Hence, from a practical perspective vulnerability of

Bangladesh to cyclones/storm surges may increase even more as result of climate change (Dasgupta et al., 2010).

Table 2.3: List of major cyclones that made landfall to Bangladesh and associated coastal storm surges and casualties since 1995 (Source: Data upto 2007 from Karim and Mimura, 2008 and after that from Dasgupta et al., 2010)

Landfall date	Location of landfall	Maximum wind speed (km/h)	Maximum surge height (m)	Death
19 May 1997	Chittagong, Feni	225	4.6	126
26 Sep 1997	Chittagong	150	3.0	155
16 May 1998	Chittagong, Cox's Bazar	165	2.5	12
15 Nov 2007	Barguna, Patuakhali	220-250	6.0	3500
25 May, 2009	West Bengal, India	95	4	190

2.2 Impact of Climate Change on Tropical Cyclone Formation

An increase in sea surface temperature is strongly evident at all latitudes and in all oceans. The scientific evidence indicates that increased sea surface temperature will intensify cyclone activity and heighten storm surges. These surges will in turn, create more damaging flood conditions in coastal zones and adjoining low lying areas (Dasgupta et al., 2010).

Some recent scientific studies suggest that increases in the frequency and intensity of tropical cyclones in the last 35 years can be attributed in part to global climate change (Emanuel 2005; Webster et al. 2005; Bengtsson, rogers, and Roeckner 2006). Others have challenged this conclusion; citing problems with data reliability, regional variability, and appropriate measurement of sea-surface temperature and other climate variables (e.g., landsea et al. 2006). Although the science is not conclusive (IWTC 2006; Pielke et al. 2005), the International workshop on Tropical Cyclones (IWTC) has recently noted that “if the projected rise in sea level due to global warming occurs, then the vulnerability to tropical cyclone storm surge flooding would increase” and “it is likely that some increase in tropical cyclone peak wind-speed and rainfall will occur if the climate continues to warm. Model studies and theory project a 3-5% increase in wind-speed per degree Celsius increase of tropical sea surface temperature.”

2.2.1 Wind speed

The formation of tropical cyclones is strongly influenced by SST of the underlying ocean or, more specifically, by the thermal energy available in the upper ocean waters. One necessary but not sufficient condition for tropical cyclone formation is that the sea surface should have a minimum temperature of about 26 to 27°C. This leads to the speculation that any rise in sea surface temperature (SST) due to climate change is likely to be accompanied by an increase in cyclone frequency. A normally occurring cyclone may have a higher intensity as a result of warmer seas due to global warming. Any increase in SST is likely to cause greater convective instability, leading to an increase in the wind speed. The stress exerted by wind on water underneath is proportional to the square of the wind velocity (Ali, 1999). Emanuel (1987) has explained the significance of SST in the increase of cyclone intensity and established relationships between minimum sustainable central pressure and maximum wind speed as a function of SST. If the IPCC (2007) standard of a lower bound of 2°C and an upper bound of 4.5° C rise in temperature by 2100 is considered, the corresponding increases in maximum cyclone wind speed using Emanuel's table (Emanuel, 1987) are 10 % and 25%, respectively, relative to the present threshold temperature of 27°C in the Bay of Bengal (Table 2.4).

Table 2.4: Relationship of maximum wind speed (V_m) in cyclones to sea surface temperature.

Sea surface Temperature (° C)	**V_m (ms^{-1})**	$V_m/V27$[§]
27	72	1.00
28	75	1.04
29	79	1.10
30	83	1.15
31	88	1.22
32	93	1.29
33	99	1.38
34	106	1.47

[§] $V_m/V27$ is the ratio of maximum wind speed at different temperatures to maximum wind speed at 27° C. Source: Emanuel, 1987.

2.2.2 Storm surge

The scientific evidence indicates that climate change will intensify storm surges for two reasons. First, they will be elevated by a rising sea level as thermal expansion and ice cap melting continues. The most recent evidence suggests that sea-level rise could reach 1 meter or more during this century. Second, a warmer ocean is likely to intensify cyclone activity and heighten storm surges. IPCC (2007) cites a trend since the mid-1970s toward longer duration and greater intensity of storms, and a strong correlation with the upward trend in tropical sea surface temperatures. As storm surges increase, they will create more damaging flood conditions in coastal zones and adjoining low-lying areas (Dasgupta et al., 2009). Larger storm surges threaten greater future destruction because they will move further inland, threatening larger areas than in the past.

As predicted by Emanuel (2005), any increase in SST will cause intensifcation of tropical cyclones. This phenomenon should be included in any future prediction of cyclonic storm surges. Ali (1999) is one of the few studies that predicted cyclone-induced surges at the coast by incorporating SST rise and SLR into the cyclone model. The main inputs to the cyclone model are minimum sustainable central pressure and the maximum wind speed as a function of SST. Table 2.5 shows the surge heights for a total of nine climate scenarios correspond to three SSTs and three sea levels. Scenario I represents the base condition, while Scenario V is considered as an average climate condition by 2050. It shows that storm surge height may increase as much as 21 % if SST rises by 2°C (Scenario II) and 49% if SST rises by 4°C (Scenario III). Another analysis based on continental shelf length and wind speed (Chowdhury, 1994) also produced similar surge heights at the coast. These predictions are relatively large compared with the results of Mitchell et al. (2006) in which they predicted 0.5-0.7 m increase in surge height of a 50-year return period storm surge. It is interesting to note that surge height reduces by 7% if SLRs by 1.0 m, but SST remains unchanged (Scenario VII). The reason is that the amplification of the surge is less if the water depth is increased, due to the differences in bottom friction on the propagating waves.

Table 2.5: Storm surges under different SLR and SST conditions (Scenario I represents base condition that corresponds to wind speed and central pressure as observed during the 1991 cyclone) [adopted from Karim and Mimura, 2008]

Climate scenarios	SLR (m)	SST rise (°C)	Wind speed (km/h)	Central pressure (hPa)	Surge height (m, MSL)
Scenario I	0.0	0	225	926	7.6
Scenario II	0.0	2	246	924	9.2
Scenario III	0.0	4	274	921	11.3
Scenario IV	0.3	0	225	926	7.4
Scenario V	0.3	2	246	924	9.1
Scenario VI	0.3	4	274	921	11.3
Scenario VII	1.0	0	225	926	7.1
Scenario VIII	1.0	2	246	924	8.6
Scenario IX	1.0	4	274	921	10.6

2.2.3 Sea level rise

The consequences of SLR are of particular concern for low-lying deltas, such as Bangladesh whose half of the area lie within five meters of the mean sea-level (MCSP, 1993). The warming of the earth implies a warming of the oceans with a consequent sea-level rise due to thermal expansion. A 0.4°C warming in the last century has apparently led to a 5 cm rise in sea-level. Although it is not yet possible to predict future sea-level rise precisely, the present sea-level rise is predicted to rise on the order of 1 m by the year 2100 (ASCE Task Committee, 1992).

As a low-lying country, Bangladesh is considered as one of the most vulnerable countries in the world to climate change and SLR (IPCC, 2007). The country is experiencing rising sea level along its coast (SMRC, 2003; Unnikrishnan et al., 2006) due to global SLR and the subsidence of the Ganges delta (Alam, 1996; Haque, 1997). As outlined by Alam (1996), the Ganges–Brahmaputra delta is subsiding at a rate of 2-4 mm/ year. The impacts of SLR are profound throughout the western coastal zone as it is low lying and the coastal lands are subsiding (Mohal et al., 2007). SLR can also cause the relative decrease of existing shelter heights with respect to mean sea level (MSL). The Bangladesh country study (Agrawala et al., 2003) put the range at 30-100 cm by 2100, while IPCC projected 26-59 cm global SLR under scenario A1F1 (Meehl et al., 2007). In an earlier study, potential SLR in Bangladesh was predicted as 30-150cm by 2050 (DOE, 1993). Based on IPCC reports and available SLR studies, the NAPA for Bangladesh recommended SLRs of 14, 32 and 88 cm for the years 2030, 2050 and 2100, respectively (MOEF, 2005).

Increasing water depth due to SLR would cause increase in the speed of wave propagation. As a result the wave lengths of tides and cyclonic storm surges would increase. Also, the shoreline would retreat toward inland as a result of sea-level rise. This would enhance the travel distance of the cyclonic storm surge wave over sea surface. However, study from Karim and Mimura (2008) suggests that surge height reduces by 7% if SLRs by 1.0 m, but SST remains unchanged. The reason is that the amplification of the surge is less if the water depth is increased, due to the differences in bottom friction on the propagating waves. This phenomenon is known as shoaling.

2.3 Vulnerability to Storm Surge

Vulnerability can be defined as the degree of loss to a given element at risk or set of such elements resulting from the occurrence of a natural phenomenon of a given magnitude. Cyclonic storms have always been a major concern to coastal plains and offshore island of Bangladesh. The people who live in the exposed coast are considered as vulnerable partly or fully exposed to surge flooding. The administrative districts Satkhira, Khulna, Bagerhat, Barguna, Patuakhali, Jhalkhati, Pirojpur, Barisal and Bhola are located in the exposed coast.

Vulnerability is defined as the extent to which a natural or social system is susceptible to sustaining damage from climate change. Vulnerability is a function of the sensitivity of a system to changes in climate (the degree to which a system will respond to a given change in climate, including both beneficial and harmful effects) and the ability to adapt the system to changes in climate (the degree to which adjustments in practices, processes or structures can moderate or offset the potential for damage or take advantage of opportunities created, due to a given change in climate) (IPCC, 1997).

According to Chowdhury and Rahman, (1998) the vulnerability of the people to hazard due to storm surge floods in the coastal region of Bangladesh is affected by many factors. Some of them are population density, road communication, water supply, disaster preparedness, employment, income level, savings etc. In assessing the risk due to storm surge density of unprotected population was taken as the vulnerability indicator in that study.

Vulnerability was taken as a function of population density in the exposed coast by Karim and Mimura (2008) for the assessment of the impact of climate change and sea-level rise on cyclonic storm surge floods in Bangladesh.

Dasgupta et al. (2009) calculated vulnerability in three steps for cities in each developing country whose coastal areas will be most affected by future increases in storm surges. First, they ranked cities in each region by percent increase in the future inundation area relative to the current inundation area. To weight for current vulnerability, they ranked cities in each region by percent of coastal area on the basis of inundation zone. Then they computed the average for the two ranks and re-ordered the cities by their average ranks.

2.4 Vulnerability Assessment

The conceptual idea of vulnerability given by White and others (2005) shows vulnerability is the interrelation of the exposure and the susceptibility as stressor of the system with the coping capacity as the potential of the system to decrease the impact of the hazard.

$$Vulnerability = \frac{Exposure \times Susceptibility}{Coping\ capacity} \tag{2.1}$$

According to UNDRO (1991) vulnerability analysis starts with the identification of elements at risk. Then a relationship between hazard and damage, that is relationship of vulnerability factor V (u) on a scale from 0 (no damage) to 1 (maximum damage) and maximum damage per element D (u) are to be established for every category of elements at risk. Thus the vulnerability of a given element v (u) is usually expressed by

$$V(u) = V(u)\, D(u) \tag{2.2}$$

Vulnerability (V) was taken as a function of density of population (exposed) by Mott Macdonalds and others (1993) for the hazard and risk mapping for Bangladesh.

$$V = \frac{d\ of\ the\ land\ unit \times 10}{highest\ d\ among\ all\ land\ units} \tag{2.3}$$

where d is the density of population.

2.5 Risk

Risk is the possibility of loss or injury to people and property. During a cyclonic storm loss and injury to people and property may occur from two sources. One is the strong wind and the other is the storm surge flooding. The study area prone to storm surge flooding has been termed as Risk Zone (RZ) where there is a risk that damages to properties may occur due to inundation by storm surge water. The RZ is further categorized as the High Risk Area (HRA) where there is a possibility of loss of lives due to appreciable inundation by storm surge (MCSP, 1993).

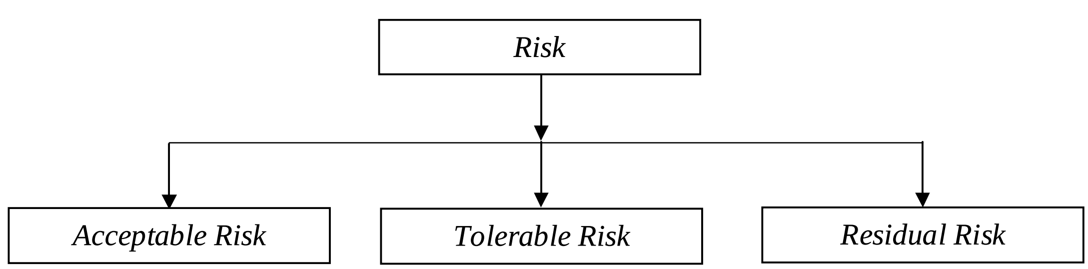
Risk, as defined in UNDRO (1991), is the sum of all losses that can be expected from the occurrence of a particular natural phenomenon. Risk may also be defined as the expected degree of loss due to a particular natural phenomenon and as a function of both natural hazard and vulnerability.

Risk is defined as that which involves the likelihood of harm or other form of loss (Carson, 1996). There is a relationship between hazard and risk which is dependent on vulnerability. There is no risk if there are hazards but no vulnerability, or if there is vulnerability but no hazard (Blaikie et al., 2003). Risk is therefore a product of both hazard and vulnerability.

Chowdhury and Rahman, (1998) measured risk on the basis of spatial distribution of flooding and the population vulnerability. It takes flood hazard is a function of the storm surge flood depth and the probability of flooding and the vulnerability factor is a function of the unprotected population density in the planning unit.

Types of risk

Risk may be of several types: (a) Acceptable risk (b) Tolerable risk (c) Residual risk



Acceptable risk: The level of potential losses that a society or community considers acceptable given existing social, economic, political, cultural, technical and environmental conditions.

In engineering terms, acceptable risk is also used to assess and define the structural and non-structural measures that are needed in order to reduce possible harm to people, property, services and systems to a chosen tolerated level, according to codes or "accepted practice" which are based on known probabilities of hazards and other factors (ISDR, 2009)**.**

Tolerable risk: Risk that is accepted in a given context based on the current values of society. A level of risk deemed acceptable by society in order that some particular benefit or functionality can be obtained, but in the knowledge that the risk has been evaluated and is being managed (John Daintith, 2004).

Residual risk: The risk that remains in unmanaged form, even when effective disaster risk reduction measures are in place, and for which emergency response and recovery capacities must be maintained.

