INTEGRATED APPROACH TO CYCLONE WIND ANALYSIS AND DISASTER PLANNING FOR THE BANGLADESH COAST

by

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CONTENTS

ABSTRACT

Tropical cyclones present the most serious natural hazard in the coastal areas of Bangladesh. In the past century, two of the deadliest tropical cyclones in modern history hit the coast of Bangladesh and each caused more death counts than the total number of casualties from all of the past U.S. hurricanes. Being a developing country, government and a majority of people in Bangladesh cannot afford to prepare for natural hazards and there is lack of research and mitigation measures to reduce the impact of damage from tropical cyclones. The purpose of this study is to understand the characteristics of landfalling tropical cyclones in Bangladesh and the associated risk and vulnerability in the coastal areas, which can help taking proper mitigation measures and would contribute towards effective disaster planning.

Wind and storm surge are crucial factors in the determination of how much damage occurs in the coastal areas in association with any tropical cyclone. It is also important to delineate the regions based on cyclone risk and vulnerability for planning considerations.

In this dissertation, the wind and storm surge from the tropical cyclones along the coast of Bangladesh are analyzed using the Monte Carlo simulations and cyclone risk and vulnerable regions of the coastal areas are identified. A reliable and comprehensive climatological database for the landfalling tropical cyclones, first of its kind for Bangladesh has been developed in this purpose for a 127-year period (1877-2003).

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CHAPTER I

INTRODUCTION

1.1 General statement of the problem

People have been trying to understand natural hazards for a long time. Throughout the human history, the advancement of man has been challenged by the destruction of cyclones, earthquakes, tornadoes, tsunamis, and many other natural hazards in different times. Yet, man has neither succeeded in preventing these natural hazards from happening nor was able to keep them under control. The recent events of the Hurricane Katrina in the United States in 2005 and the great Asian tsunami disaster in 2004 have showed again that even in this modern era of technological advancement, people are highly vulnerable to natural hazards. As it is not possible yet to prevent or to control the natural hazards, the principles of disaster planning and management are established based on minimizing the damage by saving lives and properties during the strike of a natural hazard. Understanding of natural hazards is actually the primary key of taking proper mitigation efforts to minimize the damage.

In terms of definition, there is a difference between a natural hazard and a natural disaster. Natural hazard is defined as the probability of occurrence of a potentially damaging natural phenomenon within a specific period of time in a given area (Office of the United Nations Disaster Relief Coordinator, 1991). On the other hand, natural disaster is defined as the consequence of the occurrence of a natural phenomenon affecting a vulnerable social system (Appel, 2001). Thus, natural hazards represent potential events whereas naturals disasters result from actual events (Tobin and Montz, 1997). Natural phenomena themselves do not necessarily lead to natural hazards or disasters. It is only their interaction with people and their environment that may generate impacts and turn them into natural hazards, which may reach disastrous proportions and cause natural disasters. For instance, meteors as natural phenomena only become natural hazards when they enter into the earth's atmosphere and have potential to affect people. And when the earth is struck and people are affected, it may produce a natural disaster.

The process of disaster planning and management involves four phases (Figure 1.1): i) mitigation, ii) preparedness, iii) response, and iv) recovery (David, 2002).

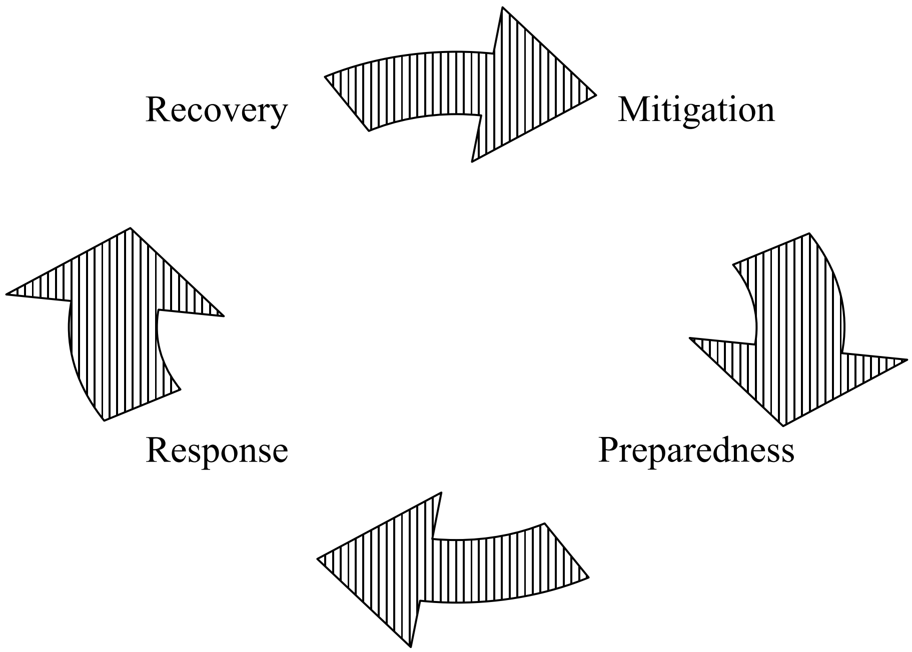

Figure 1.1 Disaster planning and management cycle

i) Mitigation: This phase involves taking measures to minimize the effects of disaster.
Examples: building codes, zoning, risk and vulnerability analyses, public education, etc.
ii) Preparedness: This phase involves planning how to respond.
Examples: preparedness plans; emergency exercises/training; warning systems, etc.
iii) Response: Reactive phase during and after the disaster.
Examples: search and rescue; emergency relief, etc.
iv) Recovery: Returning the community to normal.
Examples: temporary housing; grants; medical care, etc.

Developing countries are more vulnerable to natural hazards than the developed countries. Approximately 95% of deaths caused by natural hazards occur in developing countries (United Nations Environmental Program, 1992). It is very rare that natural hazards caused a large number of deaths in the developed countries. For instance, the devastating Hurricane Katrina caused only 1,800 deaths although it is the costliest hurricane in the U.S. history with around $82 billion dollar worth of damage (Johnson, 2006). On the other hand, Hurricane Mitch in 1998 caused more than 10,000 deaths in Central America (NCDC, 2004). In Bangladesh, an estimated 300,000 to 500,000 persons were killed by a 1970 cyclone and 140,000 by a 1991 cyclone (Karim, 1995). Figure 1.2 shows that the number of reported natural disaster events during 1990-1999 in the United States were over 2 times higher than India and about 3 times higher than Bangladesh. However, the number of deaths in India was 14 times higher than in the United States, whereas in Bangladesh the number of deaths was 34 times higher (CRED, 2000).

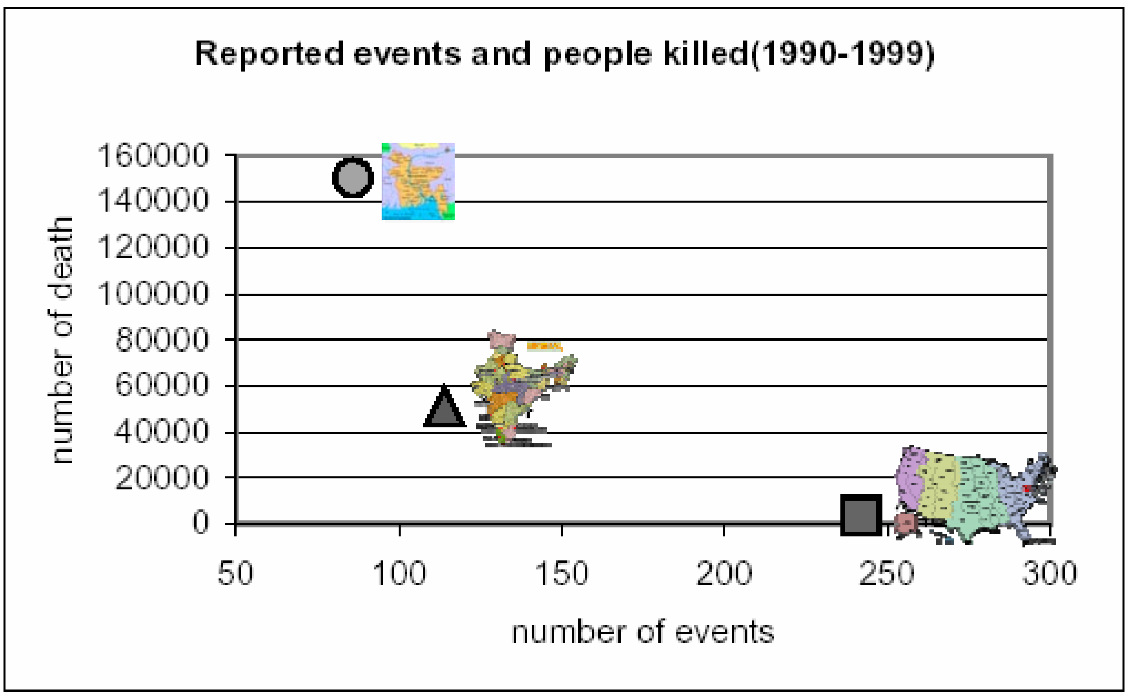

Figure 1.2 Natural disasters and fatalities in 3 selected countries (Hossain, 2001)

The main reason for higher vulnerability in the developing countries is their economic situation (Ono, 2001). Governments and a majority of people in developing countries cannot afford to prepare for natural hazards. Unlike developed countries, disaster planning and management is reactive rather than proactive in the developing countries and works mostly in the Response and Recovery phases. The lack of mitigation measures and minimum or haphazard preparedness results the inability to minimize the damage during a disaster.

High population density is another reason for the higher death toll in the developing countries. Since 1950, the number of people in the world has increased from 2.5 billion to more than 6.2 billion and mostly has occurred in the developing countries (UNEP, 1992). As population increases and more land is utilized, more people are forced to live in the hazard-prone areas. Hurricanes or tropical cyclones are one of the most dangerous natural hazards in the coastal areas of many countries near tropical oceans. In a recent study, the Center for Climate Systems Research (CCSR) at Columbia University has predicted that the world's coastal population will increase by 35 percent from 1995 to 2025 and will put more people at risk from natural hazards such as tsunamis or tropical cyclone (CCSR, 2006).

Bangladesh is one of the most densely populated and poorest countries in the world. A tropical cyclone is the most serious natural hazard in the coastal areas of Bangladesh. This study aims to understand the landfalling tropical cyclones of Bangladesh and the associated risk and vulnerability in the coastal areas. It is hoped that this research will contribute to taking proper disaster planning efforts in Bangladesh especially in the Mitigation phase for the reduction of damage from the cyclone hazard.

1.2 Specific problem

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 20º34´ N and 26º38´ N latitude, and with a 440-mile long coastline is highly vulnerable to tropical

Figure 1.3 Map of Bangladesh

(http://www.hrw.org/reports/2003/bangladesh0803/image002.gif) cyclones and associated storm surges. Figure 1.3 shows the location of Bangladesh and its borders with the neighboring countries along with the coast of the Bay of Bengal.

Table 1.1 lists the number of deaths in different countries associated with the deadly cyclone disasters where death tolls were in excess of 5000 lives. It can be easily discerned from the table that most of these deadly disasters occurred in Bangladesh from tropical cyclones.

Table 1.1 Deaths in tropical cyclones worldwide (Dube et al., 1997)

Year	Countries	Deaths	Year	Countries	Deaths
1970	Bangladesh	300,000	1965	Bangladesh	19,279
1737	India	300,000	1963	Bangladesh	11,520
1886	China	300,000	1961	Bangladesh	11,466
1923	Japan	250,000	1985	Bangladesh	11,069
1876	Bangladesh	200,000	1971	India	10,000
1897	Bangladesh	175,000	1977	India	10,000
1991	Bangladesh	140,000	1963	Cuba	7,196
1833	India	50,000	1900	USA	6,000
1864	India	50,000	1960	Bangladesh	5,149
1822	Bangladesh	40,000	1960	Japan	5,000
1780	Antilles (W. Indies)	22,000	1973	India	5,000

Bangladesh has experienced two of the deadliest cyclones of the last century, one was in 1970 and the other was two decades later in 1991. The former was the deadliest in the cyclone history with a death count over 300,000. Although only 7% of the global tropical cyclones (Neumann, 1993) occur in the North Indian Ocean, even storms with low intensity can be very deadly at landfall in Bangladesh because of the shallow bathymetry of the Bay of Bengal, funneling shape of the coastline with low-lying flat terrain and very high population density.

Disaster planning in Bangladesh especially for tropical cyclones is very reactive like other developing countries. Bangladesh gained independence in 1971, and before the independence, there was hardly any effort in terms of disaster planning and management. In the 1970 cyclone, the death tolls were huge mainly because there was no dissemination of cyclone warning by the ruling government. After independence, efforts have been taken sporadically; for example, construction of cyclone shelters and cyclone preparedness program by the Red Crescent Society. But these efforts are insufficient as in 1991 more than 140,000 people died from another tropical cyclone. Bangladesh is still politically unstable, and with its limited resources and saturated poverty, disaster planning is not at the top of the priorities from the government perspective. Thus, there has been scarcely any Mitigation measure taken to reduce the impact of tropical cyclones.

In this study, an attempt has been made to understand the characteristics of the landfalling tropical cyclones in Bangladesh by estimating the maximum wind speed and maximum surge height at landfall locations which can help taking Mitigation measures to minimize the damage. In addition, a cyclone risk and vulnerability analysis is carried out in the coastal areas of Bangladesh, which is very much needed for disaster planning considerations. After the 1991 tropical cyclone, a United Nations field study strongly recommended the formulation of a cyclone risk and vulnerability map for the coastal areas of Bangladesh (UNCRD, 1991).

1.3 Goals and objectives

a) To estimate the maximum wind speed and maximum surge height along the coast of Bangladesh. The return period of maximum wind speed will provide the design wind speed for structures. This can help to enforce a standard building code for the coastal areas and to improve the basic wind speed map for Bangladesh. The wind, surge and return period information can also be utilized in different mitigation measures.

b) To establish a comprehensive and reliable tropical cyclone climatology for Bangladesh, which can be useful for this study and for future research as well.

c) To identify and compare the regions based on cyclone risk and vulnerability. Delineation of areas based on risks and vulnerability due to cyclones and storm surges is necessary for disaster planning considerations. It is also important to evaluate the availability and allocation of resources in these areas that can help people to cope with cyclone and such other disasters. Moreover, this study will indicate the inter-regional disparities in respect of cyclone risks and coping facilities showing vulnerable and less-vulnerable regions to cyclone. In turn, it will give a broad picture about the regions that need immediate attention to the policy makers to provide more facilities in order to cope with cyclone disaster.