The presence of residual risk implies a continuing need to develop and support effective capacities for emergency services, preparedness, response and recovery together with socio-economic policies such as safety nets and risk transfer mechanisms (ISDR, 2009)**.**

For human life loss this terminology may not be acceptable. Residual risk is the only term that can be used in case of human life loss.

2.6 Risk Assessment

UN (1991) and the UNDP (2004) define a conceptual super-structure for risk as follows:

$$Risk = Hazard * Vulnerability \qquad (2.4)$$

Thus, risk results from a future interplay of a hazard and the various components defining vulnerability.

A method of risk assessment has been used by Mott MacDonald and Others (1993) to prepare comprehensive disaster management programme under the Ministry of Relief of the Government of Bangladesh. It was a Risk Index (RI) for a unit of land based on a Hazard Factor (HF) and a Vulnerability Factor (VF) as expressed below.

$$\mathrm{RI} = \mathrm{HF} * \mathrm{VF} \qquad (2.5)$$

$$HF = \frac{HI\ of\ the\ land\ unit \times 10}{highest\ HI\ among\ all\ land\ units} \tag{2.6}$$

$$VF = \frac{DP\ of\ the\ land\ unit \times 10}{highest\ DP\ among\ all\ land\ units} \tag{2.7}$$

Where HI is the hazard index and DP is the density of population. In the formulation in Equations (1) and (2), the magnitude of R lies in the range of 0 and 100.

Another method of risk assessment has been used by Hoque and others (1997) for the study of storm surge flooding in Chittagong city and associated risks. Risk of a storm surge for a particular area depends mainly upon depth of inundation, population density and land use. A method to assess the risk from a natural disaster is given by the risk index:

$$\text{Risk Index (RI)} = HF * VF \tag{2.8}$$

where HF = hazard factor and VF = vulnerability factor. HF and VF are defined as:

$$HF = \frac{10 \times hazard\ index\ of\ an\ area}{highest\ hazard\ index} \tag{2.9}$$

$$VF = \frac{10 \times importance\ index\ of\ an\ area}{highest\ importance\ index} \tag{2.10}$$

The hazard index is defined as the element that causes the risk and in this case the depth of the storm surge is the hazard index. The importance index is defined as the element that indicates the economic value of the area flooded and in this case the land-use type is the importance index. In this method the higher the value of the risk index the higher the degree of risk.

A quantifiable measure of risk has been derived by Sener and others (1996) for a Cyclone Shelter Preparatory Study for the Government of Bangladesh whose objectives was to develop a project to provide access to a safe havens for all the inhabitants, both human and animal, of the coastal area at the time of cyclone. A risk index has been devised to assist in ranking of the mouzas, unions and thanas in the coastal area for priority measure. The risk index, R, was calculated as below

$$R = q * d \tag{2.11}$$

Where q is the hazard index and d is the population per hectare.

Peduzzi and others (2009) made a hypothesis that risk follows a multiplicative formula as described in the simplified equation-

$$R = H_{fr}\ Pop\ Vul \tag{2.12}$$

where:

R = number of expected human impacts [killed/year].

H_{fr} = frequency of a given hazard [event/year].

Pop = population living in a given exposed area [expose population/event].

Vul = vulnerability depending on socio-politico-economical context of this population [non-dimensional number between 0-1].

According to this formula, if there is no hazard, then the risk is null (the same if population or vulnerability is null).

Although there are information's and equations regarding vulnerability and risk assessment have been given in the literature review but all of them have not been used in this study.

CHAPTER THREE: STUDY AREA

3.1 Coastal Zone

The coastal zone of Bangladesh was selected as the study area in this study (Figure 3.1). In Bangladesh the coastal zone has been delineated based on three geo-physical characteristics that distinguish the coastal zone from rest of the country: interplay of tidal regime, salinity in soil and water and cyclone and storm surge; with economic and social implications on the population. The coastal zone comprises 19 administrative districts; these are Bagerhat, Barguna, Barisal, Bhola, Chandpur, Chittagong, Cox's Bazar, Feni, Gopalganj, Jessore, Jhalkati, Khulna, Lakshmipur, Narail, Noakhali, Patuakhali, Pirojpur, Satkhira and Shariatpur (PDO-ICZMP, 2003a). Coastal zone of Bangladesh encompasses a land area of 47201 km^2 (32% of total area of the country). Among coastal districts a total of 48 upazilas in 12 districts that are exposed to the sea and or lower estuaries, are defined as the exposed coast and the remaining 99 upazilas of the coastal districts are termed interior coast (PDO-ICZMP, 2003a). The coastal zone is low-lying with 62% of the land have an elevation of up to 3 metres and 86% up to 5 metres.

3.2 Physical characteristics of the study area

The study area has been delineated into three major zones (Figure 3.2) based on physiographic and hydro-geo-morphological characteristics and the process by which it has been formed. These are: Ganges Tidal Plain (GTP) comprising the areas from Hariabhanga rivers along the Indo-Bangladesh border to west bank of Tetulia channel in the east; the Meghna Deltaic Plain (MDP) in the middle extending from the Tetulia channel to the Sandwip channel in the east and the Chittagong coastal Plain (CCP) comprising the narrow low-lying stretch extending upto the Naaf river. These three physiographic zones can also be termed as West zone, the Central Zone and East Zone respectively (MCSP, 1993). Brief descriptions of the three zones are given below:

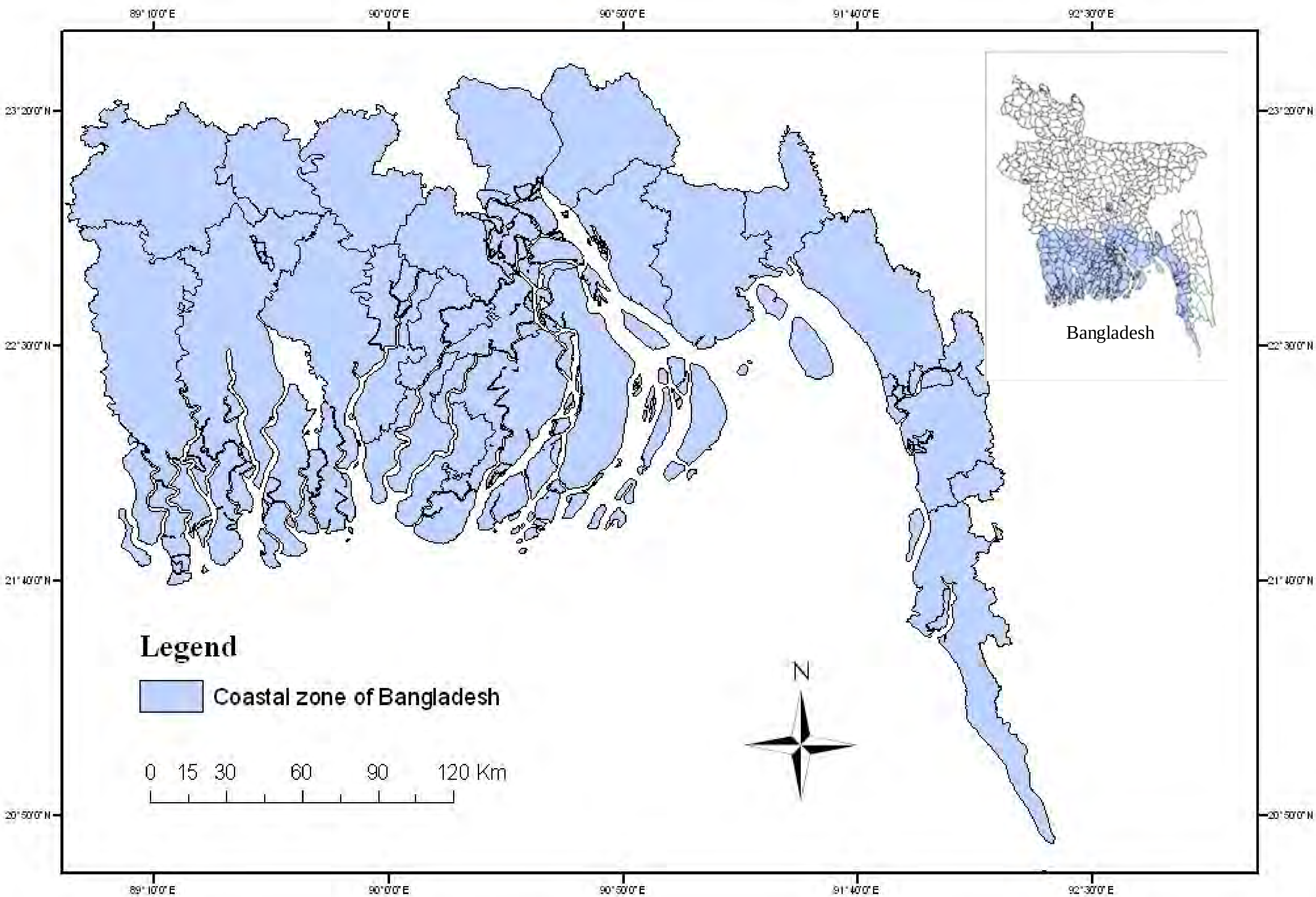


Figure 3.1: Map shows coastal zone of Bangladesh (Source: Coastal zone delineated by PDO-ICZMP, 2003)

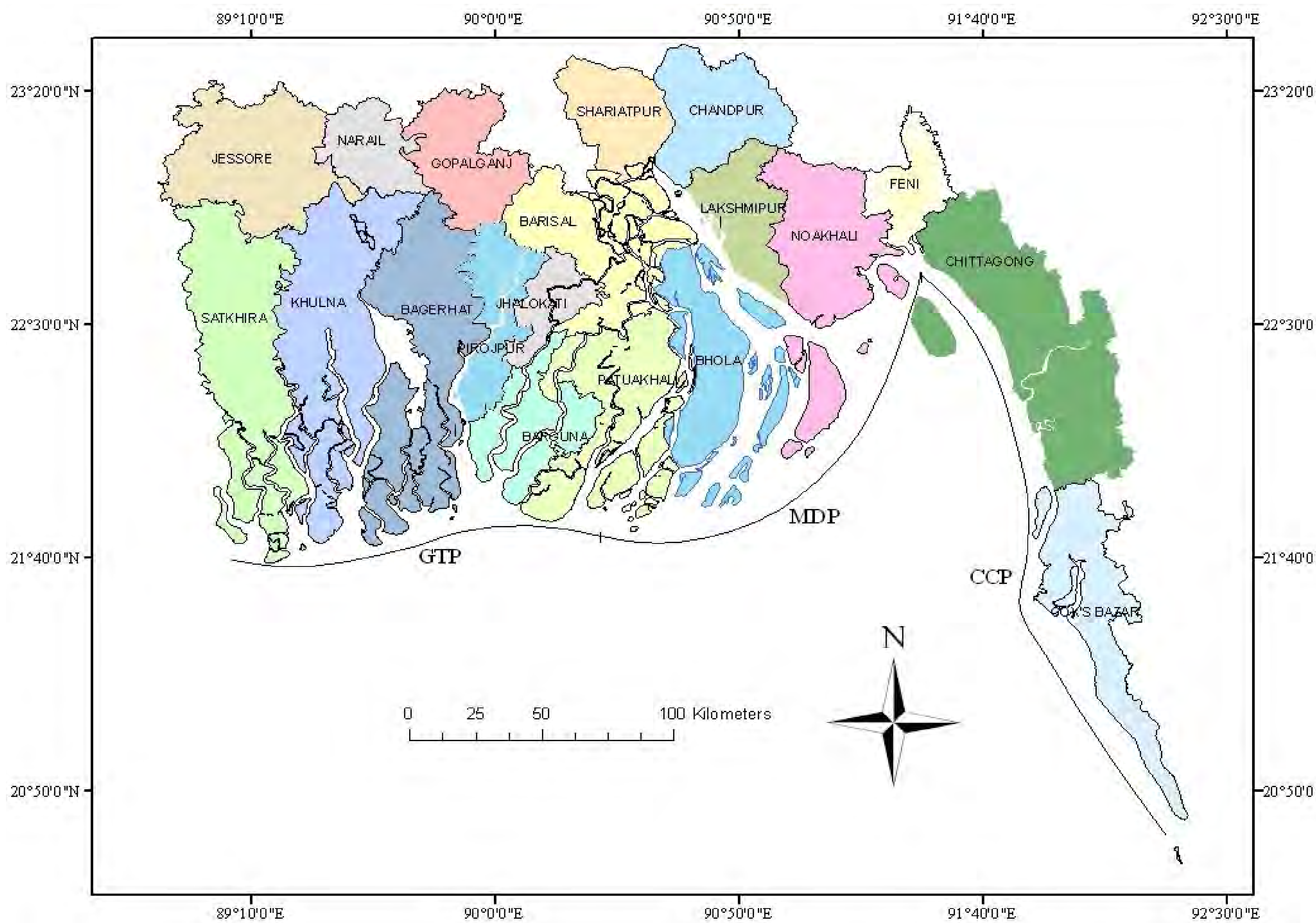


Figure 3.2: Coastal districts and three different coastal regions (Source: Coastal zone delineated by PDO-ICZMP, 2003)

Western Coastal Zone (GTP)

The entire zone is the floodplain of the Ganges river. This zone, located on the south-west of the coastal region, is characterized by large and interconnected network of tidal rivers and creeks, with relatively stable land mass. Rivers in the region carry relatively small quantity of sediments, and land erosion and land accretion rates relatively low. There are four major river systems having width of several kilometers in this region which are Sibsa river, Pussur river, Bishkhali-Buriswar river and Tetulia river. The largest mangrove forest in the world, the Sunderbans (6017 km^2), is located to the western part of the region. Average land elevation is below 1.5 m MSL.

Central Coastal Zone (MDP)

This is the deltaic region of the Ganges-Brahmaputra-Meghna rivers. It is the most active coastal zone in Bangladesh. The river system in the region carries massive volume of discharge and sediments into the Bay of Bengal causing large scale land erosion and land accretion. The most dynamic Meghna estuary is located in this region

Eastern Coastal Zone (CCP)

This zone comprises of land masses along the Chittagong and Cox's Bazar coast. It is the most stable part of country's coastal zones. The coastal plain includes the Matamuhuri Delta and Karnafuli estuary. This zone is formed by narrow strip of land between the coastline and the hills on the east. The world longest natural beach (120 km) is located in this region.

3.3 Natural system

The natural configuration of the coastal zone is related to its unique composition and landscape that includes:

- Inter-tidal land;
- Beach;
- Wetland/ rivers, beels and estuaries;
- Floodplain; and
- Hill.