CHAPTER II

METHODOLOGY AND LITERATURE REVIEW

2.1 General background

The estimation of maximum wind speed and surge height in hurricane-prone regions can be developed in either of two ways: (1) directly from historical measurement, or (2) indirectly using numerical simulation procedures e.g., Monte Carlo method. (Kriebel et al.,1996).

Batts et al. (1980) determined that it is not possible to use statistical analysis of the highest annual wind speeds at a particular site in order to determine the extreme wind speeds in hurricane-prone regions. The first method can only be performed if sufficient data exists on extreme annual wind speed and extreme annual water level at locations of interest.

In practice, it is found that very few tropical storms or hurricanes actually strike at a particular site and historical records only exist for upwards of a hundred years. Thus, there exists a limited number of observations at each site. Therefore, it is preferable to follow the second procedure, i.e., an indirect numerical simulation method to obtain the extreme wind statistics for the cyclone prone regions. In this case, the Monte Carlo simulation method is chosen as the indirect method to obtain the extreme wind statistics for the coastal areas of Bangladesh.

2.2 Monte Carlo method

The theoretical basis of the Monte Carlo method is well established. During the nineteenth and early twentieth centuries, statistical problems were sometimes solved with the help of random selections, which is, infact the Monte Carlo method. But the generally accepted birth date of the Monte Carlo method is 1949, when an article entitled “The Monte Carlo Method” written by J. Neyman and S. Ulam appeared in the *Journal of the American Statistical Association* (Sobol, 1974).

Before the age of computers, the Monte Carlo method was not widely applicable as carrying out the simulation process by hand is very laborious. The method has become popular as a highly universal numerical technique with the advent of computers. The method is named after the city of Monte Carlo, the principality of Monaco, which is very famous for gambling games such as the roulette wheel, which is a simple random number generator (Sobol, 1974).

Kriebel et al. (1996) described the advantages and disadvantages of using the Monte Carlo method in the cyclone wind analysis as given below.

Advantages of the Monte Carlo approach:

1. A sufficiently large number of storms can be generated to ensure some reasonable statistical significance at the desired 50- to 100- year return periods;
2. Several sets of Monte Carlo simulations can be generated and the statistical variability of the design parameter, e.g., the 50- year wind speed, can be assessed; and
3. Rare combinations of meteorological parameters can occur in the simulation that, although within the bounds of past observations, have not yet been experienced in the relatively short period that storms have been observed at most coastal sites.

Disadvantages of the Monte Carlo method:

1. Limitations associated with using past meteorological observations to characterize future storm conditions;
2. Simplifications inherent in the various numerical models;
3. Inability to simulate non-hurricane extreme wind or surge events (such as localized fronts or poorly organized storms) that form the bulk of the high-frequency events in some coastal areas; and,
4. Inability to ensure adequate model calibration when used outside the range of observed extreme events.

2.3 A case study on the Monte Carlo method

Skwira (1998) in his master's thesis, used the Monte Carlo simulation technique to determine the extreme wind speeds for the United States Gulf and Atlantic coasts. A Monte Carlo simulation results from a large number of realizations of any event of interest, which was, in this case, a hurricane making landfall. Skwira defined the strike of a hurricane or tropical storm if the center of the storm passes within 150 nautical miles of the site of interest. One thousand randomly generated individual storms (realizations) in the form of hurricanes, tropical storms, or tropical disturbances were simulated for the 11 sites chosen along the United States coast. The sites are: Port Isabel, Galveston, Pensacola, Fort Myers, Palm Beach, May port, Myrtle Beach, Virginia Beach, Atlantic City, Long Island and Portsmouth. As each storm was simulated the maximum wind and the direction of the maximum wind were identified and cataloged. Using the generated wind information at a site, the extreme wind speed for a particular return period was determined. Exactly the same procedure is used in this study to determine the extreme cyclone wind speed for the sites along the Bangladesh coast of the Bay of Bengal.

2.4 Wind field models

A wind field is required in the Monte Carlo simulation to represent the storms that made landfall. Descriptions of the available wind field models are given below.

2.4.1 The Rankine Vortex (Letzmann and Wegener, 1930)

The Rankine Vortex (Rankine,1901) is probably the simplest model used for representing any type of vortex. The model is represented in the following formulas:

$$V/r = K_i \qquad (r \le r_m) \tag{2.1}$$

$$Vr = K_o \qquad (r > r_m) \tag{2.2}$$

where, V is the calculated wind speed, K_i and K_o are constants determined from the data, and r is the distance from the center of the storm to the point of interest. Equation (2.1) represents the wind speed within the radius of the maximum wind (r_m) and equation (2.2) is for the wind speed outside the radius of the maximum wind. The model requires that the radius of the maximum wind, r and maximum wind speed, V must be known to determine K_i and K_o, which may be inconvenient sometimes.

2.4.2 Modified Rankine Vortex (Depperman, 1939)

Another similar model is the Modified Rankine wind field model. The mathematical representation for the model is:

$V/r = C \qquad (r \le r_m)$ (2.3)

$Vr^x = D \qquad (r > r_m)$ (2.4)

where, V is the calculated wind speed, C and D are constants determined from the data, x is an empirical constant ($0.4 < x < 0.6$), and r is the distance from the center of the storm to the point of interest. Equation (2.3) represents the wind speed within the radius of the maximum wind (r_m) and equation (2.4) is for the wind speed outside the radius of the maximum wind. The model is identical to the Rankine wind field model inside the radius of maximum winds. The wind speed decreases at a rate inversely proportional to r^x outside of the radius of maximum winds. This model has problems similar to those of the Rankine wind field model, as it requires the radius of the maximum wind, r and maximum wind speed, V must be known to determine C and D, which is inconvenient.

2.4.3 Gradient wind model

The Gradient wind model was used by Batts et al. (1980). It is a commonly used hurricane wind model (Holton, 1992). The mathematical representation of this model is:

$V_{gr} = V_c\,(\sqrt{(\gamma^2+1)} - \gamma)$ (2.5)

$V_c \equiv \{(\Delta P\ R\ \exp(-R/r))/(\rho\ r)\}^{1/2}$ (2.6)

$\gamma \equiv (1/2)\{(rf + V_f \sin \Theta)/V_c)$ (2.7)

where, V_{gr} is the gradient wind, V_c is the cyclostrophic flow, γ is a calculated parameter, ΔP is the pressure difference from the center of the storm to its periphery, R is the radius of maximum winds, ρ is the air density, f is the Coriolis parameter, V_f is the forward speed of storm, and Θ is the angle counterclockwise from the forward velocity vector to radius r at the point of interest. Equation (2.5) is the actual representation of the gradient wind model, which can be solved by substituting equations (2.6) and (2.7). Since the model requires only available meteorological parameters to solve rather than actual maximum winds at R, the Gradient wind field model is more desirable than Rankine and Modified Rankine wind field models.

2.4.4 Holland wind field model (Holland, 1980)

The mathematical representation of the Holland (1980) wind field model is:

$$V = \{[(AB)/(\rho r^B)](P_n-P_c)\exp(-A/r^B) + (r^2 f^2)/4\}^{1/2} - (rf)/2 \quad (2.8)$$

$$R = A^{1/B} \quad (2.9)$$

$$1.0 \leq B \leq 2.5 \quad (2.10)$$

where, A and B are empirically determined, R is the radius of maximum winds, ρ is the air density near the surface of the earth, r is the radius of interest, P_n is the environmental surface pressure, P_c is the central surface pressure of the hurricane and f is the Coriolis parameter. Similar to the Gradient wind model, this wind field model does not require the actual maximum wind speed at the radius of maximum winds; rather it requires only the available meteorological parameters to solve.

2.4.5 Modified Holland wind model (Hubbert et al., 1991)

Hubbert et al. (1991) modified the previous wind field model with the following equation:

$$V = \{B(R/r)^B(P_n-P_c)\exp[-(R/r)^B]/\rho - (r^2 f^2)/4\}^{1/2} - (rf)/2 \quad (2.11)$$

where, all the common symbols are the same as defined previously. However, the empirical parameter B has been explicitly solved in this model as:

$$B = 1.5 + (980 - P_c)/120 \quad (2.12)$$

Therefore, it is not necessary to choose a random value for B between 1.0 and 2.5. The empirical parameter B affects the size of the storm. The larger the B, the smaller the overall dimensions of the storm. In equation (2.12), the lower the central pressure, the larger the value of B, which in turn creates a more compact, intense and stronger storm.

2.4.6 Comparison of the wind field models

Skwira (1998) compared the five wind models using the parameters of Hurricane Hugo (Figure 2.1), which struck the coast of South Carolina, for all the simulations. Figure 2.1 gives a cross-sectional view of the different wind field models. The horizontal axis is the distance the eye is from the coastline normalized by the radius of maximum wind. At distance 0, the eye is directly over the site, at any negative distance the eye is approaching the site offshore, at positive distance the eye of Hugo is moving away from the site onshore.

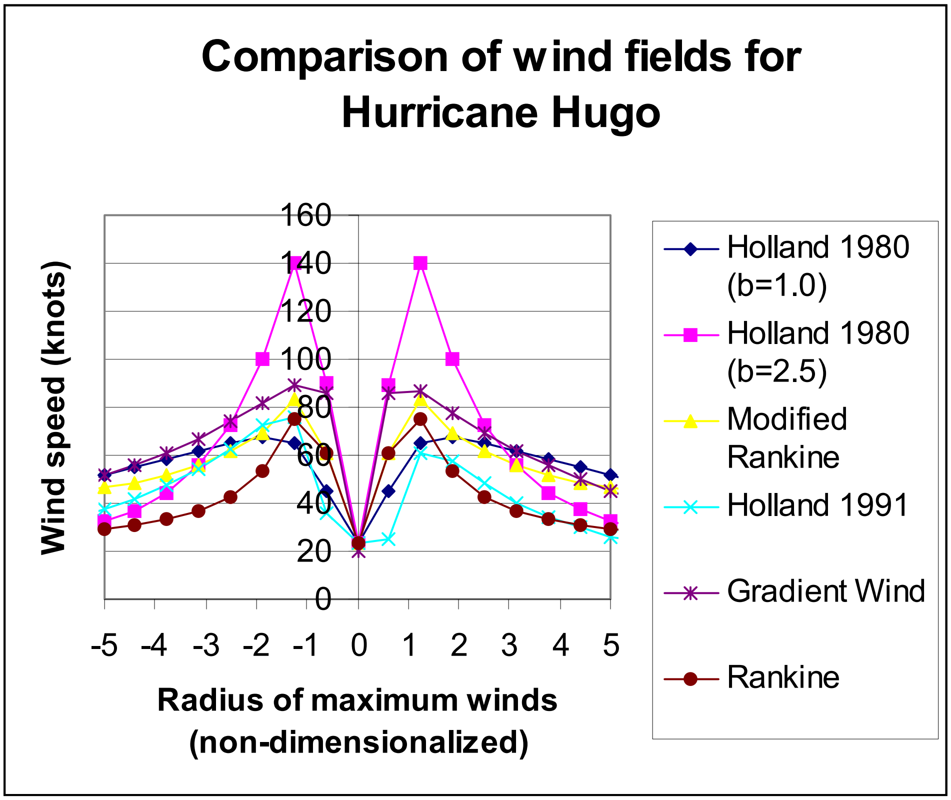

Figure 2.1 Comparison of wind fields for Hurricane Hugo (Skwira,1998)

The Rankine Vortex model produces a smaller spatial wind field compared to the Modified Rankine Vortex model and the Gradient wind field model. Thus, the latter models better represent hurricanes with substantial size, whereas the Rankine Vortex model is better to represent compact hurricanes. The Holland wind field model (1980) represents a wide variety of hurricanes depending upon the value of the empirical parameter B. The larger the value of B, the wind field becomes more compact with high wind speeds. The Modified Holland wind field model (1991) is the only model that does not create a symmetric wind pattern. The Modified Holland wind field model (1991) was chosen by Skwira (1998) and also in this study to carry out the Monte Carlo simulation because of the following reasons (Hubbert et al.,1991):

Firstly, this model is flexible and can represent a wide variety of storms in both size and shape. All of the other wind models are basically locked into one particular shape, and only their size can change depending on the radius of maximum winds. In reality, hurricanes are observed to occur in a wide variety of both shapes and sizes.

Secondly, in the Holland model (1991) the wind is shifted 20º counterclockwise in order to place the maximum wind speeds 70º to the right of the direction of the cyclone motion. The maximum winds are actually less as the radius of maximum winds passes the site for the second time than its first passage over the site. This creates an asymmetric wind pattern unlike the other wind field models, which is more realistic in nature.

Lastly, the radial wind field is constructed by rotating the flow to a constant inflow angle of 25º outside the radius of maximum winds. According to the research with this new wind and pressure model, it appears that these pressure and wind fields are as good and are often better than previous models.

2.5 Storm surge model

A storm surge is a massive rise in the sea-surface level caused by strong wind-stress forcing and (to a lesser extent) by a drop in the atmospheric pressure. In tropical regions, these forcing agencies result from the often erratic passage of a tropical cyclone, hurricane or typhoon (Johns and Lighthill, 1993). A detailed review of the problem of storm surges in the Bay of Bengal is given by Dube et al. (1997), Das (1994), Murty et al. (1986) and Murty (1984).

Numerical storm surge models provide good sources of information concerning the range of expected peak surge heights during tropical cyclones. The governing hydrodynamic equations in most of the storm surge models are the depth-integrated equations for the conservation of momentum for shallow water long wave motions in the x- and y-directions:

$$\frac{\partial U}{\partial t} + \frac{U}{D}\frac{\partial U}{\partial x} + \frac{V}{D}\frac{\partial U}{\partial y} = fV - gD\frac{\partial S}{\partial x} - \frac{D}{\rho}\frac{\partial P}{\partial x} + \frac{1}{\rho}(\tau_{wx} - \tau_{bx}) \tag{2.13}$$

$$\frac{\partial V}{\partial t} + \frac{U}{D}\frac{\partial V}{\partial x} + \frac{V}{D}\frac{\partial V}{\partial y} = -fU - gD\frac{\partial S}{\partial y} - \frac{D}{\rho}\frac{\partial P}{\partial y} + \frac{1}{\rho}(\tau_{wy} - \tau_{by}) \tag{2.14}$$

and also the equation for conservation of mass:

$$\frac{\partial S}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0 \tag{2.15}$$

where,

S	=	storm surge or departure of water surface from mean sea level;
U	=	depth-integrated flow in x-direction (units: length squared per time);
V	=	depth-integrated flow in y-direction (units: length squared per time);
D	=	total water depth;
P	=	atmospheric pressure at water surface;
ρ	=	density of water;
τ_w	=	shear stress at water surface due to wind;
τ_b	=	shear stress at sea floor due to bottom friction;
x	=	defined as positive in the offshore direction, zero at shoreline; and
y	=	defined as positive to the left when facing in the $+x$ direction (right hand coordinate system), zero at the point of interest.

(Kriebel et al.,1996)

In the United States, the SLOSH (Sea, Lake, and Overland Surges for Hurricanes) storm surge model has been developed by the National Weather Service (Jarvinen and Lawrence, 1985). This is an extension of the previous SPLASH (Special Program to List Amplitudes of Surges from Hurricanes) model developed by Jelesnianski (1972). Both

SLOSH and SPLASH models are based on the linearized equations (2.13-2.15). Model formulations are discussed in detail by Jelesnianski (1965, 1966, 1967).

A number of surge models have been developed and used for the Bay of Bengal. Das (1972) conducted a numerical experiment and computed the surge generated by an idealized cyclone striking the coast of Bangladesh (Dube et al., 1997). Das et al. (1974) extended the model for the coast of West Bengal and Orissa. Ghosh (1977) adapted the SPLASH model to the east coast of India. Johns (1981) and Johns and Ali (1980) have developed a non-linear model for the storm surge simulation along the Bangladesh coast in which the dynamic effects of the deltaic plain have been incorporated (Dube et al., 1997). A hierarchy of four models of increasing complexity has been developed by the Indian Institute of Technology (IIT) to simulate storm surges in the Bay of Bengal (Johns and Lighthill,1993). Flather (1994) also developed a surge prediction model for the northern Bay of Bengal. The model was successfully applied to simulate the disastrous storm surge caused by the Bangladesh tropical cyclone in April 1991. Pre-computed nomograms are also used for operational surge predictions in the northern Bay of Bengal. Mandal (1991) prepared the Probable Maximum Storm Surge for the Indian and Bangladesh coastlines using pre-computed nomograms.

In this study, the wind model developed by Holland (1991) is installed into a simplified Bathystrophic Storm Surge model. The simplified model, the Bathystrophic storm surge model as developed by Freeman et al. (1957), has the following key assumptions:

1. Nonlinear convective acceleration terms are neglected;
2. The bathymetry, the wind field, and the storm surge are assumed to be uniform in the alongshore direction so that spatial gradients in the y-direction are zero. As a result, computations are carried out along a single line specifying the bathymetry perpendicular to the coast at the point of interest; and,
3. Onshore flows are assumed to reach steady-state such that any onshore-directed flow due to onshore wind stress is balanced by an offshore-directed return flow near the ocean bottom. Thus, there is no net discharge, U, in the cross-shore

direction.

As a result of these simplifications, equations (2.13) through (2.15) are reduced to the following form:

$$\frac{\partial S}{\partial x} = \frac{f V}{gD} - \frac{1}{\rho g}\frac{\partial P}{\partial x} + \frac{n \ \tau_{wx}}{\rho gD} \tag{2.16}$$

$$\frac{\partial V}{\partial t} = \frac{1}{\rho}(\tau_{wy} - \tau_{by}) \tag{2.17}$$

where,

n = coefficient to approximate effects of bottom stress.

Equations (2.16) and (2.17), though quite simplified compared to the full governing equations, represent the dominant physical mechanisms responsible for storm surge generation on the open coast (Kriebel et al.,1996).

2.6 Landfalling tropical cyclone climatology

There is a dearth of climatological studies on the landfalling tropical cyclones for Bangladesh. The Indian Meteorological Department (IMD) and other Indian investigators have done most of the research on the Bay of Bengal and North Indian Ocean cyclones. However, this research was almost exclusively conducted for the Indian coast of the Bay of Bengal. Rai Sircar (1956), Raghavendra (1973) and Mooley (1980) studied cases on the Bay of Bengal tropical cyclones, which included the Bangladesh coast.

Raghavendra (1973) did a statistical analysis of the number of tropical storms and depressions in the Bay of Bengal for the period 1890-1969. Mooley (1980) studied the severe cyclonic storms in the Bay of Bengal during 1877-1977. Mooley did another study with Mohile (1983) on the landfalling Bay of Bengal cyclones for different sections of the coast including Bangladesh. More recently, Alam et al. (2003) performed a study on the frequency of Bay of Bengal cyclonic storms and depressions crossing different coastal zones. But the study period is not that long, only from 1974 to 1999.

The SAARC Meteorological Research Center (SMRC), which is located in Dhaka, Bangladesh, published SMRC Report - No.1 on the impact of tropical cyclones in different South Asian countries. A total of 82 cyclonic storms are mentioned for the period 1582 through 1997 that made landfall in Bangladesh. Tropical depressions are not included in the study. Not much information was given about these 82 cyclones except monthly distributions along four different parts of the coast. These are: i) Khulna / Sundarban coast, ii) Barisal / Patuakhali - Noakhali coast, iii) Noakhali – Chittagong coast, and iv) Chittagong – Cox's Bazar coast. The landfall locations were mostly assumed based on different sources and not following the storm tracks. This is the best available data so far on the landfalling tropical cyclones of Bangladesh.

Ho et al. (1987) developed a landfalling hurricane climatology for the Atlantic and Gulf coasts of the United States. The input parameters for the Holland (1991) wind field model in the Monte Carlo simulation are readily available from such sources (Skwira,1998). The existing climatological studies discussed above on the landfalling tropical cyclones in Bangladesh and the Bay of Bengal are not useful to provide information on the input parameters of the Holland (1991) wind field model in order to carry out Monte Carlo simulation along the Bangladesh coast. A detailed and comprehensive landfalling tropical cyclone climatology of Bangladesh needs to be developed so that statistical properties of the input parameters can be extracted from it.

2.7 Cyclone risk and vulnerability analysis

It is difficult to analyze a single hazard component like cyclone with respect to risk and vulnerability of a certain area as people are vulnerable to many other hazards at the same time. Hossain and Singh (2002) analyzed human vulnerability to cyclone in India in a paper titled "Application of GIS for assessing human vulnerability to cyclone in India." First, a GIS storm risk map for India is collected which is developed by the Earth Satellite Corporation based on the historic cyclones distribution during 1971-1999.

Then, the storm risk map is overlaid with a population density map and a state boundary map of India to show the vulnerable population at cyclone risk in different states of India. After that the per capita income of each state (as a coping capacity factor) is introduced to compare relative vulnerability in different states of India. Figure 2.2 shows the steps taken for cyclone vulnerability assessment.

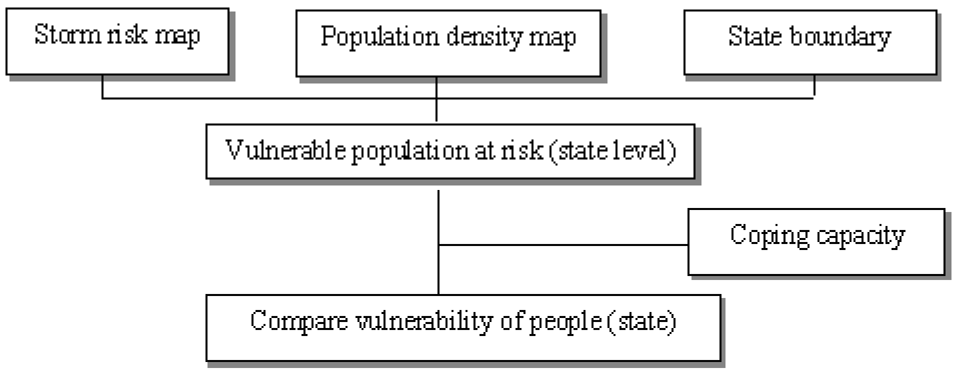

Figure 2.2 Methods for cyclone risk model (Hossain and Singh, 2002)

In this study, a more detailed approach is taken to analyze and compare the cyclone risk and vulnerability for the coastal districts of Bangladesh. As there is no storm risk map for Bangladesh, it needs to be created first in order to analyze the cyclone vulnerability.

By definition, risk means to expose to a chance of hazard or loss (UNDRO, 1979). So, cyclone risk means exposure of an area to the chance or threat of cyclone hazard. In the past cyclones, most of the people died from the associated storm surges in Bangladesh (Ali, 1979). Cyclone wind is also responsible for damaging houses and properties. Usually, a location which is located farther from the coastline, experiences less exposure from the cyclones and storm surges. Therefore, cyclone risk can be a function of cyclone wind speed, surge height, average distance of the coastal district from coastline and locational distribution of the past cyclones. In this study, all of these physical features are considered to analyze the cyclone risk in the coastal areas of

Bangladesh. Figure 2.3 shows a schematic diagram of the cyclone risk model for Bangladesh.

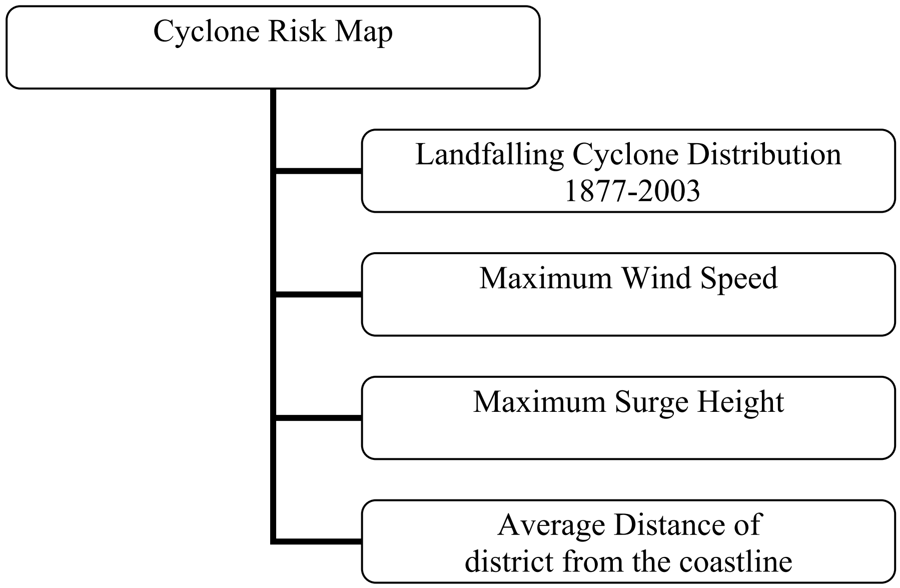

Figure 2.3 Cyclone risk model for Bangladesh

Vulnerability, on the other hand, is a complex term and difficult to define. Timmerman (1981) defined vulnerability as the degree to which a system acts adversely to the occurrence of a hazardous event. The degree and quality of the adverse reaction are conditioned by a system's resilience (a measure of the systems capacity to absorb and recover from the event). Cutter (1996) defined vulnerability as the likelihood that an individual or group will be exposed to an adversely affected by a hazard. It is the interaction of the hazards of the place (risk and mitigation) with the social profile of the communities. Clark et al. (1998) defined vulnerability as a function of two attributes: 1) exposure (the risk of experiencing a hazardous event); and 2) coping ability, subdivided into resistance (the ability to absorb impacts and continue functioning), and resilience (the ability to recover from losses after an impact).

From the above definitions, it can be easily discerned that vulnerability is strongly related with the coping capacity of the people or society. For instance, the United States is more exposed to natural hazards than Bangladesh, but is less vulnerable due to its strong coping capacity (CRED, 2000). Coping means ability to withstand risks at a particular point of time. Coping could be money, deployment of technology, infrastructure or emergency response system. Coping is also the manner in which people act within existing resources and range of expectations of a situation to achieve various ends. This means how people are able to respond in unusual, abnormal, and adverse situations (Hossain and Singh, 2002).

In this study, the parameters chosen for coping capacity are: per capita income, population density, distribution of cyclone shelter and road network distribution. In addition, distribution of casualties from the past cyclones is considered to show the vulnerability more realistically (Figure 2.4).

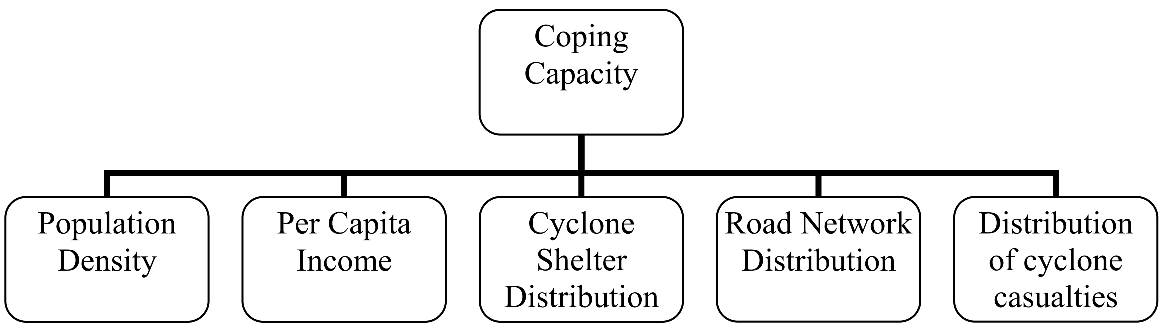

Figure 2.4 Coping capacity parameters

Since, vulnerability is a combination of risk and inability to cope; thus, cyclone vulnerability can be conceptualized as a combination of cyclone risk and coping capacity of the people (Figure 2.5).