This natural system has some explicit functions. These are: flood alleviation, storm surge, water retention and drainage, habitat of fish, assimilation of wastes, regulation of saltwater intrusion, transport of sediments and sedimentation/accretion. The coastal zone has a myriad of natural resources that stems from its natural system. Some are renewable (freshwater, soil, forest, salt, wind, solar energy, wildlife, etc) and some are non-renewable (oil/gas, sand, minerals, space, etc). The natural system sets the stage where the people pursue their livelihoods (PDO-ICZMP, 2005).

3.4 Islands and Chars

About 60 islands are identified in the coastal zone to date (Islam, 2004). Most of the islands are located in the central coastal zone, because of the dynamic river flow of the Ganges- Brahmputra-Meghna river system. Hatia, Sandweep and Maishkhali are three upazilas and Bhola, an administrative district are four bigger islands in the zone. A total number of 177 char lands are also identified in the coastal zone (Islam, 2004). The offshore islands are isolated, exposed to natural calamities and little access to services. In the PDSCL survey (PDO-ICZMP), it has been indicated that in islands, chars and eastern part of the coast, cyclone is the main vulnerability issue.

The sea level rise threatens the low-lying coastal belt and small islands. Much of our coast is protected with 4 to 5 meter high dykes and will be further protected with additional planned polders. The main impacts of SLR would be: Chars and offshore islands are difficult to access that impedes investments (PDO-ICZMP, 2003).

3.5 River Network

A vast river network, a dynamic estuarine system and a drainage basin intersect the coastal zone, which made coastal ecosystem as a potential source of natural resources, diversified fauna and floral composition, though there also have immense risk of natural disasters (Shamsuddoha *et. al.*, 2007).

A large number of rivers, including the Ganges-Brahmaputra-Meghna Rivers which constitute one of the largest river systems in the world, discharge through Bangladesh, into the Bay of Bengal. A river system can have a number of effects on surges and tides. Numerical models have shown that surges at the coast are higher without rivers than with rivers (Sinha *et. al.,* 1985). Fresh water discharge through rivers modifies sea surface elevations resulting from surges and tides. Surges, tides and south-west monsoonal wind produce back water effect on river. This is particularly important during flood period (June-September).

The presence of a large number of wide estuaries and rivers in Bangladesh allows a potentially deep inland penetration of surge waters leading to flooding in the areas adjacent to the rivers (MCSP, 1993).

A direct consequence of SLR would be intrusion of salinity with tide through the rivers and estuaries. It would be more acute in the dry season, especially when freshwater flows from rivers would diminish. According to an estimate of the Master Plan Organization, about 14,000 sq km of coastal and offshore areas have saline soils and are susceptible to tidal flooding. If some 16,000 sq km of coastal land is lost due to a 45 cm rise in sea level, the salinity front would be pushed further inland (Shamsuddoha *et. al.,* 2007).

3.6 Demographic and Socio-economic features

3.6.1 Demography

According to 2001 population census, the coastal zone of Bangladesh has a population of about 35 million (Table 3.1). They are 28 percent of the total population. Average size of household is 5.1. The density of population is 743 per km^2. Women are 49 percent, while 23 percent are urban-dwellers. Size of the labor force (population of 15-59 year age group) is 18.6 million who 53 percent of the population (PDO-ICZMP, 2004).

3.6.2 Educational status

Coastal zone has a higher literacy rate compared to the national rate (46%) of educational status. Average literacy in the coastal zone is 51%; male 48% and female 52% (BBS, 2001).

Table 3.1: Area and population of the coastal districts

No	District	Area(sq.km)	Population	Population
1	Bagerhat	3959	1,549,031	1785331
2	Khulna	4394	2,378,971	2741876
3	Satkhira	3858	1,864,704	2149159
4	Barguna	1831	848,554	977998
5	Barisal	2785	2,355,967	2715363
6	Bhola	3403	1,703,117	1962922
7	Jhalokati	749	694,231	800134
8	Patuakhali	3221	1,460,781	1683619
9	Pirojpur	1308	1,111,068	1280558
10	Shariatpur	1182	1,082,300	1247402
11	Chandpur	1704	2,271,229	2617698
12	Feni	928	1,240,384	1429601
13	Lakshmipur	1456	1,489,901	1717181
14	Noakhali	3601	2,577,244	2970395
15	Chittagong	5283	6,612,140	7620802
16	Cox's Bazar	2492	1,773,709	2044283
17	Gopalgong	1490	1,151,800	1343032
18	Jessore	2567	2,106,996	2848582
19	Narail	990	655,720	804993
Total		47201	34927847	40740928

Source: PDO-ICZMP, 2003a

3.6.3 Socio-economic condition of the study area

Major livelihood groups

Coastal livelihood groups are those who earn their living from activities defined by coastal conditions (Table 3.2). They often vary from each other in terms of production relations and marketing. Some work independently (fry collector), some work as lessee or sharecropper (salt farmer, shrimp farmer) and some are contractual laborer (fisher hired by a bahadder). Some live on exploitation of natural resources (salt farmer, fry collector, fisher, honey collector) and some live on skill-based human resources (boat-building carpentry, net making). Other livelihood groups are extractor of forest resources, agricultural laborer, small farmer, urban poor (PDO-ICZMP, 2004).

Table 3.2: Major livelihood groups

Livelihood group	Estimation of households (2001)	Percentage
Rural	5,254,000	**76.7**
Farm laborer	1,744,000	25.5
Small farmer	1,724,000	25.2
Medium and large farmer	462,000	6.7
Fisher	514,000	7.5
Salt farmer	38,000	0.6
Shrimp fry collector	185,000	2.7
Forest resources collector	119,000	1.7
Others (Boatmen etc.)	809,000	11.8
Urban	1,596,000	**23.3**
Poor	798,000	11.7
Non-poor	798,000	11.7
Total	6,850,000	100

Source: PDO-ICZMP, 2004

Livelihood options in the coastal area

Certain activities are common everywhere and some are typical of the coastal zone. Coastal zone-specific activities are those, which stem from special geo-physical specialty of the area conditioned by its natural systems and the opportunities unique to the area. Some occupations can be exclusively attributed to the coastal zone and some are prevalent in the coastal districts to a greater extent than other areas. These are the following: salt production; fishing (coastal and marine); fish processing (drying); net making; fry collection; shrimp farming; crab/shell collection; extraction of forest products (wood, honey, golpata and wax collection from Sundarban); and boat building (boat carpentry) (PDO-ICZMP, 2004). Relative condition of the coastal zone in Bangladesh is given in Table 3.3.

Table 3.3: Relative position of the coastal zone

Indicator	Unit	CZ	BD	Reference year (source)
Above national average				
Sex ratio	Males/100 females	105	107	BBS (2001)
Agriculture daily wage rate	Taka	49	46	1997/98 PDO-ICZMP
Literacy rate (7+)	%	51	45	BBS (2001)
Primary school density	No/10,000 persons	6.9	6.3	2001 (PDO-ICZMP)
Household with durable wall	%	47	42	BBS (1991)
Household with sanitary latrine	%	45.60	36.87	BBS (2001)
Density of road	Km/km^2	0.71	0.67	1996 (PDO-ICZMP)
Land accretion	Ha/yr	5,080		1973-2000 (MES)

Below national average				
Average size of household	Number	5.1	4.9	2001 (BBS)
Small farm households	% owing 0.05-2.49 acre	57.7	52.9	BBS (1996)
Per capita GDP	Taka	18,198	18,269	BBS (1999-200)
Primary school enrolment rate	% of child 6-10 years	95	97	2001 (PDO-ICZMP)
Per capita gross cropped area	Ha	0.093	0.109	BBS (1996)
Functionally landless household	% owing <0.50 acre	53.5	52.6	BBS (1996)
Share of Industrial sector in GDP	%	22	25	BBS (1999-200)
Susceptibility to severe cyclone and storm surge	No of occurrence	51		1948-98 (PDO-ICZMP)

Source: PDO-ICZMP, 2005

3.7 Institutional Environment

The people have intricate relationship with government institutions. They are utilizing services provided by the government, like, physical infrastructures, health and educational services, water; sanitation, access to the national electricity grid, relief and rehabilitation services for the destitute and agricultural extension services for farmers. Similarly formal institutions like Union Parishad, VGD committee, other service providers, legal regime, etc. and informal institutions like samaj, salish, traditional laws and tenets, social sanctions, community regulations, etc have direct bearing on the quality of life of the coastal dwellers.

Many households in the coastal zone consider membership of NGO groups an important asset. NGOs are an important provider of certain services, particularly micro-credit. Their coverage has a direct correlation with the coping capacity of the people. Areas with higher NGO coverage enable the poor people to diversify their options. Accessing to the services provided by the institutions is influenced by many factors, like economic and social status of the people, relation with power brokers and rules and regulations (PDO-ICZMP, 2004). Different NGOs have constructed cyclone shelter in the coastal area of Bangladesh. They are playing vital role in this regard. Some of them are Caritas, Grameen Bank, Bangladesh Lutheran Mission, South Asia Partnership, Nijera Kori, Heed-Bangladesh, Community Health Care Project, World vision of Bangladesh, Gonoshasthya Kendra, Prism-Bangladesh etc (MCSP, 1993).

After the catastrophic cyclone of November 1970, the Coastal Area Rehabilitation and Cyclone Protection Project (CPP-1) was implemented to undertake a programme of rehabilitation, reconstruction preparedness in the coastal areas and offshore islands. CPP-2 was initiated following the cyclone of 1985. A follow-on Coastal Embankment Rehabilitation Project (CERP) was launched after the cyclone of April 1991.

The Bangladesh Red Crescent Society (BDRCS) initiated Cyclone Preparedness Program (CPP) in the early 1970s that eventually developed into a world model of physical and institutional infrastructure for disaster management in cyclone prone areas. More than 2000 multi-purpose cyclone shelters were built so far to provide security to the people in the vulnerable areas. An extensive network of radio communication contributes in cyclone preparedness of coastal communities (WARPO, 2006).

3.8 Infrastructure

Infrastructures for land and water management and disaster preparedness includes polders, cross dams, flood protection structures, erosion protection structures, cyclone shelters, infrastructure for emergency communication network, agricultural water supply and domestic water supply infrastructures.

Infrastructure for economic activities: Regulator, Low lift pump, Sluice gate, different Industries, Tourism, Hotels and Other facilities.

Infrastructure for health, education, services and transportation: Health infrastructure, Sanitation infrastructure, Education infrastructure, Electricity, Gas, Renewable energy, Telephone, Other communication infrastructure, Transportation Roads and railways, Railways, Ports and waterways, land ports and Airports (PDO-ICZMP, 2005).

The coastal region of Bangladesh has 123 embanked polders, which were constructed in late sixties to protect the land from saline water and to increase the crop production.

Coastal Embankment

A typical flood mitigation option in the coastal region of Bangladesh is the construction of earthen embankments along the rivers as well as parallel to coastline. It is considered as one of the best measures against tidal flooding and saline water intrusion. The construction of embankment was started during the sixties to protect the agricultural lands from saline water intrusion. Its crest level is determined based on normal high tide and a freeboard which is 1.5 m in general. In the design procedures, neither storm surge height nor its energy is considered as its main purpose is to prevent flooding during high astronomical tides. Even though the embankments are designed primarily for tidal flooding, it serves as a safe guard during cyclone-generated storm surge especially when the magnitude of surge is small. Embankments obstruct the penetration of surge wave to the land and even if the surge overtops them, the wave energy as well as surge height behind the embankment reduces to a considerable extent (IWM, 2002).

Cyclone shelter/Refuge shelter

An important and widely acceptable flood management option in Bangladesh is the construction of refuge shelters commonly known as ‘Cyclone-Shelter’ which have been built since 1960s. However, major constructions were started after the historical worst cyclone of April 1991. The shelters are being used as refuge for human beings and their properties, animals etc during cyclonic periods and as primary school, family welfare center, local government office-cum-community center, storage compartment and so forth during normal times (Chowdury 2003). At present 3,777 cyclone shelters (CDMP) present in the coastal zone of Bangladesh of which 2591 are usable cyclone shelter, 262 are non usable and 924 are Primary Education Development Progaramme (PEDP) buildings (Table 3.4).

Table 3.4: Cyclone shelters and Primary Education Development Programme

District	Usable Cyclone Shelters	Not usable Cyclone Shelters	Primary Education Development Programme, Phase II (PEDP-II)
Bagerhat	97	12	54
Barguna	147	10	59
Barisal	37	0	15
Bhola	417	65	195
Chandpur	21	1	58
Chittagong	578	30	71
Cox`s Bazar	507	10	104
Feni	58	13	5
Jhalokati	12	2	3
Khulna	77	2	46
Lakshmipur	113	10	119
Noakhali	250	34	16
Patuakhali	165	72	103
Pirojpur	36	1	33
Satkhira	65	0	16
Shariatpur	11	0	27
Total	**2591**	**262**	**924**

Source: CDMP, 2010

CHAPTER FOUR: METHODOLOGY

4.1 Research Design and data collection

The research was designed based on secondary data collection on storm surge and then projection for the future due to climate change. Mainly quantitative data were collected for the study. Data regarding SST for the future were obtained from the IPCC Fourth Assessment Report (IPCC, 2007). Wind speed data in relation with SST were generated using Emanuel table (Emanuel, 1987). SLR information was obtained from different literature that predicted SLR rise along South Asia and the Bangladesh coast. Surge height data were generated by using the combination of different factors such as SST, SLR, meteorological tide, astronomical tide etc. Then intrusion distances of different surge height over land were produced by using equation developed by Freeman and Le Mehaute (1964). For the calculation of intrusion distance, bed slope and friction factor were needed. Bed slope and friction factor data were obtained from MCSP (1993). Cyclone shelters or safe havens information were collected from CDMP. Projection of population was made from the BBS census report 2001.

4.2 Surge Height Prediction

To identify the risk zone at first it is necessary to estimate the maximum surge height (h_m) at the coast. The maximum surge height (h_m) at the coast is a function of surge height (h) at the estuary inlet, mean tide level (h_0) and amplitudes of semi-diurnal tidal constituents (M_2 and S2).

$$h_m = h + M_2 + S_2 + h_0 \qquad (4.1)$$

A study by Tareque and Chowdhury (1992) at the Institute of Flood Control and Drainage Research (IFCDR), BUET indicates that the length of the continental shelf is an important factor in determining the maximum surge height along the coast of Bangladesh. Using the formula proposed by Reid (1956), applying correction for second order effects due to shallow water condition as suggested by Bretschneider (1966) and making mathematical transformations to avoid iterative procedure, a formula has been developed by Tareque and Chowdhury (1992) for estimating the maximum surge height at a location along the coast. It is given by

$$h = \frac{13 \times 10^{-6} lV^2}{(5 \times 10^6 + lV^2)^{1/5}} + 14 \times 10^{-6} V^2 \tag{4.2}$$

where h is surge height in m, V is the wind speed in km/ hr., and l is the distance in km between the coast where surge height is required and the 200 m depth contour of the continental shelf.