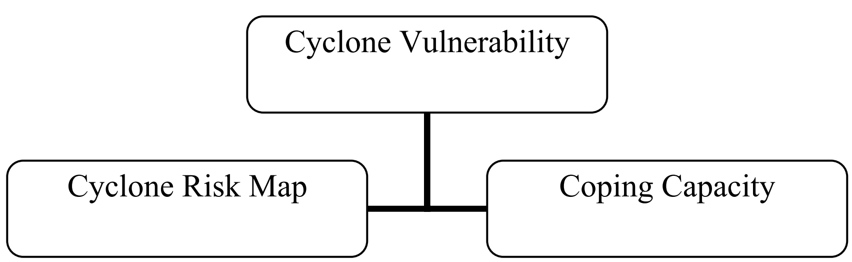

Figure 2.5 Cyclone vulnerability

In this study, an attempt has been made to compare the 14 coastal districts of Bangladesh in terms of cyclone risk and coping capacity, which leads to the cyclone vulnerability of the coastal areas in Bangladesh. Using GIS, a comparative cyclone risk and cyclone vulnerability map is produced along with maps for each parameter examined. In the maps, coastal districts or the regions are categorized as high risk/vulnerable, medium risk/vulnerable and low risk/vulnerable areas. The districts, in which condition of a particular variable or variables is average among all the districts, are placed in the medium risk/vulnerable regions. The extreme regions are placed in the high or low risk/vulnerable regions based on their condition. The z-score formula is used here to identify the values that are far away from the mean or in other words to reveal the extreme regions.

In statistics, a z-score (also called standard score or normal score) is a dimensionless quantity derived by subtracting the population mean from an individual (raw) score and then dividing the difference by the population standard deviation (Sprinthall, 2003).

The original z-score formula is:

$$z = \frac{X - \mu}{\sqrt{\frac{\sigma^2}{N}}} \tag{2.18}$$

where, X is a raw score to be standardized,

σ is the standard deviation of the population, and,

μ is the mean of the population

The quantity z represents the distance between the raw score and the population mean in units of the standard deviation; z is negative when the raw score is below the mean, positive when above.

The following modified z-score formula is used to make regional comparison in this study:

$$z = \frac{K - \frac{\sum K}{N}}{\sqrt{\frac{\sum \left[K - \left(\frac{\sum K}{N} \right) \right]^2}{N}}} \tag{2.19}$$

where, N is the number of comparable regions or coastal districts,

K is the weighted value of regions in a scale 0-1.

Figure 2.6 shows the steps that are followed in this dissertation. First, a landfalling tropical cyclone climatology of Bangladesh is developed from which the data input for the Holland (1991) wind model are extracted. This wind field model represents the structure of landfalling cyclones in the Monte Carlo simulations and the surge model calculates the surge height at landfall locations. Using the Monte Carlo simulation method, a cyclone wind analysis is carried out for the selected coastal sites of Bangladesh by estimating the maximum wind speed and maximum surge height of 1000 simulated storms at each coastal site. Finally, a cyclone risk and vulnerability analysis is performed using information from the cyclone wind analysis and the climatology. Using GIS, a cyclone risk map and a cyclone vulnerability map are produced for the coastal districts of Bangladesh.

In this dissertation, chapter III presents a comprehensive landfalling tropical cyclone climatology and database (1877-2003) for Bangladesh. The statistical properties of wind field parameters and cyclone wind analysis are presented in Chapter IV. Chapter V contains a comparative analysis on cyclone risk and vulnerability among the coastal districts of Bangladesh. The goal of this dissertation is threefold: (1) to develop a new climatological dataset on landfalling cyclones for Bangladesh; (2) to estimate the extreme wind speeds and surge heights along the coast of Bangladesh; and then (3) to incorporate all these in a comparative cyclone risk and vulnerability study among the coastal districts, which can provide a strong base towards effective disaster planning for Bangladesh.

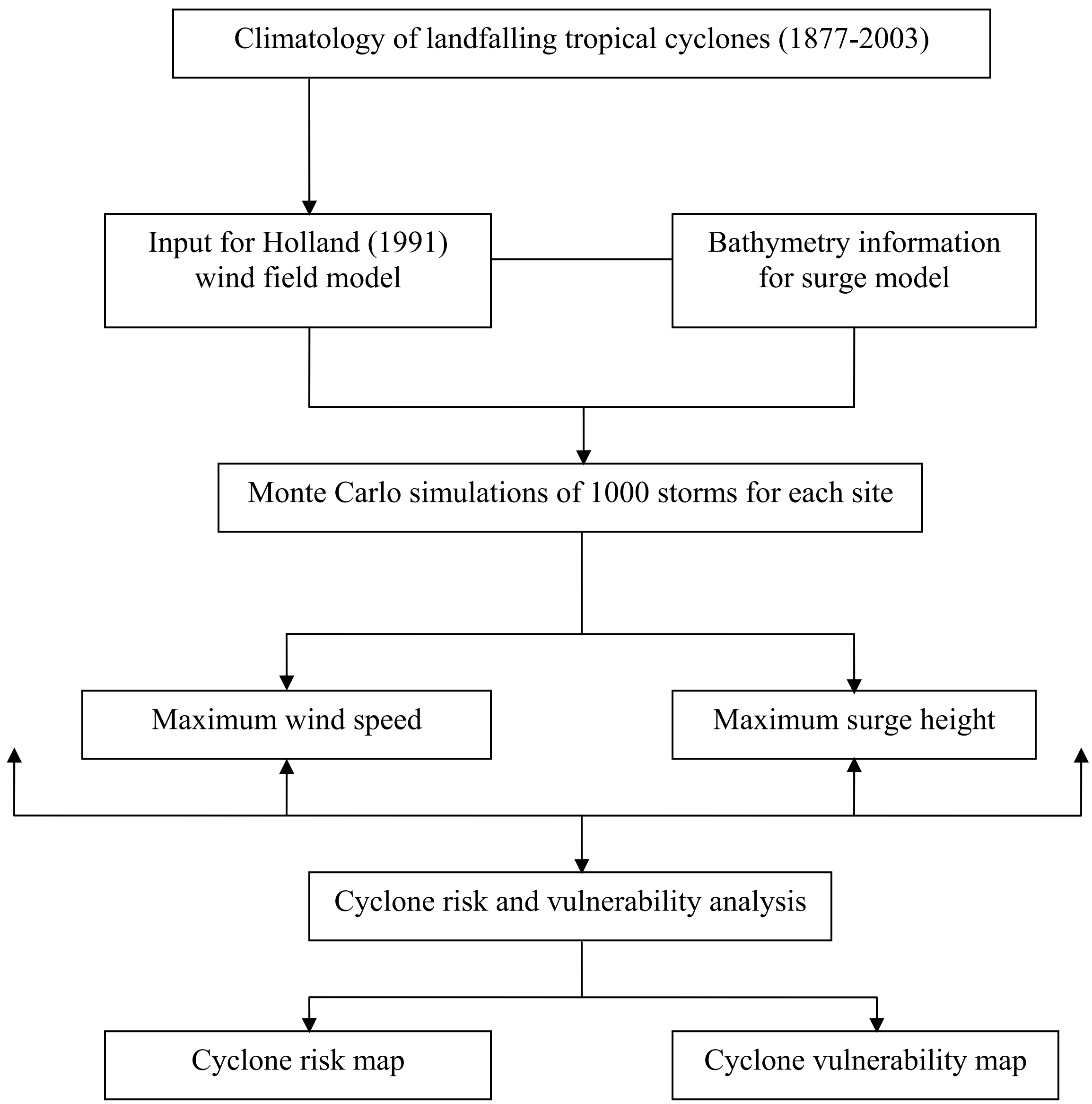

Figure 2.6 Methodology diagram

CHAPTER III

CLIMATOLOGY OF LANDFALLING CYCLONES IN BANGLADESH 1877-2003

Development of a climatological database on the landfalling tropical storms in Bangladesh is needed to use in a Monte Carlo simulation of extreme winds and storm surge for the Bangladesh coastal areas. For this purpose, storm tracks with hourly latitude/longitude information for a 127-year period (1877-2003) are examined. The storm tracks are geographically represented using GIS. Although the primary intention of this database is to extract statistical properties of the Bay of Bengal storms to use in a Monte Carlo simulation, a comprehensive climatological study on the landfalling cyclones of Bangladesh is performed based on the database for a 127-year period (1877-2003).

3.1 Data resources

The hourly latitude/longitude information is obtained from the Global Tropical Cyclone Climatic Atlas (GTCCA Version 1.0 and 2.0), which is prepared by the Fleet Numerical Meteorology and Oceanography Center (FNMOC). The database of GTCCA is a compilation of two historical digital tape deck data files (TD-9636 and TD-9697) archived at the National Climatic Data Center (NCDC), a Joint Typhoon Warning Center (JTWC) historical data file from Guam, and data forwarded to NCDC by the Regional and Specialized Meteorological Centers (RSMC) participating in the World Meteorological Organization's (WMO) Tropical Cyclone Program (FNMOC, 1998). These data were then validated by the database of the Unisys Corporation (UNISYS, 2004) which also uses the same JTWC source.

The Center for Research on the Epidemiology of Disasters (CRED), based in Belgium, has an online International Disaster Database, from which casualty and other damage records are collected.

3.2 Study area

For assigning landfalling locations in this study, the coast of Bangladesh is divided into five parts. These are: Khulna, Barisal, Noakhali, Chittagong and Cox's Bazar. Landfalling locations are shown in Figure 3.1. In the map, Sundarbans - the largest mangrove forest located in the Khulna coast - is also depicted.

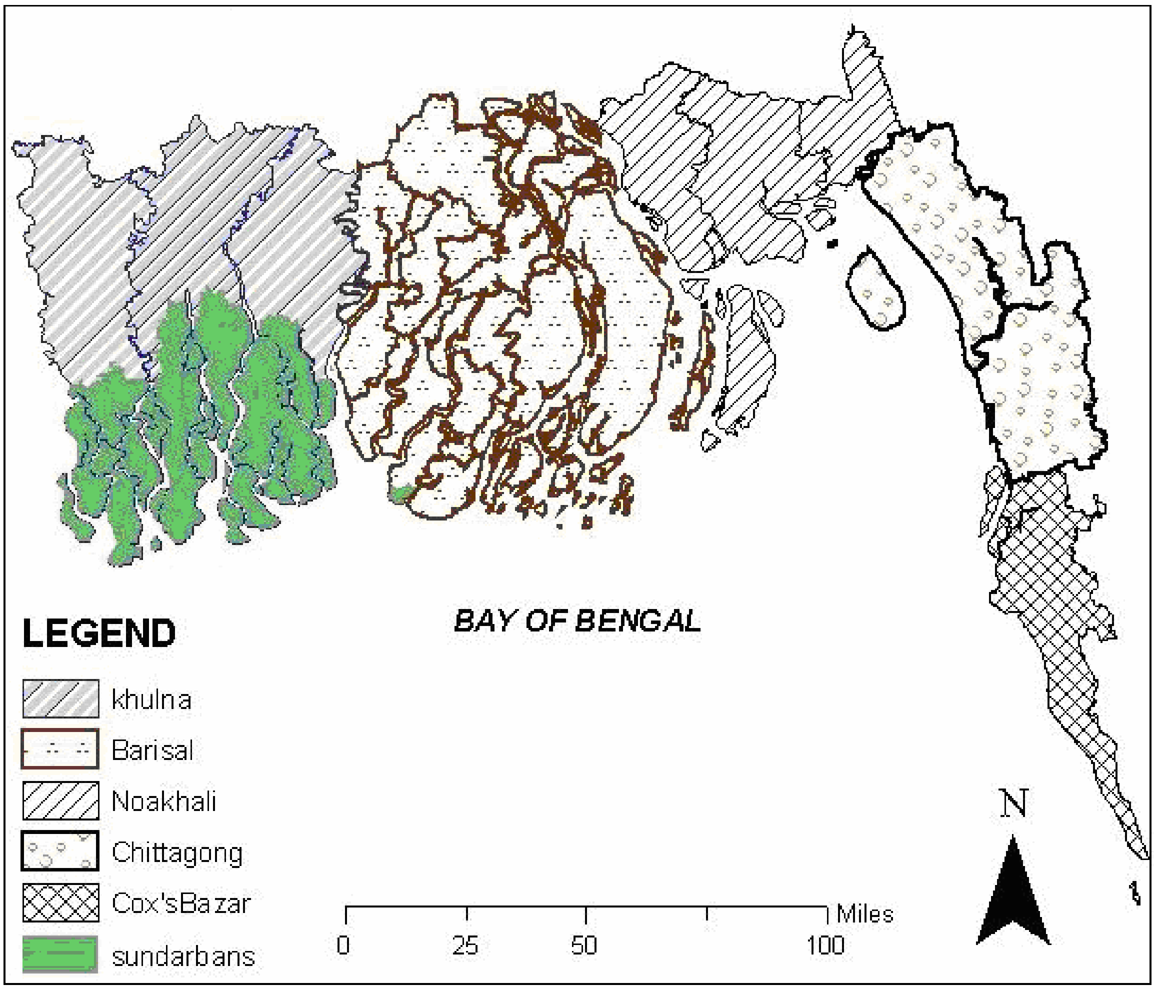

Figure 3.1 Coast of Bangladesh with subdivisions.

3.3 Organization of data

In the GTCCA database, for earlier storms many of the dates, positions, and intensities are deduced through estimates and compromise among various reports using synoptic and climatological judgment. The cyclones in the GTCCA database are classified by the following criteria:

Table 3.1 GTCCA classification

Type	Category	Wind Speed (knots)
Tropical Depression	TD	<34
Tropical Storm	TS	34-63
Hurricane		64>

Using these criteria, the number of landfalling cyclones in Bangladesh is as follows:

Table 3.2 Frequency of Bangladesh landfalling cyclones

Type	Frequency
Tropical Depression (TD)	39
Tropical Storm (TS)	52
Hurricane	26
Total	**117**

Based on the Saffir-Simpson Hurricane Scale (Simpson, 2003) on potential damage, the number of hurricanes can be further categorized as follows:

Table 3.3 Hurricanes by Saffir-Simpson intensity category

Category	Wind Speed (Knot)	Frequency
1	64-83	8
2	84-96	0
3	97-113	2
4	114-135	5
5	>135	1
	Wind speed not available	10

Bangladesh is a member country of the World Meteorological Organization (WMO), and it follows the classifications described in the WMO Tropical Cyclone Operational Plan (TCP-21) for the region (WMO, 1986).