Tareque (1992) farther developed the model to make best fitted with specific coast of the country. He developed three different models for calculating maximum surge height for three different coast of the country named as:

- Ganges Tidal Plan (GTP)
- Meghna Deltaic Plain (MDP)
- Chittagong Coastal Plain (CCP)

$$h_{GTP} = \frac{7.54 \times 10^{-4} V^2}{(31.25 \times 10^3 + V^2)^{0.2}} + 14 \times 10^{-6} V^2 \tag{4.3}$$

$$h_{MDP} = \frac{12.13 \times 10^{-4} V^2}{\left(17.24 \times 10^3 + V^2\right)^{0.2}} + 14 \times 10^{-6} V^2 \tag{4.4}$$

$$h_{CCP} = \frac{9.73 \times 10^{-4} V^2}{(22.73 \times 10^3 + V^2)^{0.2}} + 14 \times 10^{-6} V^2 \tag{4.5}$$

He developed the equation by considering average l. Here the length of continental shelf for GTP, MDP, and CCP are 160, 290 and 220 km, respectively.

The equations above give cyclonic storm surge height; not the total displacement of water surface. In order to obtain displacement of water surface, the cyclonic storm surge height is to be added to the tidal displacement. The interaction between storm surge and tide is non-linear, and the resultant displacement is smaller than the sum of two components (Ahsan, 1985; Das et al., 1974). For planning and design studies, the displacement of water surface can be estimated by superposing the two components.

The tidal displacement at various locations along the coast can be estimated from harmonic constants. The displacement of water surface is largest when the cyclonic storm surge reaches the coast at the time of spring tide. The amplitude of spring tide is estimated by ($M_2 + S_2$) where M_2 and S_2 are amplitudes of predominantly semi-diurnal tidal constituents. The range of a tide is the difference between high water and low water levels during a tide while the mean tide level is the average of high water and low water level. The range of a tide is two times of its amplitude. The mean tide (h_0) level also varies along the coast (MCSP, 1993).

4.3 Determination of the Intrusion Distance

The movement of the storm surge over coastal land is a very complex process. The maximum travel distance of surge water over dry land depends on several factors such as height of storm surge at the sea coast, water velocity and wave velocity of the approaching surge wave, duration of storm, length of storm surge wave, tidal condition near the coast, rate of increase in water level near the coast, configuration of coast line with respect to surge direction, slope of the beach, slope of the dry land, reflection, refraction and breaking of the wave, bed material and land topography, resistance due to land use etc (MCSP, 1993).

Development of a mathematical model to simulate the movement of storm surge wave over dry land is an extremely difficult task. An approximate solution for the maximum travel distance of a long solitary wave over dry bed in a purely one dimensional flow domain is investigated here. It is assumed that the sea bed rises with gentle slope and the rise continues beyond the shore line (zero depth) with the same slope. A solitary long wave above the horizontal still water level approaches the straight line coast along a perpendicular direction. When the leading edge of the wave crosses the shore line, the process of movement of water line into the dry bed begins. Freeman and Le Mehaute (1964) showed that the shape of the leading edge of the wave over a dry land is in the form of a parabola (MCSP, 1993).

The storm surge intrusion distance was computed using equation developed by Freeman and Le Mehaute (1964) and used in the Multipurpose Cyclone Shelter Programme (1993).

$$x = \frac{4(4+1.5h)^2}{3(4+h)(S_b + f/8)} \tag{4.6}$$

Where, x is the maximum distance travelled by the leading edge from the shoreline, h = surge height, S_b = land slope and f = friction factor.

4.4 Delineation of the RZ and HRA

RZ is the zone from the coast line to inland limit upto which surge water can reach and within the RZ where there is a possibility of loss of lives due to appreciable inundation by surge water is termed as HRA.

The HRA extends from the coast line upto a limit where the depth of storm surge inundation may reach one meter. The one meter criterion has been selected based upon the experience of narrated by survivors during past storm surge inundations. It was reported that an adult could force his way through water as long as the depth of water remained below waist height. So a depth of one meter, which is near to the height of the waist of an average adult, has been selected as the criterion for delineation of HRA (MCSP, 1993).

The distances of the boundaries of the RZ and HRA from coastlines were estimated upon results given by the mathematical model of intrusion distance. Then the boundaries of RZ and HRA were drawn on Thana maps produced from satellite maps. This methodology does not account for the local variation due to rivers and khals, depression, high ground, roads, etc.

4.5 GIS Mapping

Mapping of the RZ and HRA are extremely difficult task. Gegraphic Information System (GIS) was used to delineate the boundary of the RZ and HRA; for mapping of unprotected population in the RZ and to represent the residual risk area in the coastal area of Bangladesh. To demarcate the boundaries of the RZ and HRA, the intrusion distance of the surge were necessary which were calculated from the mathematical model of intrusion distance. Intrusion distances vary for different coastal zones because surge height were different for three distinct coastal zones. Then lengths of the intrusion distance across Bangladesh coastal area were estimated from the SRTM (Digital Elevation Model) data over Bangladesh. After that, the boundaries of the RZ for different coastal zones were demarcated. Slight smoothing were made to adjoin two different coastal zones and also in areas where large river are present. The boundaries of the HRA were also demarcated in the same way. Thana maps were superimposed on the SRTM data to demarcate the boundary of the RZ and HRA on thana maps. Finally, the boundaries of RZ and HRA were drawn on Thana maps.

Mapping of the unprotected population in the coastal districts was done by putting the value of the unprotected population in the attribute table of the GIS software. Then the boundary of the RZ layer was superimposed on the unprotected population map. It displays unprotected population in the RZ within the study area. Residual risk map of the vulnerable thanas were produced in the same way.

4.6 Assessment of the Vulnerability

Unprotected population was taken as vulnerability factor to estimate the vulnerability due to storm surge flood in the coastal region of Bangladesh because human life is the main vulnerability factor in case of storm surge. Besides, the population indicates numbers of people in any area and it also gives some indication of socio-economic status. The lower the socio-economic status of people the more likely they are to fall victims to cyclones.

To assess the vulnerability due to storm surge in the coastal zone of Bangladesh at first population data were projected for the 19 coastal districts from the BBS census report 2001. Then number of cyclone shelters and its capacity for the coastal districts were collected from CDMP. Unprotected population vulnerable to storm surge was calculated by subtracting capacity of the cyclone shelters for a district from the total number of population of that district. In a particular district all the thanas are not vulnerable to storm surge hazard. Therefore, thana wise vulnerability of the population was calculated for the study area. Vulnerability map was produced by using GIS (Geographical information system) software.

4.7 Assessment of the Risk

Risk is a function of both hazard and vulnerability. In this study, probability of inundation is taken as a function of natural hazard and unprotected population is taken as a function of vulnerability. Study considers wind speed of 50 year return period as MCSP (1993). Therefore probability of inundation is $P = 0.02$. Risk has been calculated in terms of residual risk.

Residual risk can be defined as the remaining level of storm surge risk that a community is exposed to after cyclone management measures such as cyclone shelter to reduce risk have been implemented.

Cyclone shelters/safe haven has been constructed in the coastal area of Bangladesh primarily for providing safety to coastal population from the cyclonic storm surge. Hence, residual risk of a thana is the risk that is left over after cyclonic storm surge management option (cyclone shelter) have been implemented. So, residual risk of the land units (thanas) was calculated by multiplying unprotected population of land units with probability of inundation.

CHAPTER FIVE: RESULTS AND DISCUSSION

5.1 Surge Height at the Estuary Inlet

One necessary but not sufficient condition for tropical cyclone formation is that the sea surface should have a minimum temperature of about 26 to 27°C. This leads to the speculation that any rise in sea surface temperature (SST) due to climate change is likely to be accompanied by an increase in cyclone frequency. It is almost certain that an increase in SST due to climate change will be accompanied by a corresponding increase in cyclone intensity (wind speed). A 3-5% increase in wind-speed per degree Celsius increase of tropical sea surface temperatures (Dasgupta et al., 2010). A normally occurring cyclone may have a higher intensity as a result of warmer seas due to global warming. Any increase in SST is likely to cause greater convective instability, leading to an increase in the wind speed. The stress exerted by wind on water underneath is proportional to the square of the wind velocity. Thus an increase in SST due to climate change will lead to higher storm surges and consequently enlarge the risk area.

A number of studies investigated storm surges in the Bay of Bengal using numerical models (e.g. IWM, 2005; Madsen and Jakobsen, 2004; Flather, 1994; Dube et al., 1986; Murty et al., 1986; Das, 1972) and empirical models (e.g. Chowdhury, 1994; MCSP, 1993) as part of the adaptation to cyclonic surges in Bangladesh. However, the impacts of climate change and SLR were not considered in those studies. As predicted by Emanuel (2005), any increase in SST will cause intensification of tropical cyclones. This phenomenon should be included in any future prediction of cyclonic storm surges. Among the studies only Ali (1999), and Karim and Mimura (2008) predicted cyclone-induced surges at the coast by incorporating SST rise and SLR into the cyclone model.

The main input to the surge height equation developed by Tareque (1992) is the wind speed (V) which is a function of SST. The relationship of maximum wind speed with SST has been mentioned in Table 2.4. Climate scenarios for GTP, MDP and CCP due to climate change are given in Table 5.1. Here it is to mention that the projection was made for all three coastal zones based on the 1991 cyclone that made landfall on CCP. Thus, 0°C SST rise with a wind speed 225 km/h in CCP was taken as base condition. The increase of SST was considered 2 and 4°C in this study because of the IPCC (2007) standard of a lower bound of 2°C and an upper bound of 4°C rise in temperature by 2100.

In this study, average tidal ranges of 1.12, 1.78 and 1.73 m was considered for the GTP, MDP and CCP respectively based on the amplitude of M_2 and S_2 that was predicted for three distinct coastal regions of Bangladesh by MCSP (1993). SLR along the Bangladesh coast is another critical variable that may amplify the surge height. SLR along the coast of Bangladesh has been taken as 0.18 and 0.79 m based on IPCC (2007), which predicts SLR of between 0.18 and 0.79 meters in South Asia by the last decade of the 21st century.

Table 5.1: Storm surge heights under different SLR and SST rise conditions (based on the condition that corresponds to wind speed (225 km/h) as observed during the 1991 cyclone in the CCP)

Coastal Zone	SST rise (°C)	Wind Speed (km/h)	Surge height, h (m)		
			0 m SLR	0.18 m SLR	0.79 m SLR
GDP	0	225	5.8	6.0	6.6
	2	246	6.6	6.8	7.4
	4	274	7.8	7.9	8.6
MDP	0	225	9.1	9.3	9.9
	2	246	10.3	10.5	11.1
	4	274	12.1	12.3	12.9
CCP	0	225	7.7	7.9	8.5
	2	246	8.7	8.9	9.5
	4	274	10.1	10.3	10.9

Surge height considering SST increase (IPCC, 2007) for different coastal zones of Bangladesh shows that climate change has a significant effect on surge height. Surge height increased about 13 and 33% due to 2 and 4°C increase in SST, respectively for all three coastal zones of Bangladesh. Surge height is obviously greater for larger SLR. Among the coastal zones MDP has the highest storm surge height which is consistent with the equation given by Tareque (1992). The reason may be the length of the continental shelf which is greater for the MDP than CCP and GTP.

5.2 Intrusion Distance of the Surge

Once height of the storm surge is established then it can be used for the calculation of the intrusion distance. The intrusion distance (x) of the storm surge over land was estimated by the equation developed by Freeman and Le Mehaute (1964).

$$x = \frac{4(4+1.5h)^2 R}{3(4+h)(S_b + f/8)} \tag{5.1}$$

Where, h = surge height, S_b = land slope, f = friction factor and R = radius in km of the maximum wind speed. The values of R have been calculated from Table D3.8.2 of MCSP (1993) and are given in Table 5.2. It shows that the values of R are different for different cyclonic intensity or surge height condition.

Table 5.2: The value of R for different surge height

Coastal Zone	SST rise (°C)	0 m SLR		0.18 m SLR		0.79 m SLR	
		h (m)	R (km)	h (m)	R (km)	h (m)	R (km)
GDP	0	5.8	1.34	6.0	1.34	6.6	1.29
	2	6.6	1.29	6.8	1.28	7.4	1.27
	4	7.8	1.27	7.9	1.26	8.6	1.25
MDP	0	9.1	1.23	9.3	1.23	9.9	1.21
	2	10.3	1.22	10.5	1.20	11.1	1.19
	4	12.1	1.18	12.3	1.17	12.9	1.16
CCP	0	7.7	1.28	7.9	1.26	8.5	1.25
	2	8.7	1.25	8.9	1.25	9.5	1.23
	4	10.1	1.21	10.3	1.22	10.9	1.19

Table 5.3, 5.4 and 5.5 shows the intrusion distance of surge for 0, 0.18 and 0.79 m SLR, respectively. Intrusion distance is greater for increased SLR which is very much practical. The value of the bed slope (S_b) and friction factor (f) for all three coastal zones is taken from MCSP, (1993). The intrusion distance remains small at steep slope and it is not sensitive to resistance at steep slope. The slope of the coastal area along the Chittagong-Cox's Bazar coast is large compared to other coastal areas. Thus smaller intrusion distance is expected along the Chittagong-Cox's Bazar coast. In areas with small slope or in flat lands, the intrusion distance can be large.

Table 5.3: Predicted intrusion distance of the surge for 0 m SLR under different land slope (Sb) and friction factor (f)

Coastal Zone	SST rise (°C)	Surge height (m)	Land slope S_b	Intrusion distance, x (km)				
				f = 0.01	f = 0.02	f = 0.03	f = 0.05	f= 0.10
GDP	0	5.8	0	23.5	11.8	7.8	4.7	1.8
			0.0001	21.8	11.3	7.6	4.6	2.3
			0.001	13.1	8.4	6.2	4.1	2.2
			0.01	2.6	2.4	2.1	1.8	1.3
	2	6.6	0	25.1	12.6	8.4	5.0	1.9
			0.0001	23.2	12.1	8.2	4.9	2.5
			0.001	13.9	9.0	6.6	4.3	2.3
			0.01	2.8	2.5	2.3	1.9	1.4
	4	7.8	0	28.2	14.1	9.4	5.6	2.2
			0.0001	26.1	13.6	9.2	5.5	2.8
			0.001	15.7	10.1	7.4	4.9	2.6
			0.01	3.1	2.8	2.6	2.2	1.6
MDP	0	9.1	0	31.3	15.6	10.4	6.3	2.5
			0.0001	29.0	15.0	10.2	6.2	3.1
			0.001	17.4	11.2	8.2	5.4	2.9
			0.01	3.5	3.1	2.8	2.4	1.7
	2	10.3	0	34.6	17.3	11.5	6.9	2.8
			0.0001	32.0	16.6	11.2	6.8	3.4
			0.001	19.2	12.3	9.1	6.0	3.2
			0.01	3.8	3.5	3.1	2.7	1.9
	4	12.1	0	38.3	19.2	12.8	7.7	3.2
			0.0001	35.5	18.4	12.4	7.5	3.8
			0.001	21.3	13.7	10.1	6.6	3.5
			0.01	4.3	3.8	3.5	2.9	2.1
CCP	0	7.7	0	28.2	14.1	9.4	5.6	2.2
			0.0001	26.1	13.5	9.1	5.5	2.8
			0.001	15.6	10.1	7.4	4.9	2.6
			0.01	3.1	2.8	2.6	2.2	1.6
	2	8.7	0	30.5	15.2	10.2	6.1	2.4
			0.0001	28.2	14.7	9.9	6.0	3.0
			0.001	16.9	10.9	8.0	5.3	2.8
			0.01	3.4	3.0	2.8	2.3	1.7
	4	10.1	0	33.6	16.8	11.2	6.7	2.8
			0.0001	31.1	16.2	10.9	6.6	3.3
			0.001	18.7	12.0	8.8	5.8	3.1
			0.01	3.7	3.4	3.1	2.6	1.9

Table 5.4: Predicted intrusion distance of the surge for 0.18 m SLR under different land slope (Sb) and friction factor (f)

Coastal Zone	SST rise (°C)	Surge height (m)	Land slope S_b	Intrusion distance, x (km)				
				f = 0.01	f = 0.02	f = 0.03	f = 0.05	f= 0.10
GDP	0	6.0	0	24.1	12.0	8.0	4.8	1.8
			0.0001	22.3	11.6	7.8	4.7	2.4
			0.001	13.4	8.6	6.3	4.2	2.2
			0.01	2.7	2.4	2.2	1.9	1.3
	2	6.8	0	25.5	12.7	8.5	5.1	2.0
			0.0001	23.6	12.2	8.3	5.0	2.5
			0.001	14.1	9.1	6.7	4.4	2.4
			0.01	2.8	2.5	2.3	2.0	1.4
	4	7.9	0	28.5	14.3	9.5	5.7	2.3
			0.0001	26.4	13.7	9.3	5.6	2.8
			0.001	15.8	10.2	7.5	4.9	2.6
			0.01	3.2	2.9	2.6	2.2	1.6
MDP	0	9.3	0	31.8	15.9	10.6	6.4	2.6
			0.0001	29.4	15.3	10.3	6.3	3.2
			0.001	17.7	11.4	8.4	5.5	2.9
			0.01	3.5	3.2	2.9	2.4	1.8
	2	10.5	0	34.5	17.3	11.5	6.9	2.9
			0.0001	32.0	16.6	11.2	6.8	3.4
			0.001	19.2	12.3	9.1	5.9	3.2
			0.01	3.8	3.5	3.1	2.7	1.9
	4	12.3	0	38.5	19.2	12.8	7.7	3.3
			0.0001	35.6	18.5	12.5	7.6	3.8
			0.001	21.4	13.7	10.1	6.6	3.6
			0.01	4.3	3.8	3.5	3.0	2.1
CCP	0	7.9	0	28.3	14.1	9.4	5.7	2.2
			0.0001	26.2	13.6	9.2	5.6	2.8
			0.001	15.7	10.1	7.4	4.9	2.6
			0.01	3.1	2.8	2.6	2.2	1.6
	2	8.9	0	31.0	15.5	10.3	6.2	2.5
			0.0001	28.7	14.9	10.1	6.1	3.1
			0.001	17.2	11.1	8.2	5.3	2.9
			0.01	3.4	3.1	2.8	2.4	1.7
	4	10.3	0	34.5	17.3	11.5	6.9	2.8
			0.0001	32.0	16.6	11.2	6.8	3.4
			0.001	19.2	12.3	9.1	6.0	3.2
			0.01	3.8	3.5	3.1	2.7	1.9

Table 5.5: Predicted intrusion distance of the surge for 0.79 m SLR under different land slope (Sb) and friction factor (f)

Coastal Zone	SST rise (°C)	Surge height (m)	Land slope, S_b	Intrusion distance, x (km)				
				f = 0.01	f = 0.02	f = 0.03	f = 0.05	f= 0.10
GDP	0	6.6	0	25.1	12.5	8.4	5.0	1.9
			0.0001	23.2	12.0	8.1	4.9	2.5
			0.001	13.9	8.9	6.6	4.3	2.3
			0.01	2.8	2.5	2.3	1.9	1.4
	2	7.4	0	27.1	13.5	9.0	5.4	2.1
			0.0001	25.1	13.0	8.8	5.3	2.7
			0.001	15.1	9.7	7.1	4.7	2.5
			0.01	3.0	2.7	2.5	2.1	1.5
	4	8.6	0	30.1	15.0	10.0	6.0	2.4
			0.0001	27.9	14.5	9.8	5.9	3.0
			0.001	16.7	10.7	7.9	5.2	2.8
			0.01	3.3	3.0	2.7	2.3	1.7
MDP	0	9.9	0	33.0	16.5	11.0	6.6	2.7
			0.0001	30.6	15.9	10.7	6.5	3.3
			0.001	18.4	11.8	8.7	5.7	3.1
			0.01	3.7	3.3	3.0	2.5	1.8
	2	11.1	0	35.9	18.0	12.0	7.2	3.0
			0.0001	33.3	17.3	11.7	7.1	3.6
			0.001	20.0	12.8	9.5	6.2	3.3
			0.01	4.0	3.6	3.3	2.8	2.0
	4	12.9	0	39.8	19.9	13.3	8.0	3.4
			0.0001	36.9	19.2	12.9	7.8	4.0
			0.001	22.1	14.2	10.5	6.9	3.7
			0.01	4.4	4.0	3.6	3.1	2.2
CCP	0	8.5	0	29.8	14.9	9.9	6.0	2.4
			0.0001	27.6	14.3	9.7	5.9	3.0
			0.001	16.6	10.7	7.9	5.1	2.8
			0.01	3.3	3.0	2.7	2.3	1.7
	2	9.5	0	32.3	16.1	10.8	6.5	2.6
			0.0001	29.9	15.5	10.5	6.4	3.2
			0.001	17.9	11.5	8.5	5.6	3.0
			0.01	3.6	3.2	2.9	2.5	1.8
	4	10.9	0	35.6	17.7	11.8	7.1	3.0
			0.0001	32.7	17.0	11.5	6.9	3.5
			0.001	19.6	12.6	9.3	6.1	3.3
			0.01	3.9	3.5	3.2	2.7	2.0

All the three tables show that the intrusion distance is sensitive to resistance in areas with small slope. Thus the flooding area can be reduced in flat areas by creating obstruction such as afforestation.

Table 5.3, 5.4 and 5.5 shows the intrusion distance of the storm surge under different land slope and friction factor. However, for the demarcation of the RZ and HRA it is necessary to identify specific value of land slope and friction factor for the three distinct coastal zones. The land slope for both GTP and MDP were taken as 0 while it was taken as 0.001 for the CCP because the slope of the coastal area along the CCP is large compared to other coastal areas. Friction factor were taken to 0.01 for both GTP and MDP and 0.03 for CCP. Friction factor for GTP should have been greater because of the presence of the Sundarban but there are several river mouths in the western part of the country which may over-reach the effect of surface resistance. Besides, this calculation is consistent with the delineation of the RZ and HRA by MCSP (1993).

5.2.1 Sensitivity analysis of the storm surge intrusion distance

Intrusion distance, x of the storm surge is sensitive to surface resistance. The intrusion distance is sensitive to resistance when land slope is small. The source of resistance (friction) to flooding of coastal land by cyclonic storm surge can be divided into three major categories. They are:

- Skin roughness due to the distribution of bed material size;
- From roughness due to undulations and irregularities in the land surface;
- Obstruction due to presence of weed, crops, bushes, hedges, trees, houses, foot paths and roads, embankments etc. The height, distribution and density of obstruction considerably affect the overall resistance.

Table 5.6 and Figure 5.1, 5.2 and 5.3 shows the changes in the predicted intrusion distance due to variation in the friction factor, f from 0.01 to 0.1 and land slope (S_b) for GTP, MDP and CCP respectively for 2°C increase in SST. It shows that intrusion distance is very much sensitive to friction factor

Table 5.6: Changes of the intrusion distance for different friction factor, f

f	**Intrusion distance, x (km)**		
	GTP	**MDP**	**CCP**
0.01	27.1	35.9	17.9
0.02	13.5	18	11.5
0.03	9	12	8.5
0.05	5.4	7.2	5.6
0.1	2.1	3	3

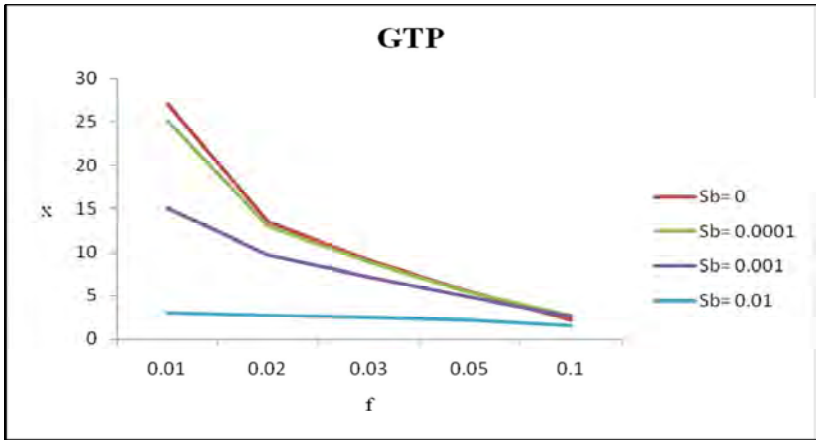


Figure 5.1: Relationship of friction factor (f), bed slope (S_b) and intrusion distance (x) in the GTP

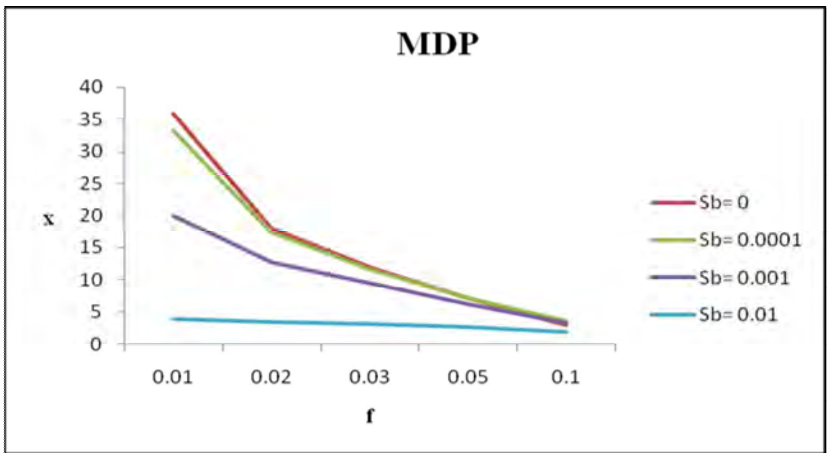


Figure 5.2: Relationship of friction factor (f), bed slope (S_b) and intrusion distance (x) in the MDP

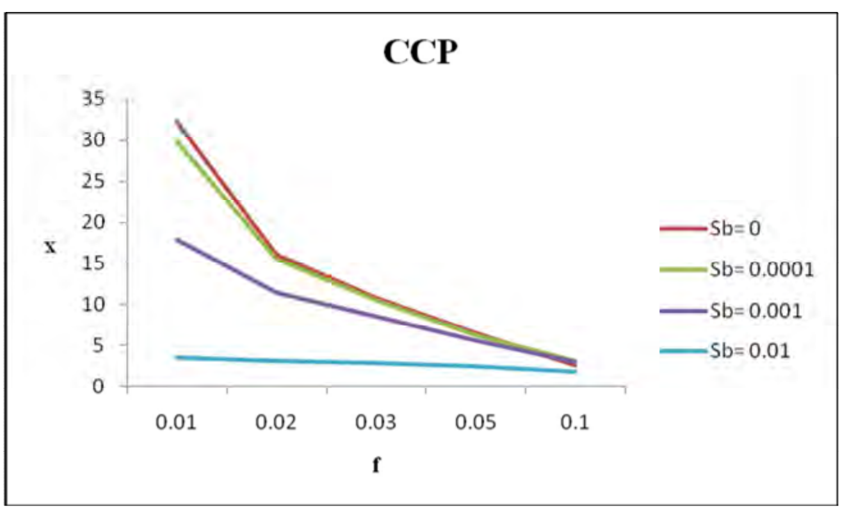


Figure 5.3: Relationship of friction factor (f), bed slope (S_b) and intrusion distance (x) in the CCP

5.2.2 Readjustment of the friction factor (f)

From the study it shows that the intrusion distance of the surge will not reach to a known union “Gabura” at Shyamnagor thana in Satkhira district, where surge water actually reached during the cyclone “Aila” and also some other places where surge water reached during 1991 cyclone. So, to justify the intrusion distance a calibration was made to adjust friction factor, f. The adjusted intrusion distance of the surge is given in Figure 5.2 for the GTP, MDP and CCP, respectively.