Table 3.4 WMO Classifications for the panel countries (TCP-21)

Weather System	Maximum Wind Speed
1. Low pressure area	Wind speed less than 17 knot (31 km/h)
2. Depression	Wind speed between 17 and 33 knot (31 and 61 km/h)
3. Cyclonic storm	Wind speed between 34 and 47 knot (62 and 88 km/h)
4. Severe cyclonic storm	Wind speed between 48 and 63 knot (89 and 118 km/h)
5. Severe cyclonic storm with a core of hurricane winds	Wind speed 64 knot (119 km/h) or more
6. Very severe cyclonic storm	Wind speed 64 and 119 knot (119 and 221 km/h)
7. Super cyclonic storm	Wind speed 120 knot & above (222 km/h)

As mentioned before, in the GTCCA database the intensities of most of the earlier storms were estimated from various reports using climatological judgment; thus, the corresponding wind speeds are not available. Only 32 storms have been found with the wind speed data. According to the WMO TCP-21 classification, these storms can be categorized as:

Table 3.5 Frequency of cyclones by WMO Classifications (TCP-21)

Category	Frequency
1. Low pressure area	-
2. Depression	-
3. Cyclonic storm	5
4. Severe cyclonic storm	11
5. Severe cyclonic storm with a core of hurricane winds	(11+5) = 16
6. Very severe cyclonic storm	11
7. Super cyclonic storm	5
Total	**32**

In this study, the frequency distribution by the GTCCA classification is used and the historical storms dataset and climatology are developed based on that.

3.4 Bangladesh historical landfalling storm tracks (1877-2003)

A dataset of historical landfalling storm tracks in Bangladesh from 1877 to 2003 is developed based on the hourly latitude/longitude information from the Global Tropical Cyclone Climatic Atlas (GTCCA). In the GTCCA, tropical cyclones are listed for the seven basins as early as 1842. Landfalling tropical cyclone information for Bangladesh is manually extracted from the North Indian Ocean basin cyclones. To check the accuracy of the landfall locations, the latitude/longitude information for each storm track is put into GIS and landfall locations are assigned.

Figure 3.2 shows all the landfalling tropical cyclone tracks in Bangladesh for a 127- year period (1877-2003). For the convenience and legibility, the list (Table 3.6) is divided into several parts each approximately a 10- year period starting from 1877 up to 2003.

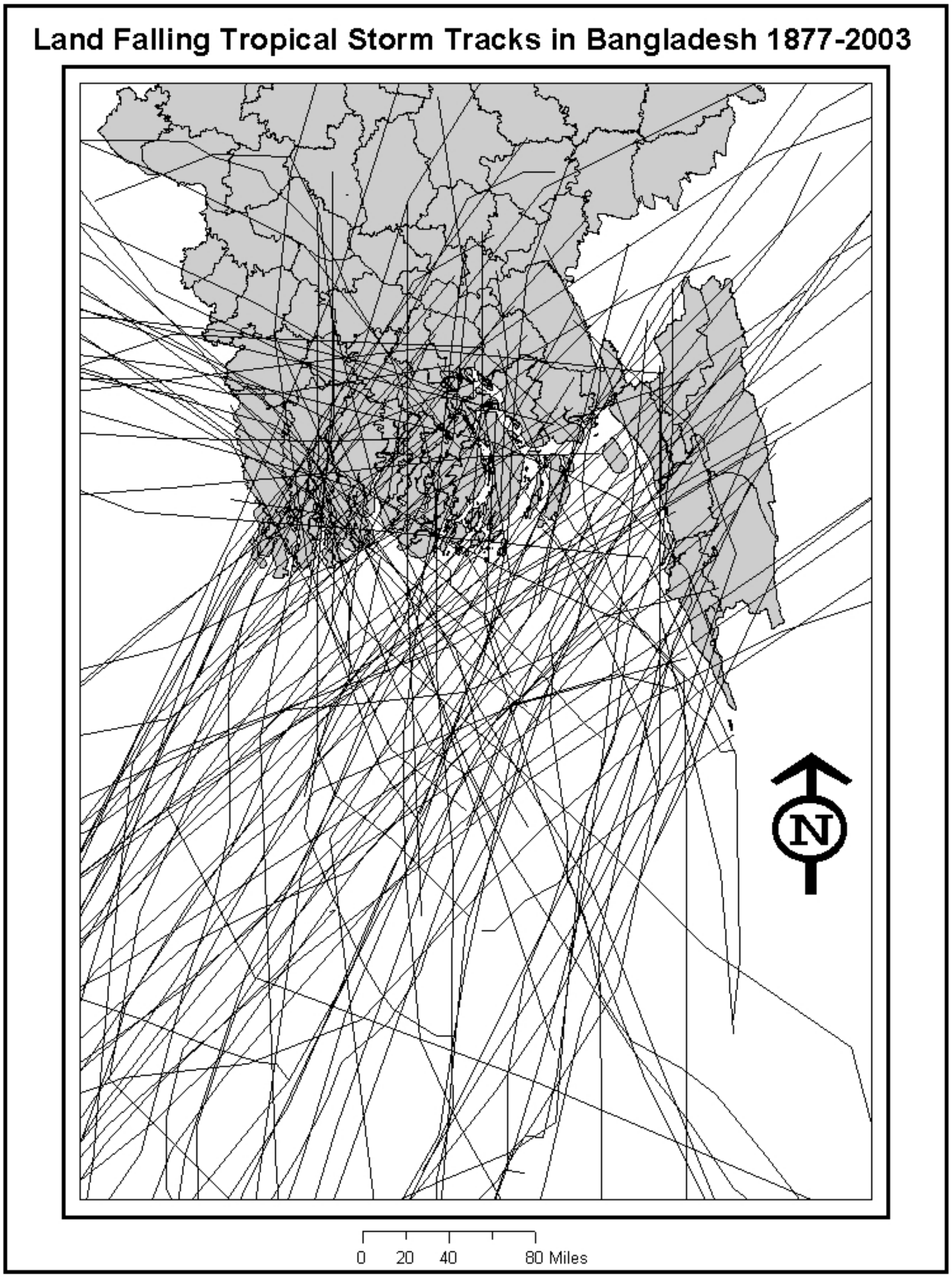

Figure 3.2 Landfalling tropical cyclone tracks in Bangladesh (1877-2003)

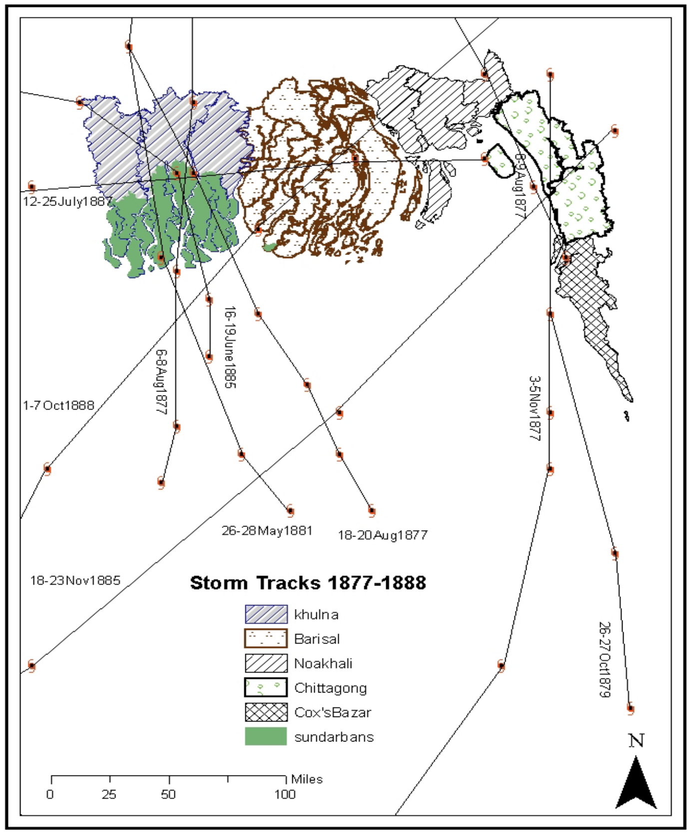

Figure 3.3 Storm tracks during 1877-1888

Table 3.6 List of historical landfalling storm tracks in Bangladesh (1877-2003)

SL. No.	Year	No. of Land-falling Storms	Month of Occurrence	Location of Landfall	Reached Hurricane Intensity	Remarks
1	1877	4	6-8 August	Khulna	-	TD
2			8-9 August	Noakhali	-	TD
3			18-20 August	Khulna	-	TD
4			November	Cox's Bazar	-	TD
5	1879	1	October	Chittagong	-	TD
6	1881	1	May	Khulna	-	TD
7	1885	2	June	Khulna	-	TS
8			November	Chittagong	-	TS
9	1887	1	July	Barisal	-	TD
10	1888	1	October	Barisal	-	TS

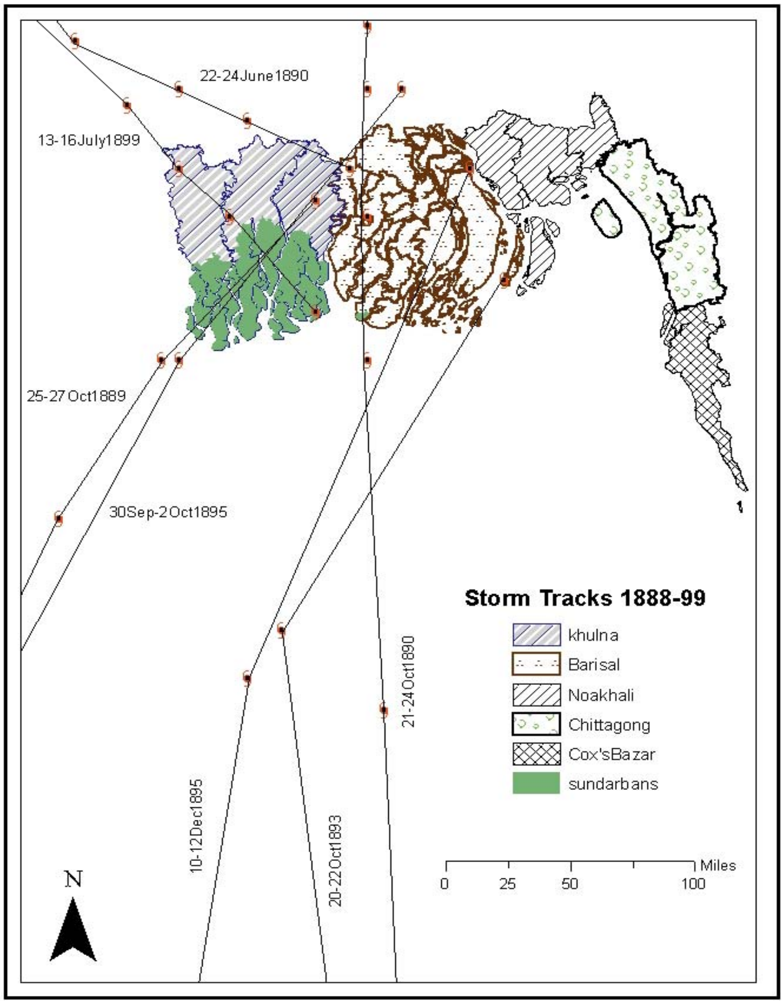

Figure 3.4 Storm tracks during 1888-1899

SL. No.	Year	No. of Land-falling Storms	Month of Occurrence	Location of Landfall	Reached Hurricane Intensity	Remarks
11	1889	1	October	Khulna	-	TS
12	1890	2	June	Khulna	-	TD
13			October	Barisal	-	TS
14	1893	1	October	Barisal	yes	Wind speed N/A
15	1895	2	September	Khulna	yes	Wind speed N/A
16			December	Barisal	yes	Wind speed N/A
17	1899	1	July	Khulna	-	TD

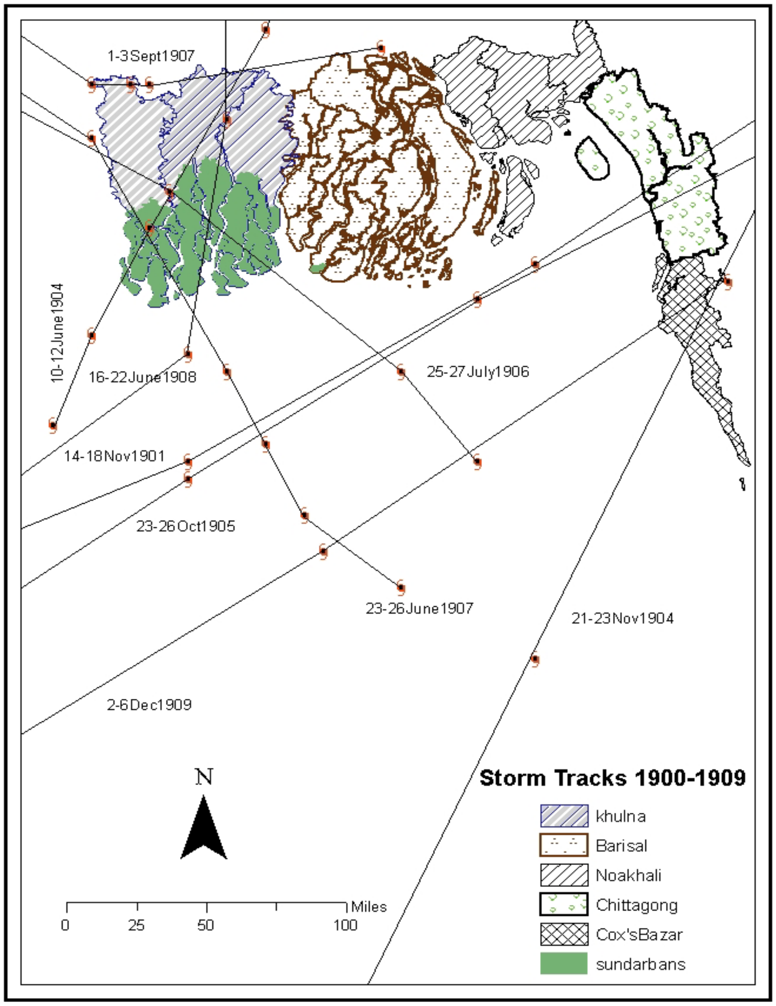

Figure 3.5 Storm tracks during 1900-1909

SL. No.	Year	No. of Land-falling Storms	Month of Occurrence	Location of Landfall	Reached Hurricane Intensity	Remarks
18	1901	1	November	Chittagong	-	TS
19	1904	2	June	Khulna	-	TD
20			November	Cox's Bazar	-	TS
21	1905	1	October	Chittagong	-	TS
22	1906	1	July	Khulna	-	TS
23	1907	2	June	Khulna	-	TS
24			September	Barisal	-	TD
25	1908	1	June	Khulna	-	TS
26	1909	1	December	Cox's Bazar	yes	Wind speed N/A

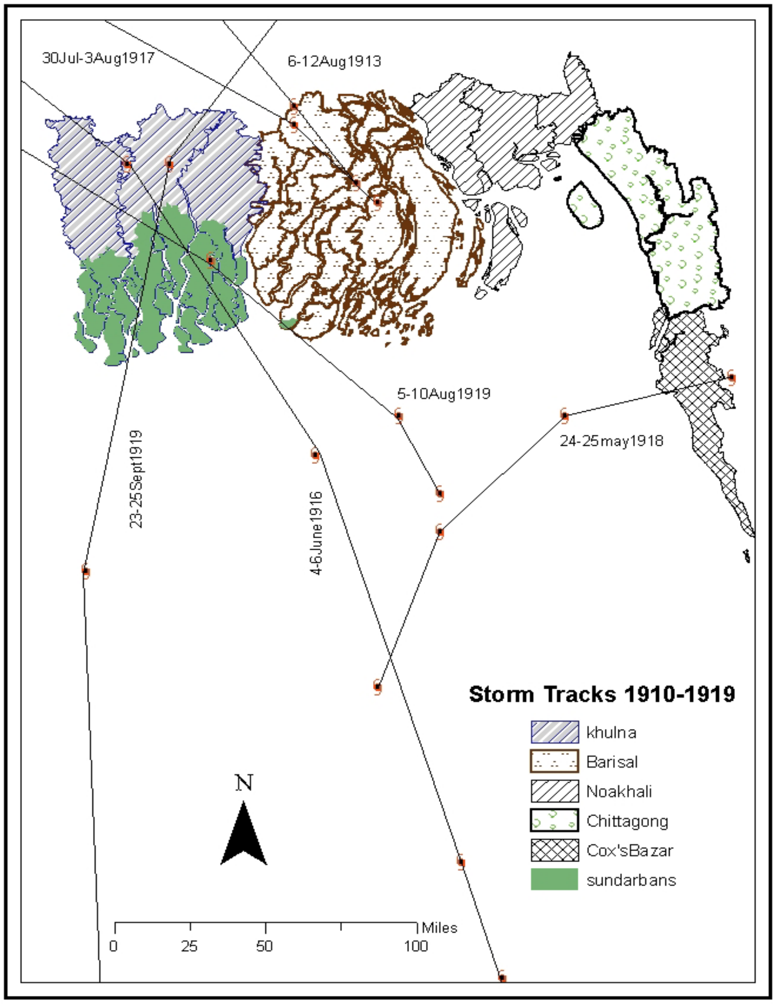

Figure 3.6 Storm tracks during 1910-1919

SL. No.	Year	No. of Land-falling Storms	Month of Occurrence	Location of Landfall	Reached Hurricane Intensity	Remarks
27	1913	1	August	Barisal	-	TD
28	1916	1	June	Khulna	-	TS
29	1917	1	July	Barisal	-	TD
30	1918	1	May	Cox's Bazar	-	TS
31	1919	2	August	Khulna	-	TD
32			September	Khulna	yes	Wind speed N/A

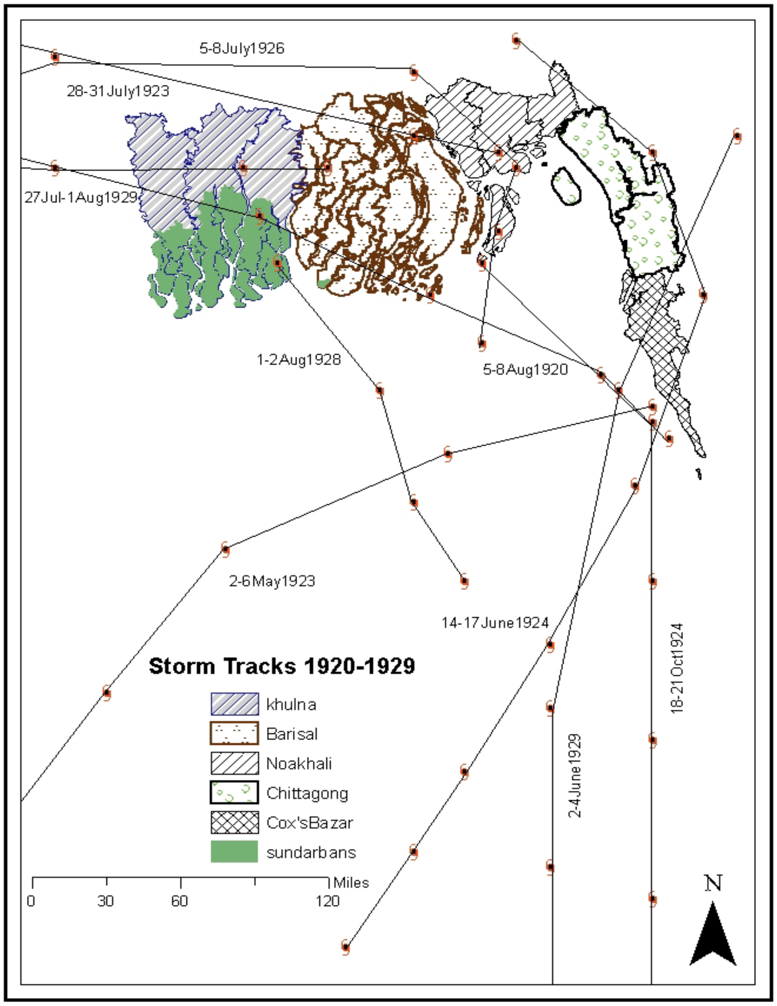

Figure 3.7 Storm tracks during 1920-1929

SL. No.	Year	No. of Land-falling Storms	Month of Occurrence	Location of Landfall	Reached Hurricane Intensity	Remarks
33	1920	1	August	Barisal	-	TD
34	1923	2	May	Cox's Bazar	yes	Wind speed N/A
35			July	Barisal	-	TD
36	1924	2	June	Cox's Bazar	-	TS
37			October	Barisal	-	TD
38	1926	1	July	Noakhali	-	TS
39	1928	1	August	Khulna	-	TD
40	1929	2	June	Cox's Bazar	-	TS
41			July	Barisal	-	TD

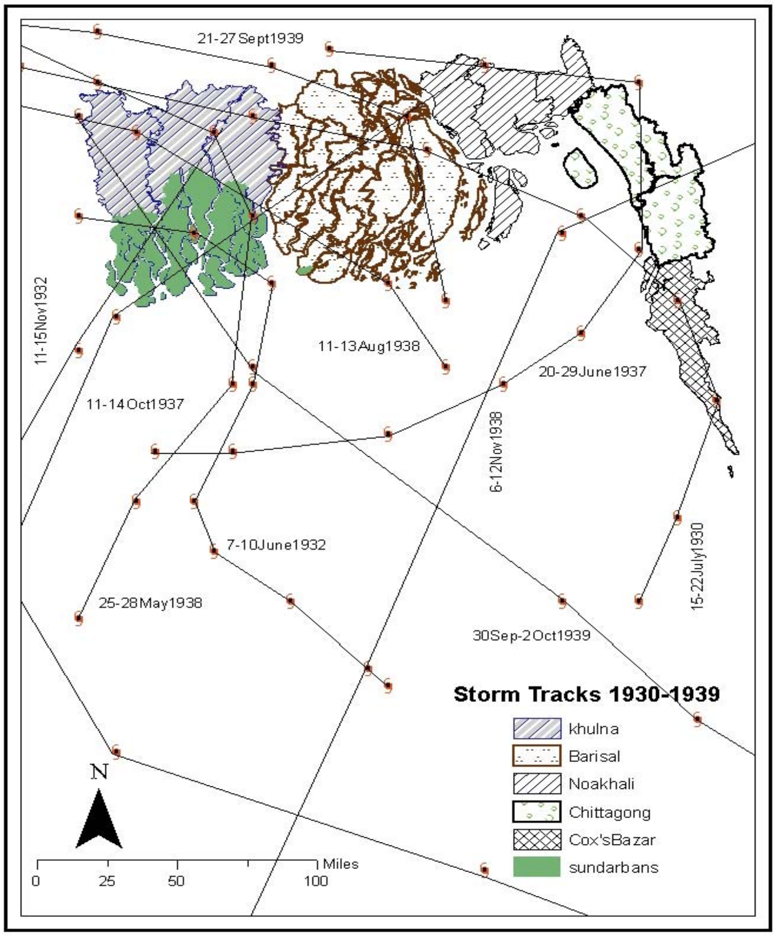

Figure 3.8 Storm tracks during 1930-1939

SL. No.	Year	No. of Land-falling Storms	Month of Occurrence	Location of Landfall	Reached Hurricane Intensity	Remarks
42	1930	1	July	Cox's Bazar	-	TS
43	1932	2	June	Khulna	-	TD
44			November	Khulna	-	TD
45	1937	2	June	Chittagong	-	TS
46			October	Khulna	-	TS
47	1938	3	May	Khulna	-	TD
48			August	Barisal	-	TD
49			November	Chittagong	yes	Wind speed N/A
50	1939	2	September	Barisal	-	TD
51			September	Khulna	-	TD

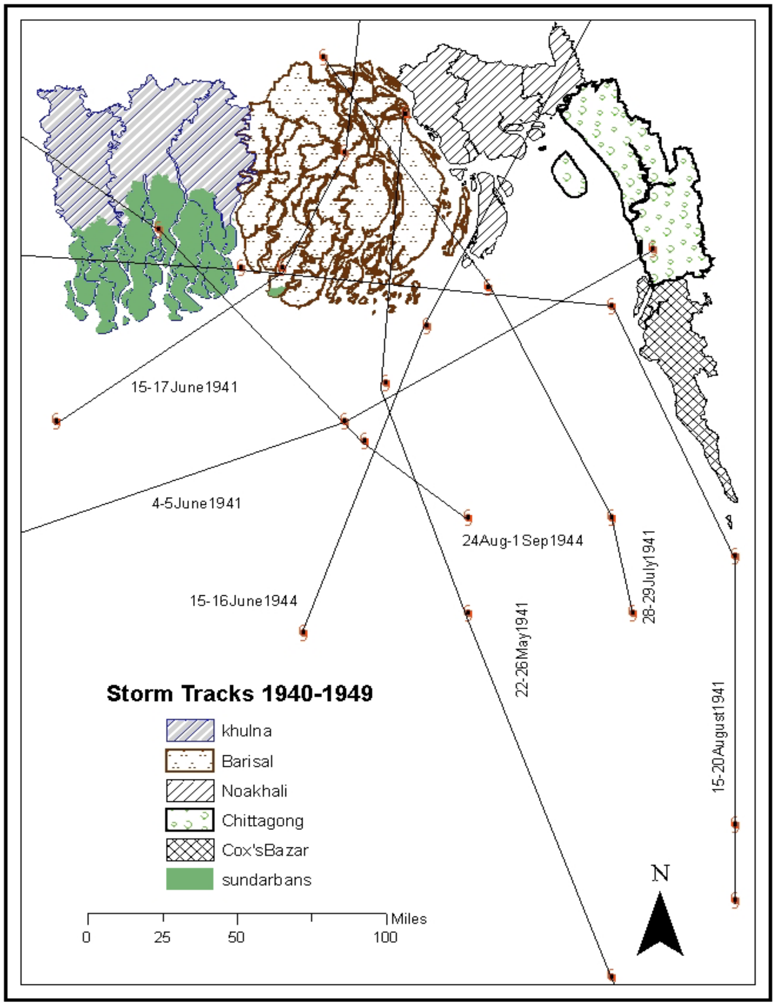

Figure 3.9 Storm tracks during 1940-1949

SL. No.	Year	No. of Land-falling Storms	Month of Occurrence	Location of Landfall	Reached Hurricane Intensity	Remarks
52	1941	5	May	Barisal	yes	Wind speed N/A
53			4-5 June	Chittagong	-	TS
54			15-17 June	Barisal	-	TD
55			July	Barisal	-	TD
56			August	Barisal	-	TS
57	1944	2	June	Noakhali	-	TD
58			August	Khulna	-	TD

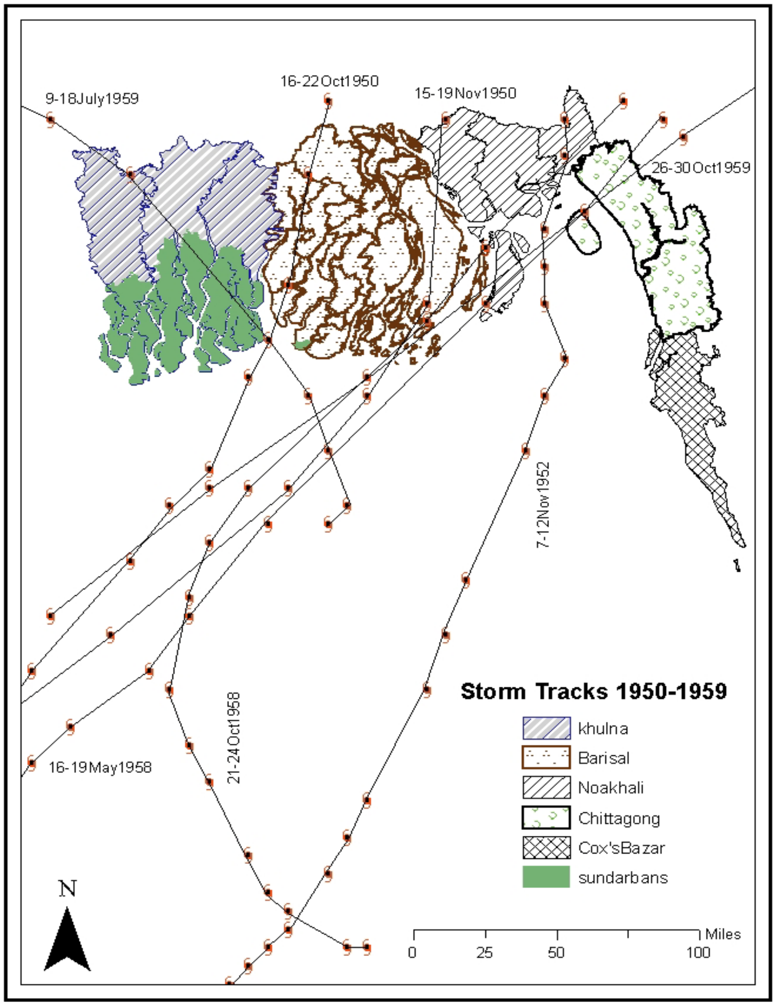

Figure 3.10 Storm tracks during 1950-1959

SL. No.	Year	No. of Land-falling Storms	Month of Occurrence	Location of Landfall	Reached Hurricane Intensity	Remarks
59	1950	2	October	Barisal	-	TD
60			November	Barisal	-	TS
61	1952	1	November	Noakhali	-	TD
62	1958	2	May	Noakhali	-	TS
63			October	Barisal	-	TD
64	1959	2	July	Khulna	-	TD
65			October	Chittagong	-	TD