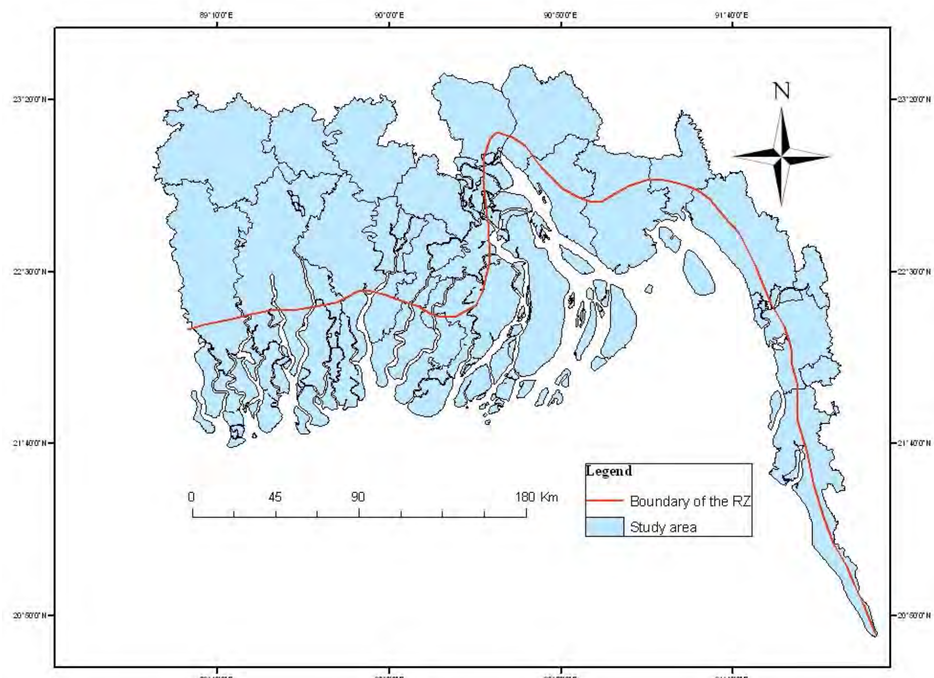


Figure 5.4: Adjusted intrusion distance of the surge

From the study it shows that the intrusion distance will be approximately 55, 50 and 9.5 km for GTP, MDP and CCP, respectively for 2°C increase in SST. Thus the adjusted friction factors (f) are 0.005, 0.008 and 0.02 for GTP, MDP and CCP, respectively. Now validating these factors with 1991 cyclone that made landfall in CCP, we get a surge height of 6.5 m. Here, it is worth mentioning that the surge height of the 1991 cyclone was 6.0-7.5 m (MCSP, 1993).

5.3 Demarcation of the RZ and HRA

The main criterion in the delineation of risk zone has been the possible extent of the inland intrusion of cyclonic storm surge. The intrusion distances of the storm surge over land for coastal regions of Bangladesh are given in Table 5.7. The intrusion distance is large at the MDP because surge height is greater in this coastal region. Inland intrusion of surge at the CCP is small due to larger bed slope and friction factor.

Table 5.7: Intrusion distance of the storm surge for specific land slope and friction factor for the three coastal regions

Coastal zones	SST rise (°C)	Surge height (m)	Land slope (S_b)	Friction factor (f)	Intrusion distance, x (km)
0 m SLR					
GDP	0	5.8	0	0.01	23.5
	2	6.6	0	0.01	25.1
	4	7.8	0	0.01	28.2
MDP	0	9.1	0	0.01	31.3
	2	10.3	0	0.01	34.6
	4	12.1	0	0.01	38.3
CCP	0	7.7	0.001	0.03	7.4
	2	8.7	0.001	0.03	8.0
	4	10.1	0.001	0.03	8.8
0.18 m SLR					
GDP	0	6.0	0	0.01	24.1
	2	6.8	0	0.01	25.5
	4	7.9	0	0.01	28.5
MDP	0	9.3	0	0.01	31.8
	2	10.5	0	0.01	34.5
	4	12.3	0	0.01	38.5
CCP	0	7.9	0.001	0.03	7.4
	2	8.9	0.001	0.03	8.2
	4	10.3	0.001	0.03	9.1
0.79 m SLR					
GDP	0	6.6	0	0.01	25.1
	2	7.4	0	0.01	27.1
	4	8.6	0	0.01	30.1
MDP	0	9.9	0	0.01	33.0
	2	11.1	0	0.01	35.9
	4	12.9	0	0.01	39.8
CCP	0	8.5	0.001	0.03	7.9
	2	9.5	0.001	0.03	8.5
	4	10.9	0.001	0.03	9.3

From the results it shows that intrusion distance increased by 6-10 and 18-23% for 2 and 4°C increases in SST for the coast. Boundary of the RZ for 0.79 m SLR and 0, 2 and 4° C SST increase are given in Figure 5.3, 5.4 and 5.5. Figure 5.6 shows the RZ for all three 0, 2, 4° C increase of SST.

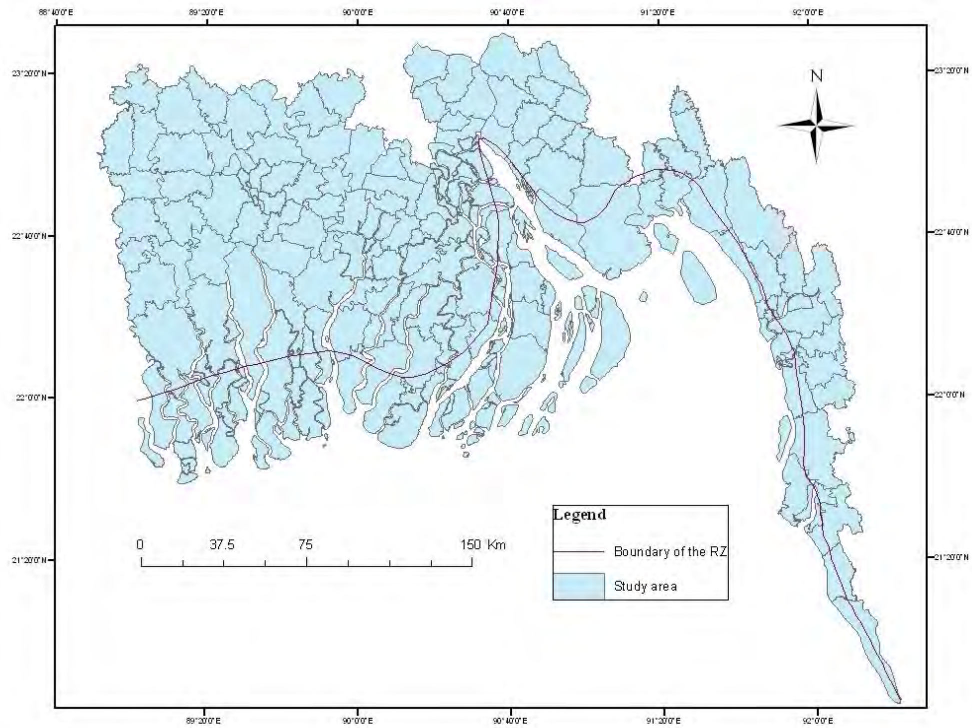


Figure 5.5: Boundary of the RZ for 0° C SST increase and 0.79 m SLR

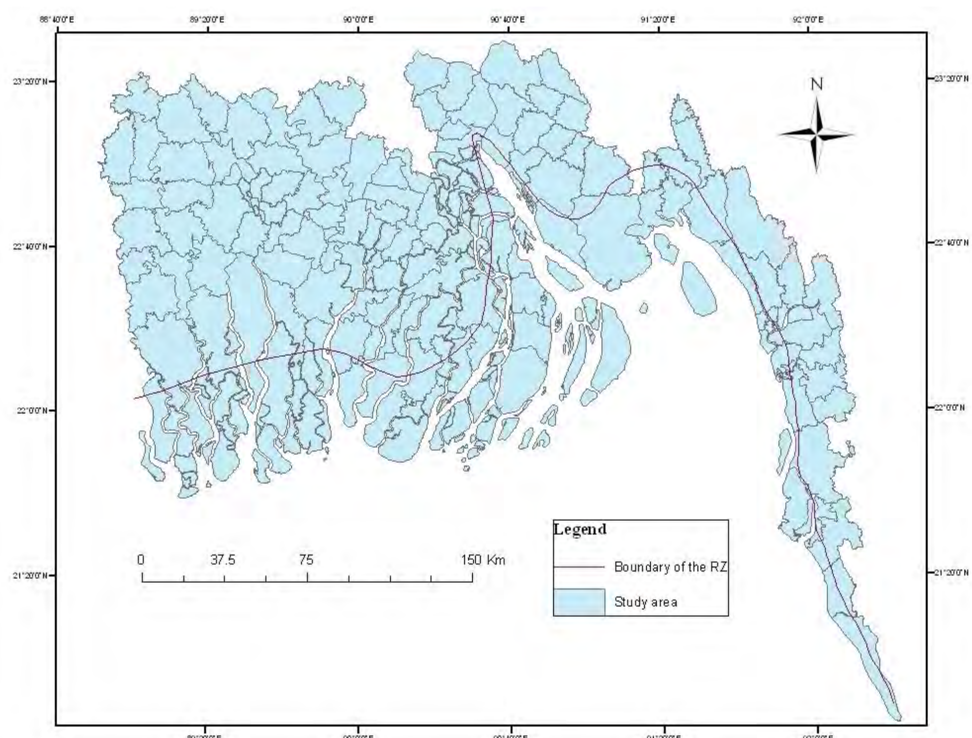


Figure 5.6: Boundary of the RZ for 2° C SST increase and 0.79 m SLR

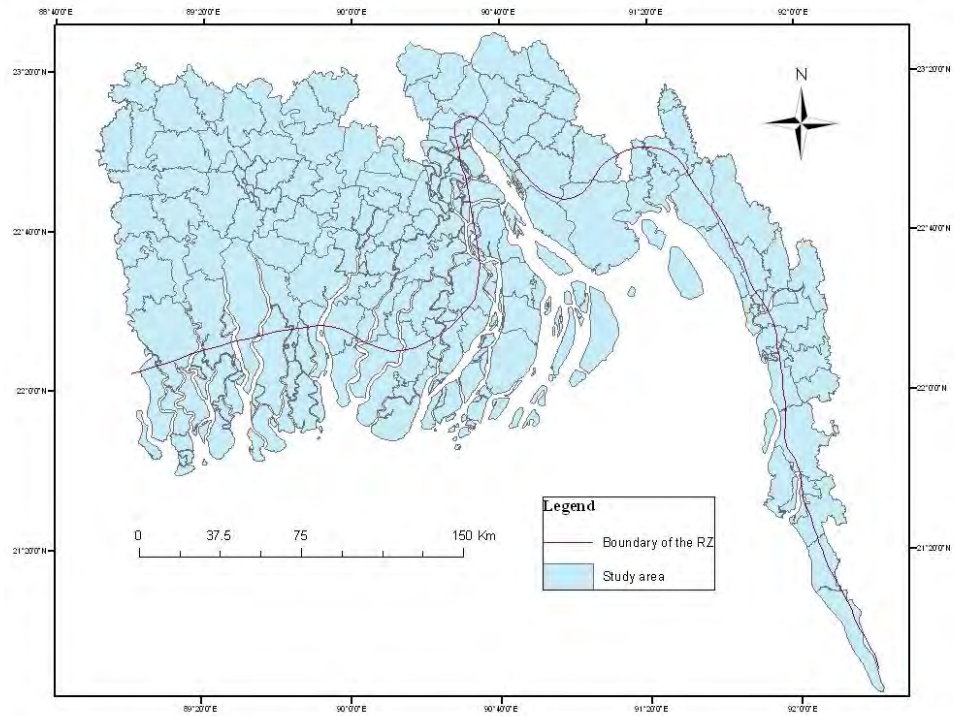


Figure 5.7: Boundary of the RZ for 4° C SST increase and 0.79 m SLR

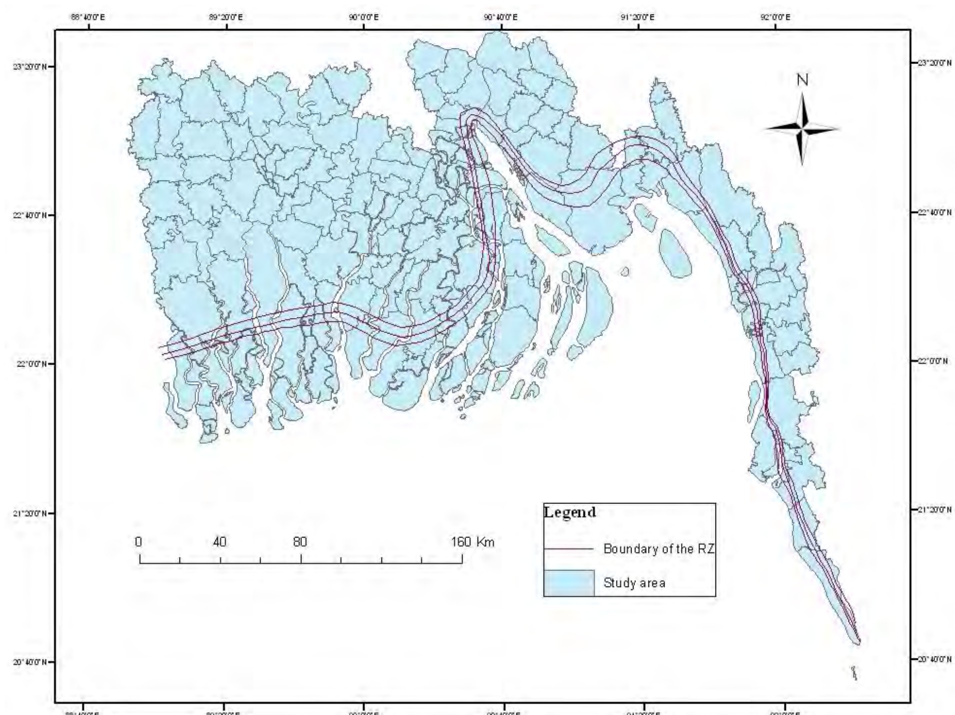


Figure 5.8: Boundary of the RZ for all O, 2 and 4° C SST increase and 0.79 m SLR

The demarcation of the boundary line is a highly difficult task because there are numerous river in the coastal zone of Bangladesh for which the intrusion distance may vary from the predicted intrusion distance. The propagation of surge wave thorough these rivers are hard to predict. However, the boundary of the RZ should increase in areas where such rivers are present.

Figure 5.6 shows that boundary of the RZ do not vary that much for 0, 2 and 4°C SST increase. This is due to the fact that surge height may increase significantly for 2 and 4°C SST increase but after putting the value of friction factor (f) and bed slope (S_b) in the equation of intrusion distance, it does not show huge change in intrusion distance.

It is found that the total area of the RZ will increase considerably for 2 and 4°C increase in SST. Area of the RZ are found approximately 10,489, 12,439 and 13,768 km^2 for 0, 2 and 4°C increase in SST, respectively. It indicates RZ will increase by approximately 16% for 2°C increase in SST and approximately 29% increase in RZ as a result of 4°C increase in SST.