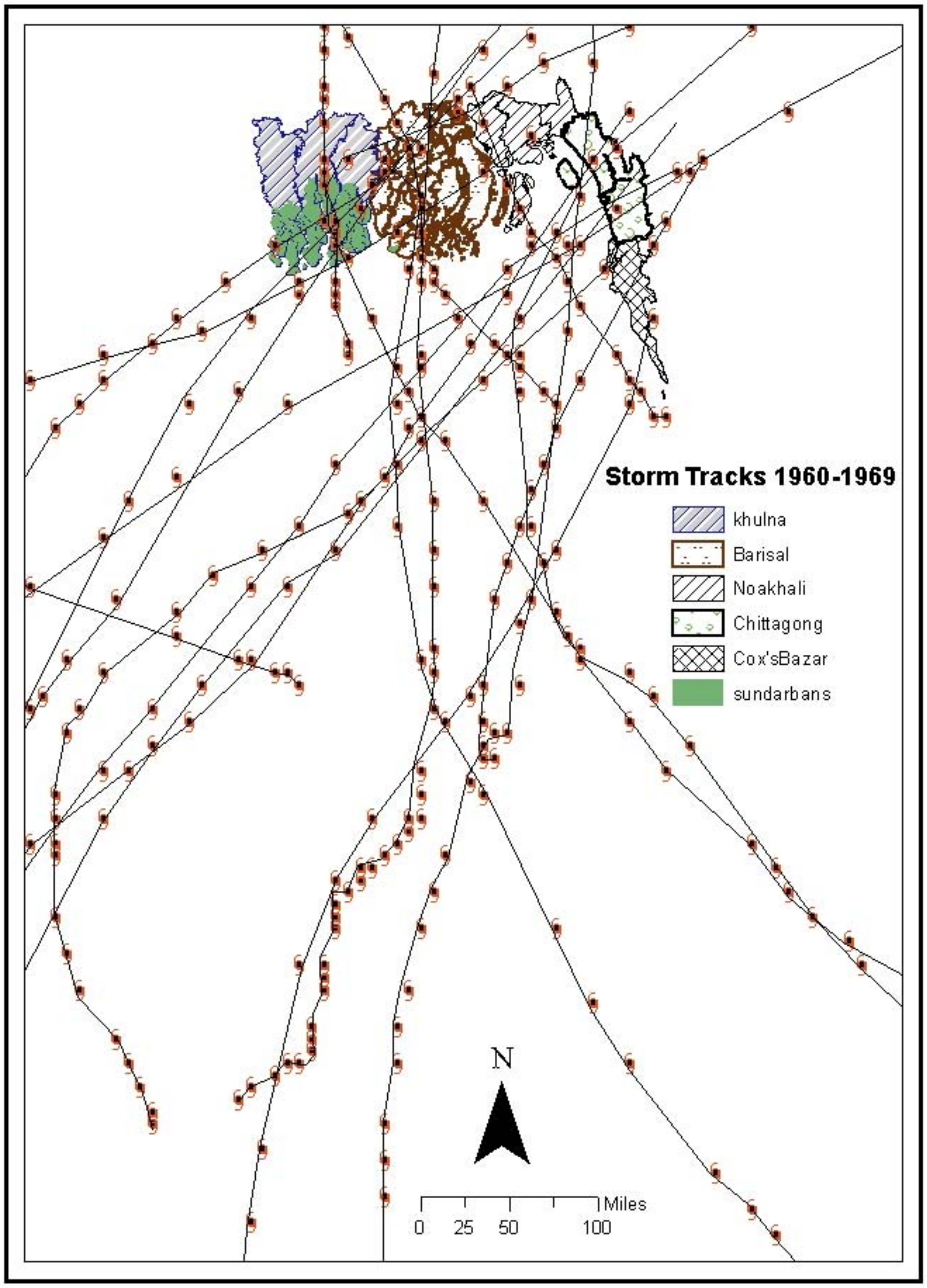

Figure 3.11   Storm tracks during 1960-1969

SL. No.	Year	No. of Land-falling Storms	Month of Occurrence	Location of Landfall	Reached Hurricane Intensity	Remarks
66[1]	1960	2	7-11 October	Noakhali	yes	64kt
67			27-31October	Chittagong[2]	yes	83kt
68	1961	3	4-9 May	Barisal	-	TS (60kt)
69			27-30 May	Chittagong	-	TS
70			October	Noakhali	-	TD
71	1962	1	October	Chittagong	-	TS
72	1963	2	May	Chittagong	yes	130kt
73			October	Khulna	-	TD
74	1964	1	October	Barisal	-	TD
75	1965	4	9-12 May	Khulna	-	TS
76			26-31 May	Barisal	yes	Wind speed N/A
77			October	Cox's Bazar	-	TD
78			December	Cox's Bazar	yes	120kt
79	1966	2	September	Khulna	-	TS (50kt)
80			December	Chittagong	-	TS
81	1967	2	7-11 October	Barisal	-	TS
82			19-23 October	Cox's Bazar	-	TS
83	1968	1	June	Khulna	-	TD
84	1969	2	June	Chittagong	-	TS
85			October	Khulna	-	TS

[1] Storm track is not shown in Figure 3.11 as latitude/longitude coordinates are not available. Landfall location is assumed based on the UNISYS dataset and from the CRED disaster database.

[2] Track data from the GTCCA is incomplete and suggests that the storm did not make landfall. But in CRED dataset, deaths and damages were reported from Chittagong. So, it is assumed that the storm hit the coast of Chittagong.

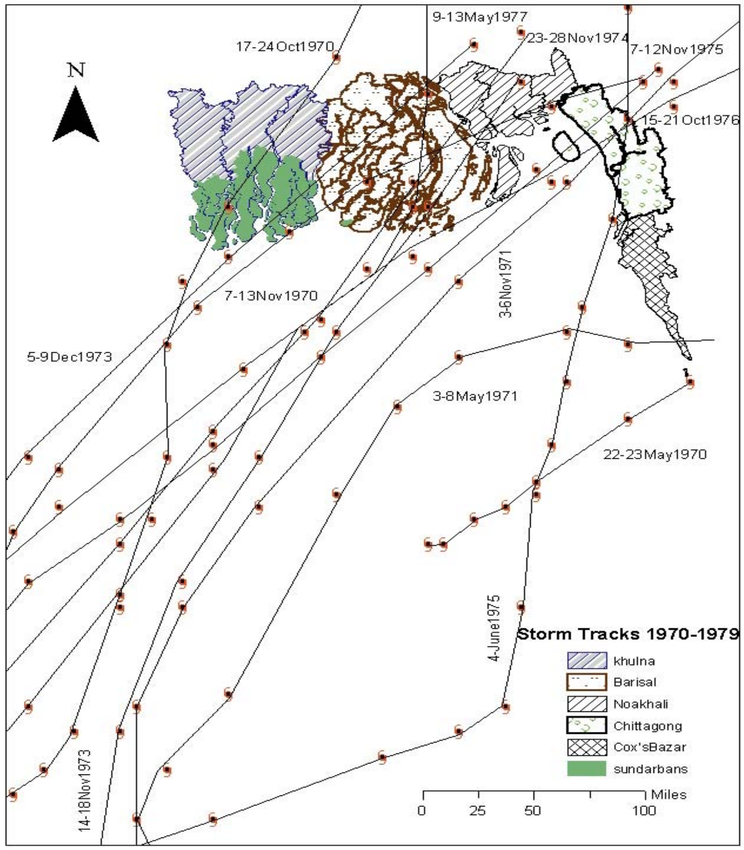

Figure 3.12 Storm tracks during 1970-1979

SL. No.	Year	No. of Land-falling Storms	Month of Occurrence	Location of Landfall	Reached Hurricane Intensity	Remarks
86	1970	3	May	Cox's Bazar	-	TS
87			October	Khulna	-	TS
88			November	Barisal	yes	130kt
89	1971	2	May	Cox's Bazar	-	TS
90			November	Chittagong	yes	Wind speed N/A
91	1973	2	November	Barisal	-	TS (55kt)
92			December	Khulna	yes	70kt
93	1974	1	November	Barisal	yes	75kt
94	1975	2	June	Chittagong	-	TS
95			November	Chittagong	-	TS (50kt)
96	1976	1	October	Chittagong	-	TS (50kt)
97	1977	1	May	Barisal	-	TS (60kt)

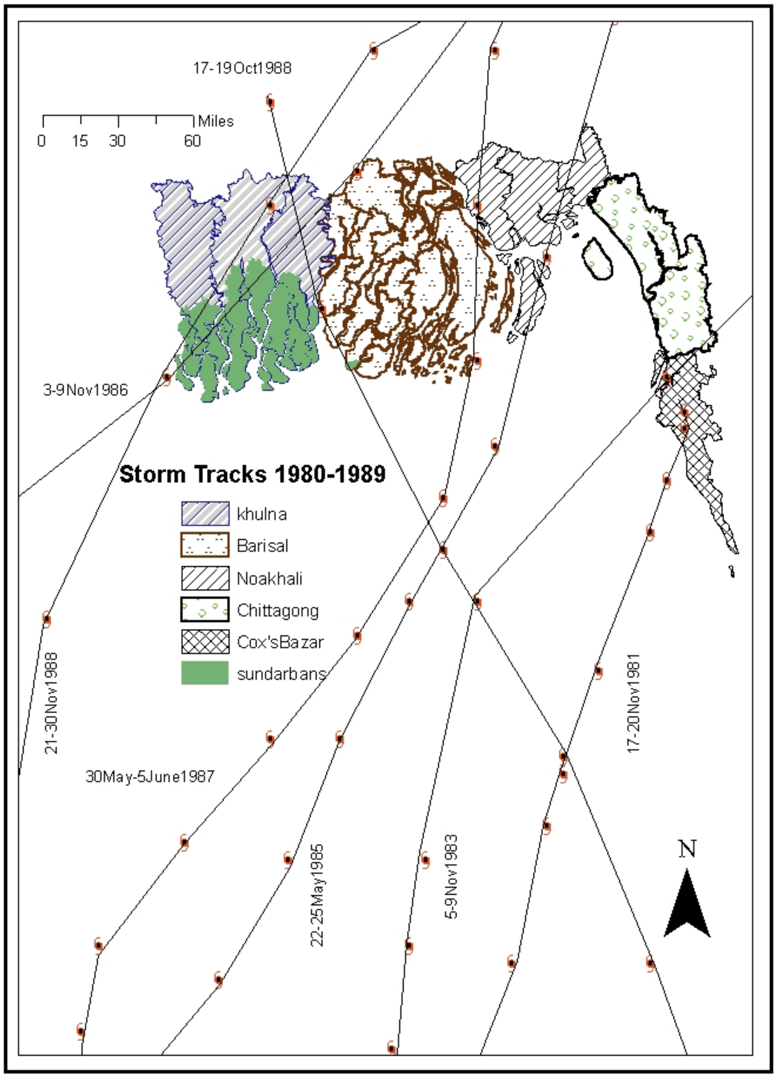

Figure 3.13 Storm tracks during 1980-1989

SL. No.	Year	No. of Land-falling Storms	Month of Occurrence	Location of Landfall	Reached Hurricane Intensity	Remarks
98	1981	1	November	Cox's Bazar	yes	75kt
99	1983	1	November	Cox's Bazar	-	TS (55kt)
100	1985	1	May	Noakhali	-	TS (60kt)
101	1986	1	November	Khulna	-	TS (50kt)
102	1987	1	June	Barisal	-	TS (55kt)
103	1988	2	October	Khulna	-	TS (35kt)
104			November	Khulna	yes	110kt

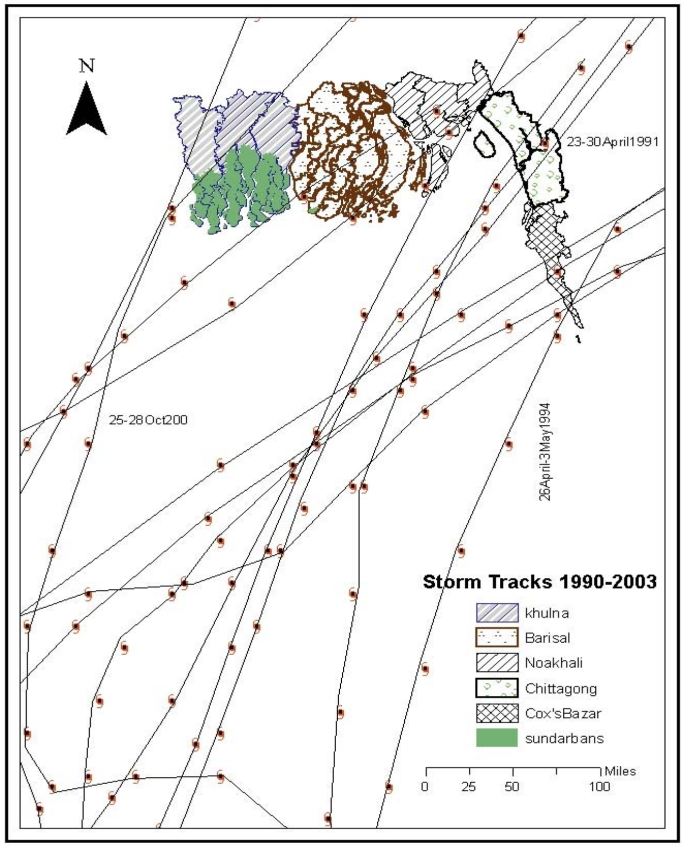

Figure 3.14 Storm tracks during 1990-2003

SL. No.	Year	No. of Land-falling Storms	Month of Occurrence	Location of Landfall	Reached Hurricane Intensity	Remarks
105	1990	1	December	Cox's Bazar	-	TS (45kt)
106	1991	2	April	Chittagong	yes	140kt
107			May	Noakhali	-	TS (50kt)
108	1992	1	October	Cox's Bazar	-	TS
109	1994	1	April	Cox's Bazar	yes	125kt
110	1995	1	November	Cox's Bazar	yes	105kt
111	1996	2	May	Cox's Bazar	-	TS (40kt)
112			October	Khulna	-	TS (45kt)
113	1997	2	May	Chittagong	yes	115kt
114			September	Barisal	yes	65kt
115	1998	2	May	Chittagong	yes	70kt
116			November	Khulna	yes	75kt
117	2000	1	October	Khulna	-	TS (35kt)

3.5 Climatology of landfalling tropical cyclones in Bangladesh (1877-2003)

A total of 117 tropical cyclones hit the coast of Bangladesh from 1877 to 2003 of which 39 are tropical depressions (TD), 52 are tropical storms (TS) and 26 reach hurricane intensity.