After delineating the RZ it is necessary to delineate the HRA which is a strip of land within the RZ where the depth of storm surge inundation may reach one meter. From the study it is found that the HRA are approximately 8,925, 10,749 and 11,946 km^2 for 0, 2 and 4°C increase in SST, respectively. It shows that the HRA will be increased by approximately 20 and 34% for 2 and 4°C increase in SST, respectively (Table 5.8). Figure 5.7 shows the boundary of the RZ and HRA for 2°C increase in SST and 0.79 m SLR.

Table 5.8: Percent increase of RZ and HRA for 2 and 4°C increase in SST

Temperature rise (°C)	Area (km^2)		% increase	
	RZ	HRA	RZ	HRA
T (0°C)	10,689	8,925		
T (+2°C)	12,439	10,749	16	20
T (+4°C)	13,768	11,946	29	34

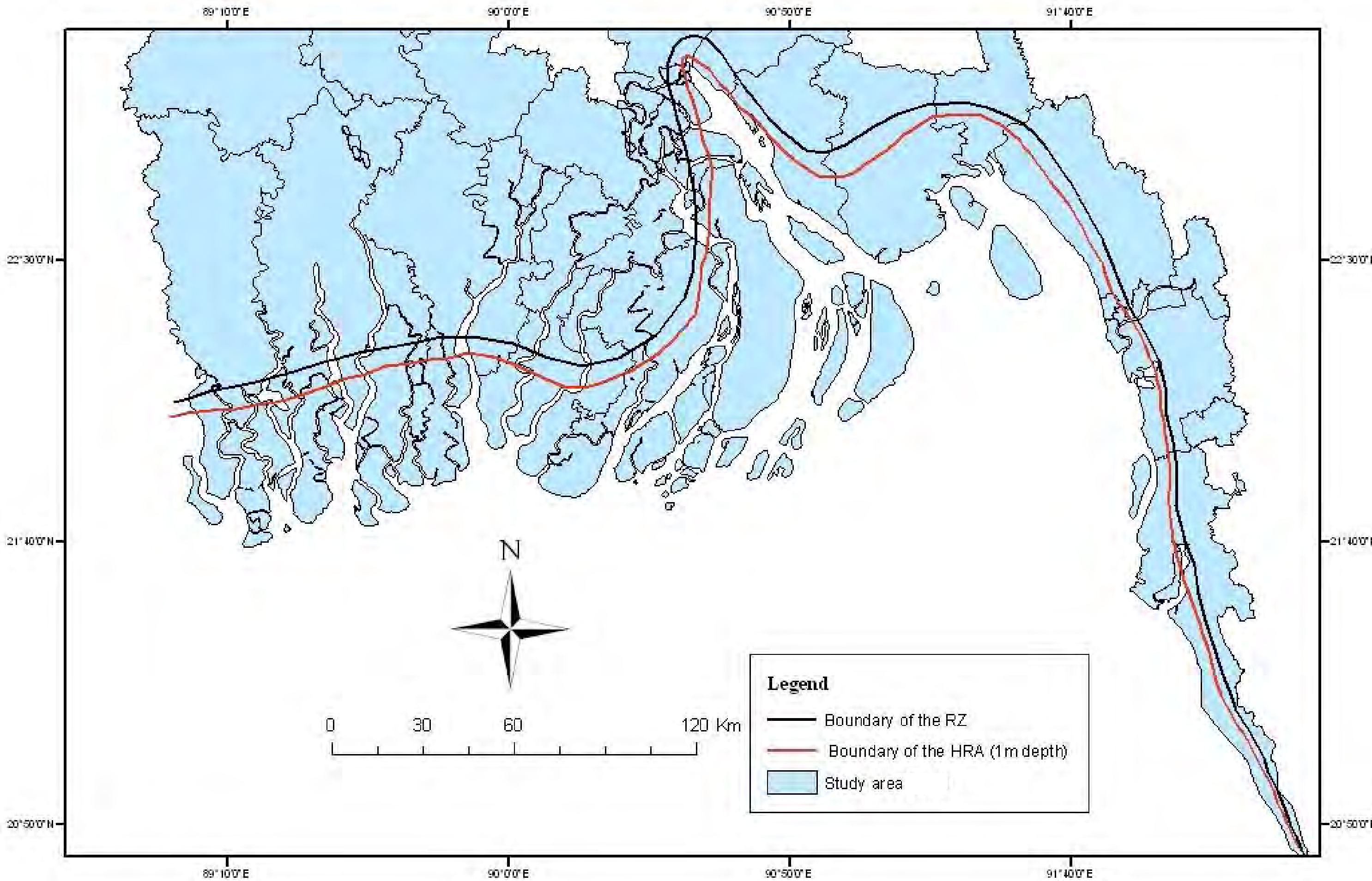


Figure 5.9: Boundary of the RZ and HRA for 2°C increase in SST

5.4 Estimation of the Vulnerable Population

Number of population that is unprotected in a coastal district is considered as vulnerable population. For vulnerability assessment population data for the coastal districts were collected from the BBS census report 2001 and were projected for 2010 and 2050 (Table 5.10).

Cyclone shelter/ safe haven provide refuge to the population likely to be affected by the storm surge. Numbers of protected population were obtained from the capacity of cyclone shelters in different coastal districts. In three administrative districts in the coastal area namely Gopalgong, Jessore and Narail there are no cyclone shelter. Information regarding cyclone shelter was collected from CDMP. Cyclone shelter information is given in Table 5.9 and vulnerable population at present (2010) and will be at 2050 for the study area is given in Table 5.10.

Table 5.9: Number of cyclone shelters and design capacity of the shelters in the study area

Districts	Population (2001)	Total Upazila	District Total	Total Usable Shelter	Total Not Usable Shelter	Pending for Maintenance	Design Capacity (No of People)	Floor Space (ft^2)
Bagerhat	1,549,031	8	163	150	12	1	96,850	340,385
Khulna	2,378,971	6	125	120	4	1	78,327	266,436
Satkhira	1,864,704	6	81	81	0	0	53,620	192,390
Barguna	848,554	5	216	196	10	10	139,270	420,176
Barisal	2,355,967	9	52	50	0	2	31,850	140,944
Bhola	1,703,117	7	677	608	65	4	346,691	1,114,984
Jhalokati	694,231	4	17	14	3	0	7,100	34,060
Patuakhali	1,460,781	7	340	262	72	6	222,860	676,613
Pirojpur	1,111,068	6	70	68	1	1	36,790	129,356
Shariatpur	1,082,300	4	38	38	0	0	24,500	84,730
Chandpur	2,271,229	6	80	77	1	2	43,112	153,284
Feni	1,240,384	4	76	61	13	2	42,390	147,597
Lakshmipur	1,489,901	4	242	230	11	1	120,016	456,342
Noakhali	2,577,244	3	300	259	34	7	161,883	494,780
Chittagong	6,612,140	22	679	638	30	11	542,933	1,324,080
Cox's Bazar	1,773,709	7	621	597	11	13	439,646	1,259,889
Summary Total	**31,013,331**	**108**	**3,777**	**3,449**	**267**	**61**	**2,387,838**	**7,236,046**
Total Surveyed Shelter		**3,932**	**Total Missing Shelter**		**88**	**Total Under Constructed Shelter**		**67**

Soruce: CDMP, 2010

Table 5.10: Vulnerable (%) populations in the study area at present (2010) and will be at 2050.

Districts	Population 2010	Population 2050	Design Capacity (No of People) of the shelters	Vulnerable population (2010)	Vulnerable population (2050)	% vulnerable (2010)	% vulnerable (2050)
Bagerhat	1785331	2190874	96850	1688481	2094024	95	96
Khulna	2741876	3364700	78327	2663549	3286373	97	98
Satkhira	2149159	2637346	53,620	2095539	2583726	98	98
Barguna	977998	1200153	139270	838728	1087730	86	91
Barisal	2715363	3332164	31850	2683513	3300314	99	99
Bhola	1962922	2408805	346691	1616231	2276287	82	86
Jhalokati	800134	981886	7100	793034	974786	99	99
Patuakhali	1683619	2066057	222860	1460759	1960032	87	95
Pirojpur	1280558	1571440	36790	1243768	1534650	97	98
Shariatpur	1247402	1530752	24500	1222902	1506252	98	98
Chandpur	2617698	3212315	43112	2574586	3169203	98	99
Feni	1429601	1754338	42390	1387211	1724040	97	98
Lakshmipur	1717181	2107243	120016	1597165	2011455	93	95
Noakhali	2970395	3645128	161883	2808512	3557956	95	98
Chittagong	7620802	9351887	542933	7077869	9026648	93	97
Cox's Bazar	2044283	2508647	439646	1604637	2270558	78	91
Gopalgong	1343032	2190874	0	1343032	2190874	100	100
Jessore	2848582	3364700	0	2848582	3364700	100	100
Narail	804993	2637346	0	804993	2637346	100	100

Table 5.9 shows that there are 3,777 cyclone shelters present in the coastal area of Bangladesh. Among the cyclone shelters 3,449 are usable, not usable shelters are 267 and 61 shelters are pending for maintenance. Table 5.10 shows that the design capacities (no of people) of the cyclone shelters vary from 1-22% of the population of the coastal districts. Therefore almost 78-100% of the populations of the coastal districts are still vulnerable to storm surge risk. From the cyclone shelters there are 267 not usable shelters and that number will be increased for SLR as well as storm surge for 2°C increase in SST. A rough study shows that from the 3449 cyclone shelters, there will be 1471 ineffective cyclone shelters (Table 5.11) in the vulnerable thanas for 2°C increase in SST and 0.79 m SLR. Thus, vulnerability of the population to cyclonic storm surge risk will be increased for 2050 and addition cyclone shelters will be needed. Figure 5.8 and 5.9 shows unprotected population in the coastal zone of Bangladesh at present (2010) and will be at 2050 considering ineffective cyclone shelters.

Table 5.11: Number of cyclone shelters that will be ineffective for 2°C increase in SST

Thana	**Number of ineffective cyclone shelter**
Amtali	26
Patharghata	10
Barguna sadar	4
Kalapara	85
Galachipa	70
Dashmina	8
Bauphal	7
Bhola Sadar	27
Burhanuddin	18
Char Fashion	146
Daulatkhan	62
Lalmohon	75
Monpura	36
Tazumuddin	53
Mehendigong	8
Roypur	5
Lakshmipur	12
Ramgati	32
Noakhali Sadar	43
Hatiya	68
Companigong	26
Sonagazi	23
Mirsarai	15
Sandwip	93
Sitakundu	31
Pahartali	4
Anawara	58
Banshkhali	62
Chittagong port	7
Patiya	2
Chakaria	57
Cox's Bazar Sadar	25
Kutubdia	87
Maheskhali	71
Ramu	22
Teknaf	13
Ukhia	15
Total	**1417**

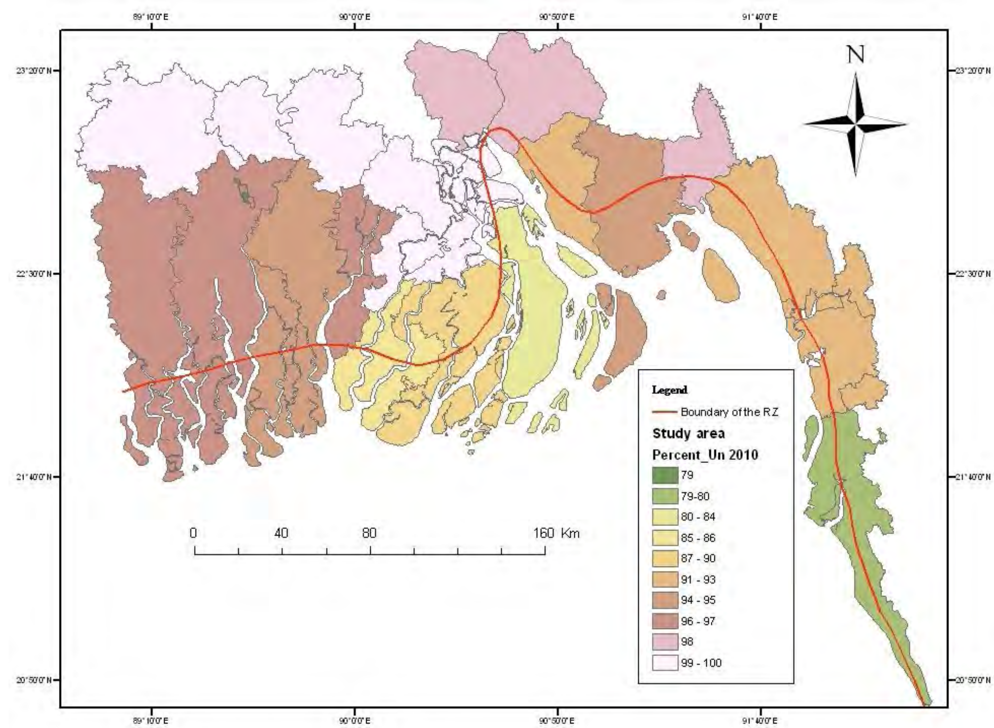


Figure 5.10: Map shows unprotected population in the study area at present (2010)

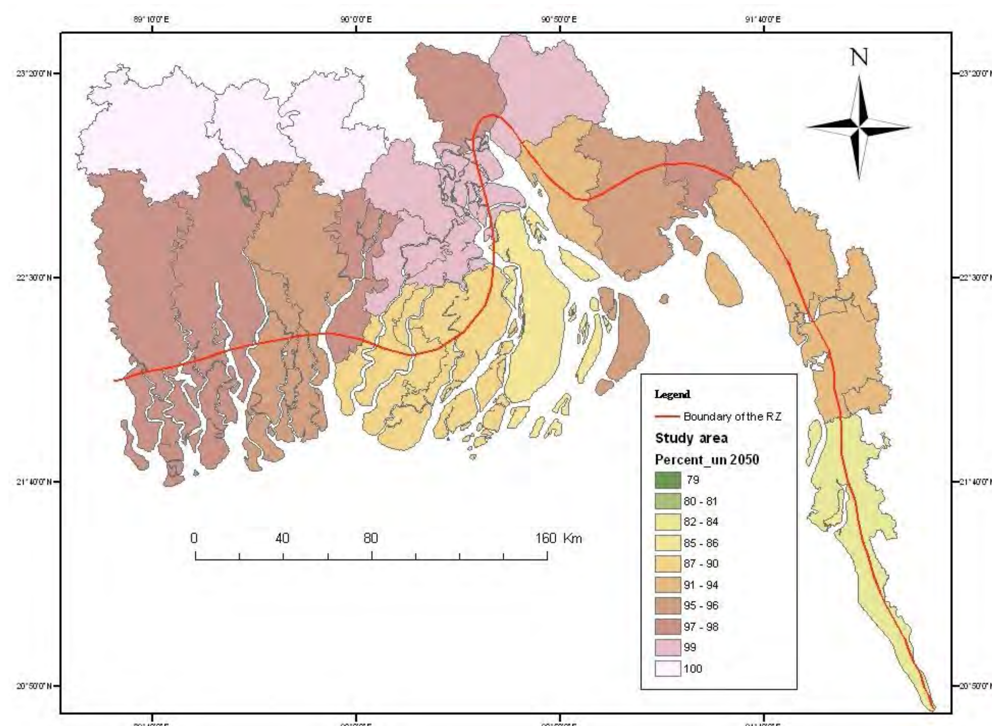


Figure 5.11: Map shows unprotected population in the study area for 2050

5.5 Calculation of Residual Risk

The coastal zone of Bangladesh comprises 19 administrative districts from which 12 districts are mainly vulnerable to cyclonic storm surge risk. Surge water will not reach in four administrative districts (Gopalgong, Jessore, Narail and Jhalokati) for either 2 or 4°C increase in SST. Three districts namely Satkhira, Khulna and Bagerhat in which surge water will reach but were excluded from the storm surge risk as those have very low risk because of very low population density (presence of Sundarban). Among the 12 most vulnerable administrative districts, there are 95 thanas from which 41 thanas are vulnerable to storm surge risk. Therefore, residual risk was calculated for only 41 thanas which is given in Table 5.12. The residual risk map for 2010 and 2050 are given in figure 5.10 and 5.11.

The residual risk was calculated on the basis of flood hazard and the population vulnerability. The flood hazard is considered as a function of probability of inundation and population vulnerability is taken as a function of unprotected population of the thana units.

Table 5.12: Residual risk of the Thanas for 2010 and 2050

Serial No	Thana	Unprotected population (2010)	Residual risk, population (2010)	Unprotected Population (2050)	Residual risk, population (2050)	% increase from 2010
1	Mathbaria	287537	5751	356530	7131	24
2	Patharghata	153611	3072	201842	4037	31
3	Barguna sadar	247810	4956	312623	6252	26
4	Amtali	256852	5137	324858	6866	34
5	Kala para	152904	3058	205809	5320	74
6	Galachipa	305759	6115	390906	8766	43
7	Dashmina	104811	2096	135451	2829	35
8	Bauphal	336730	6735	416569	8396	25
9	Burhanuddin	245453	4909	309369	6358	30
10	Tazumuddin	101333	2027	132799	3262	61
11	Lalmohon	241283	4826	313685	7014	45
12	Char Fashion	395485	7910	503766	11521	46
13	Daulatkhan	160942	3219	206301	4784	49
14	Manpura	46231	925	63851	1630	76
15	Bhola sadar	425503	8510	532343	10957	29
16	Mehendigonjg	342294	6846	421978	8537	25
17	Hizla	197529	3951	243216	4864	23
18	Gosairhat	137552	2751	170019	3400	24
19	Haimchar	134803	2696	167557	3351	24
20	Roypur	259723	5194	321762	6485	25
21	Lakshmipur	634752	12695	785362	15803	24
22	Ramgati	382306	7646	485288	10045	31
23	Noakhali sadar	820056	16401	1020787	20847	27
24	Hatiya	316100	6322	405422	8897	41
25	Companiganj	226262	4525	282458	5924	31

26	Sonagaji	242722	4854	304306	6328	30
27	Mirsharai	348732	6975	445325	9159	31
28	Sandwip	210655	4213	287304	7000	66
29	Sitakundu	325053	6501	412804	8708	34
30	Pahartali	141554	2831	174866	3502	24
31	Chittagong port	240382	4808	296303	6028	25
32	Patiya	369950	7399	454735	9139	24
33	Anwara	197092	3942	256922	6150	56
34	Banshkhali	301647	6033	404096	9309	54
35	Chakaria	451553	9031	583342	12519	39
36	Kutubdia	33938	679	62009	2596	283
37	Maheskhali	240593	4812	307758	6873	43
38	Cox's Bazar	337867	6757	428994	8976	33
39	Ramu	188672	3773	241735	5139	36
40	Ukhia	152173	3043	192802	4127	36
41	Teknaf	199841	3997	252361	5241	31

Table 5.12 shows that Noakhali Sadar, Lakshmipur and Chakaria thana have higher residual risk for both 2010. Bhola Sadar, Char Fashion, Ramgati Patiya Mirsharai, Cox's Bazar Sadar, Sitakundu, Banshkhali, Galachipa, Bauphal, Mehendigonj, Hatiya, Mathbaria, Amtali, and Roypur thana have moderate residual risk and other thanas have relatively low residual risk. More thanas will be added to higher and moderate residual risk area for 2050 (Table 5.13).

Table 5.13: Relative residual risk of the thanas for 2010 and 2050

	2010		**2050**	
Rank	**Residual risk, population**	**Thanas**	**Residual Risk, population**	**Thanas**
High	>9000	Noakhali Sadar, Lakshmipur and Chakaria	>9000	Noakhali Sadar, Lakshmipur Chakaria, Bhola Sadar , Char Fashion, Ramgati, Patiya and Mirsharai
Moderate	5000-9000	Bhola Sadar, Char Fashion, Ramgati, Patiya, Mirsharai, Cox's Bazar Sadar, Sitakundu, Banshkhali, Galachipa, Bauphal, Mehendigonj, Hatiya, Mathbaria, Amtali, and Roypur	5000-9000	Cox's Bazar Sadar, Sitakundu, Banshkhali, Galachipa, Bauphal, Mehendigonj, Hatiya, Mathbaria, Barguna Sadar, Amtali, Burhanuddin, Lalmohon, Roypur, Companiganj, Sonagaji, Sandwip, Chittagong port, Anwara, Maheskhali Teknaf and Ramu
Low	<5000	Haimchar, Barguna sadar, Kala para, Dashmina, Burhanuddin, Tazumuddin, Lalmohon, Daulatkhan, Manpura, Hizla, Gosairhat, Patharghata, Teknaf, Sonagaji, Sandwip, Pahartali, Chittagong port, Anwara, Kutubdia, Maheskhali, Ramu, Ukhia and Companiganj	<5000	Patharghata Tazumuddin, Ukhia, Kala para, Dashmina, Daulatkhan, Manpura, Hizla, Gosairhat, Haimchar, Pahartali, and Ukhia

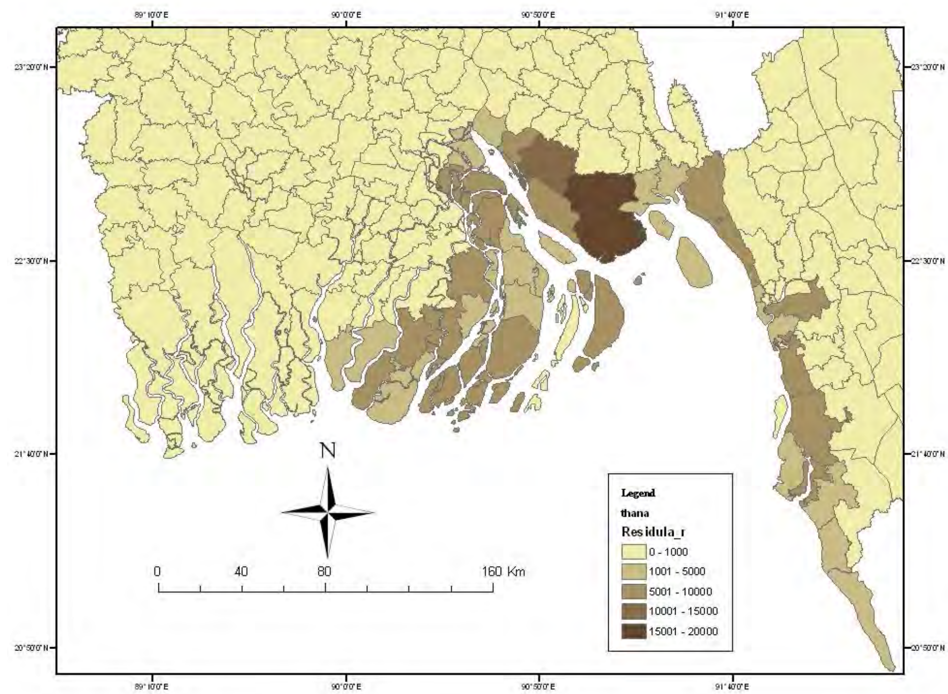


Figure 5.12: Map shows residual risk of the coastal area in 2010

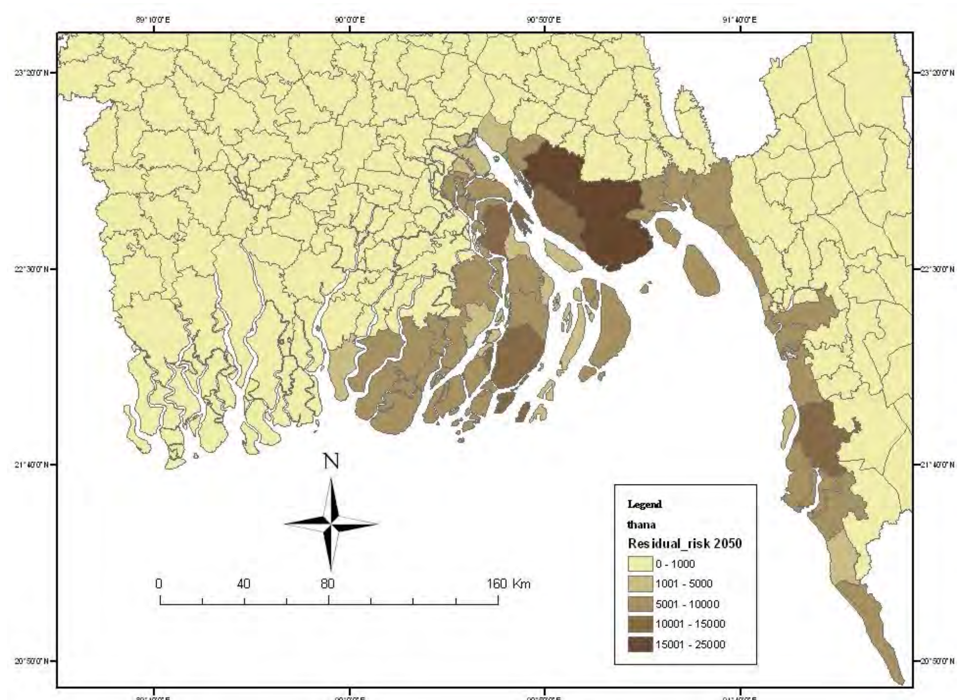


Figure 5.13: Map shows residual risk of the coastal area for 2050

CHAPTER SIX: CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Storm surge RZ and HRA in the coastal area of Bangladesh has been demarcated on the basis of climate change mainly due to increase of SST and SLR. An increase in SST will increase cyclone intensity and consequently enlarge risk zone in the coastal area of Bangladesh and SLR also has considerable effect. The presence of cyclone shelter (though its capacity is only about 6% of the total population of the coastal area) in the coastal zone of Bangladesh reduce the vulnerability of cyclonic storm surge to some extent. Thus the residual risk of the storm surge has been analyzed in this study.

Increase in SST as a result of climate change will lead to elevated storm surge and accordingly widens the storm surge RZ. Study reveals that surge height will be increased by about 13 and 33% for 2 and 4°C increase of SST, respectively for the entire coastal zone of Bangladesh.

Demarcation of the RZ depends on the possible extent of the inland intrusion distance of the cyclonic storm surge. Higher surge height brings about larger intrusion distance and a possibility of larger area to be affected by the storm surge. The study indicates intrusion distance will be increased by 6-10 and 18-23% for 2 and 4°C increase in SST, respectively in the coastal area of Bangladesh. From the study it is also found that RZ will be increased by approximately 16 and 29% for 2 and 4°C increase in SST, respectively and 0.79 m SLR. Study reveals that the HRA will be increased by approximately 20 and 34% for 2 and 4°C increase in SST, respectively. This will make the coastal area even more vulnerable to climate change.

Cyclone shelter/safe haven provide safety to the coastal population from the adverse impact of storm surge. From the study it is also found that at present, about 75-100% of the populations in the coastal area of Bangladesh are still vulnerable to storm surge risk due to lack of access to the cyclone shelter. Hence, this population will be even more vulnerable to cyclonic storm surges as a result of climate change. Residual risk map of the study area shows Noakhali Sadar, Lakshmipur, Chakaria, Bhola Sadar, Char Fashion Ramgati, Patiya and Mirsharai thana will be highly susceptible to storm surge risk for the 2°C increase of SST. Moderately vulnerable thanas are Cox's Bazar Sadar, Sitakundu, Banshkhali, Galachipa, Bauphal, Mehendigonj, Hatiya, Mathbaria, Barguna Sadar, Amtali, Burhanuddin, Lalmohon, Roypur, Companiganj, Sonagaji, Sandwip, Chittagong port, Anwara, Maheskhali Teknaf and Ramu. Hence, the populations of those thanas will be extremely vulnerable to cyclones/storm surges as a result of climate change.

6.2 Recommendations

- Coastal areas of Bangladesh are especially vulnerable to tropical cyclones and associated storm surges. With the changing climate the population of the coastal area is likely to be more vulnerable by the impact of cyclonic storm surge. So, particular emphasize should be given for the coastal population to adapt with the cataclysmic effect of the storm surge.

- Only 6% of the populations in the coastal area of Bangladesh are provided with cyclone shelter. Thus, additional shelters will be needed to accommodate people in the vulnerable HRA as well newly identified HRA to cope with the adverse impact of climate change.

- Residual risk of the districts show that Noakhali, Lakshmipur, Cox's Bazar, Patuakhali and Bhola are the most vulnerable districts in case of storm surge for climate change. Thus, during decision making for intervention priority should be given to these districts to protect the population from storm surge.

- Study shows that surge water will not reach to a known union "Gabura" at Shyamnagor thana in Satkhira district, where it actually did reach during "Aila" and also some other thanas where surge water reached during previous cyclones. Therefore, further research could be done to readjust the friction factor (f) and bed slope (S_b) for which surge water may reach some identified locations.

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