In the past century (1901-2000), the rate of tropical storms striking the coast is 10 storms/decade (Figure 3.15), or one storm per year. Since 1950, the rate of landfalling tropical storms in this area has increased (Figure 3.16), 1.18 per year for 1950-2000. Figure 3.15 shows that the rate has vacillated in the last century. The first rise is from 1920 up to 1939. The second is from 1959 up to 1969. Presently, there is an increasing trend again.

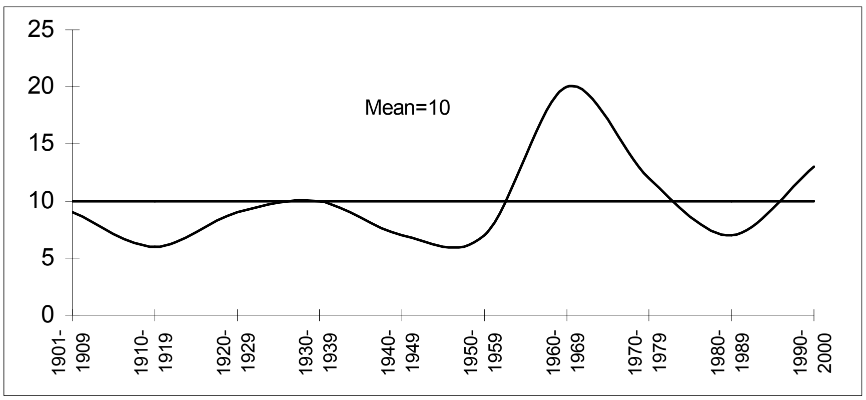

Figure 3.15 Frequency of storms in 10-year period from 1901-2000

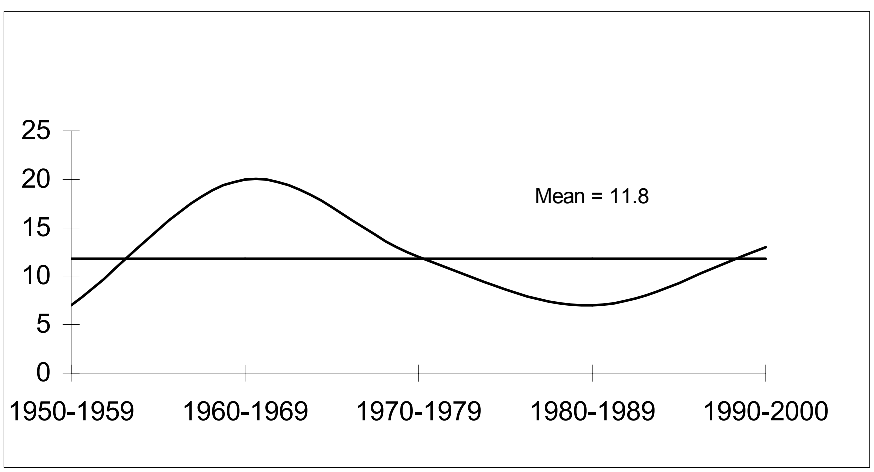

Figure 3.16 Frequency of storms in 10-year period from 1950-2000

Figure 3.17 shows the percentage of the frequency of major hurricanes during 1877-2003. 50% of the hurricanes are in Category 1, which means the wind speed range is 64-83 kt according to the Saffir-Simpson Hurricane Scale. The next largest group is Category 4 hurricanes (wind speed 114-135 kt), which is 31% of the total. (Here, the total number of hurricanes is 16 instead of 26, as the corresponding wind speeds of the earlier hurricanes are not available). During the 127 years (1877-2003), only one tropical cyclone (6%) is found as a Category 5 hurricane (wind speed > 135 kt). This was the 1991 'Super Cyclone'(140 kt) that struck the Chittagong coast on 29 April and killed 138,866 people. The 12 November 1970 cyclone that killed more than 300,000 people was a Category 4 hurricane (130 kt).

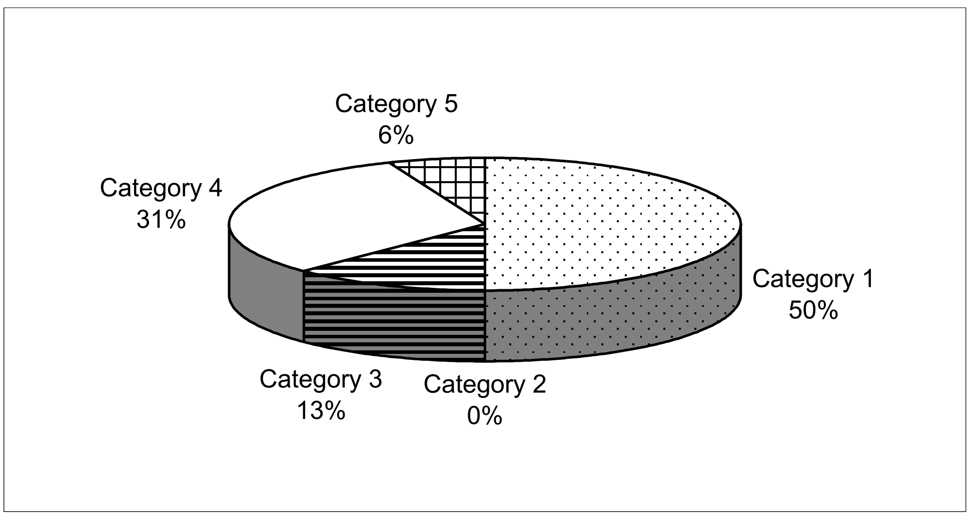

Figure 3.17 Frequency distribution of the major hurricanes 1877-2003

By landfall locations, the greatest number of hits, 36, is faced by the Khulna coast, which is located in the south-west corner of Bangladesh. This accounts for 31% of the total hit of tropical storms in Bangladesh in 1877-2003. The next subdivision is Barisal, where 31 tropical storms hit during 1877-2003 period, which is 26% of the total landfalling tropical storms. Chittagong and Cox's Bazar are very close to each other by the number of hits, 21 and 20, which are 18% and 17%, respectively, of the total number of landfalling tropical storms. The lowest number of tropical storms hit the Noakhali segment, 9, which is only 8% of the total number of landfalling storms (Figure 3.18).

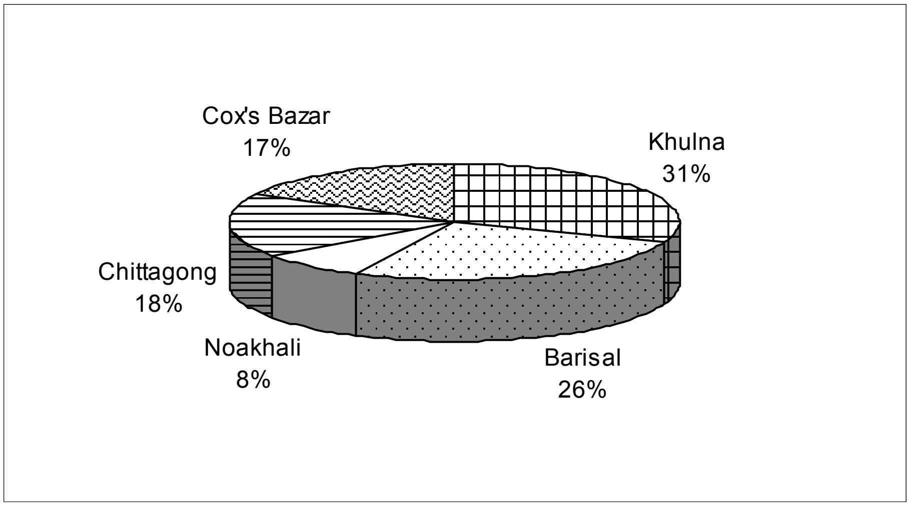

Figure 3.18 Percentage of landfalling tropical storms in different coastal segments

Table 3.7 shows the number of deaths from the cyclones in different coastal segments of Bangladesh from 1904-2000. The International Disaster Database of CRED is the primary source of this information.

Table 3.7 Number of cyclone deaths in Bangladesh 1904-2000

Coastal Subdivision	Number of Deaths
Khulna	5,267
Barisal	354,326
Noakhali	25,616
Chittagong	157,445
Cox's Bazar	413
Total	**543,067**

Barisal and Chittagong subdivisions experienced a large number of deaths compared to the other coastal segments mainly due to the 1970 and 1991 super cyclones. The former hit the Barisal coast and around 300,000 people died; the latter made landfall at Chittagong and caused 138,866 deaths. Ironically, Khulna experienced fewer deaths compared to the number of storms hit. The key mitigating factor is the location of the Sundarbans forest in this segment, which works as a shield against the wind and storm surge of tropical cyclones. Effective land-use is, therefore, very important to the reduction of hurricane damage. Cox's Bazar experienced the fewest deaths. Low population density might be one of the reasons for fewer casualties. A comparative picture of the number of storm hits and the number of cyclone deaths for different coastal segments is shown on a logarithmic scale in Figure 3.19.

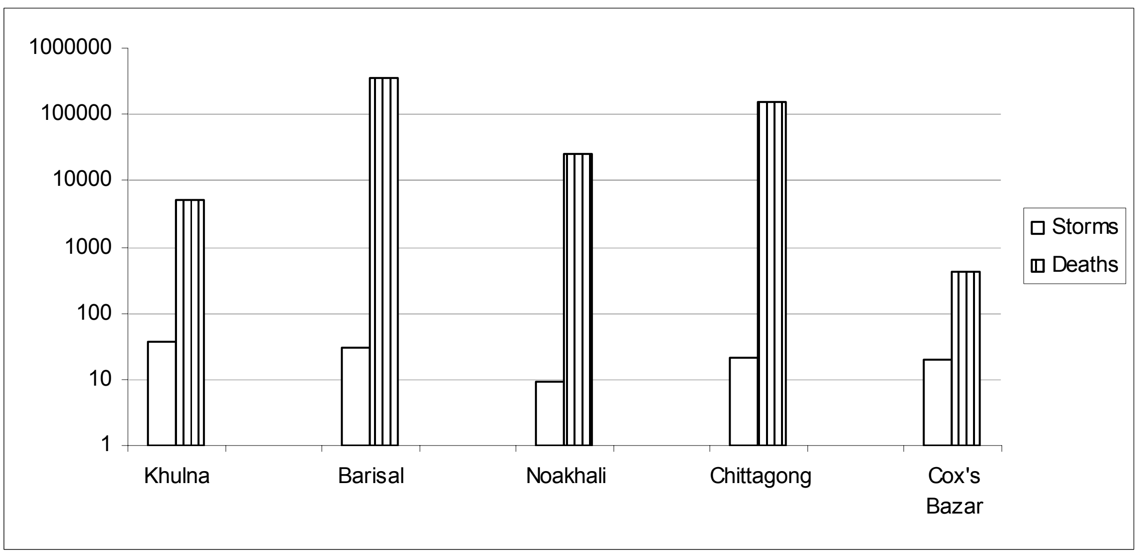

Figure 3.19 Number of storms hit and number of deaths by coastal subdivisions

Figure 3.20 shows the monthly distribution of land falling storms during 1877-2003. Cyclonic disturbances are absent for January through March but frequently occur during the pre- and post-monsoon seasons with some activities also in the monsoons.

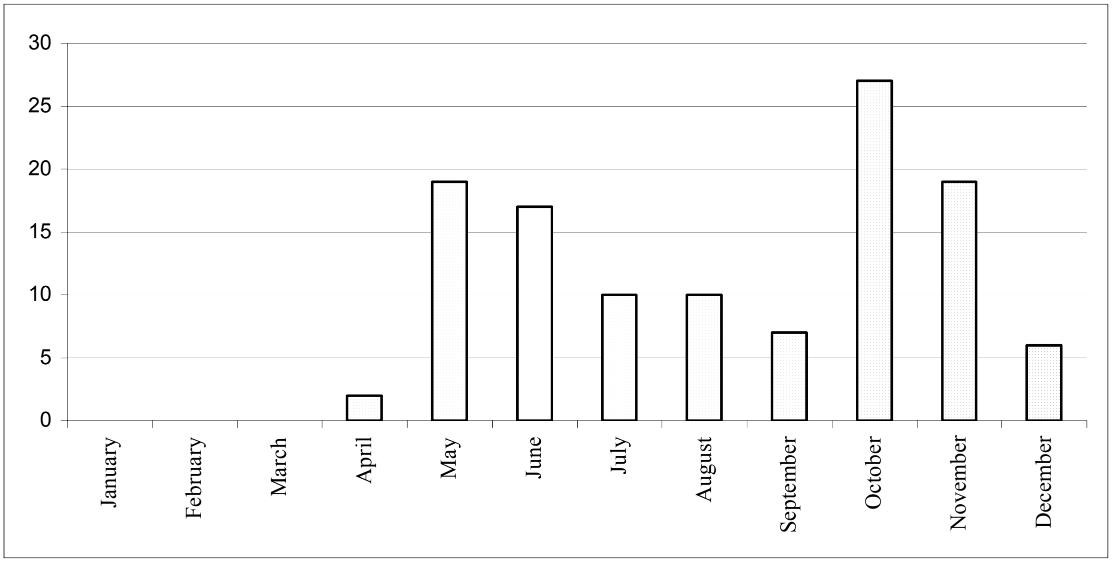

Figure 3.20 Monthly distributions of landfalling tropical storms 1877-2003

The high frequencies in May and October represent the peaks of the storm seasons. During the months of May and June, before the start of the monsoon season, and during the months of October and November, after the monsoon, the average sea surface temperature in the Bay of Bengal region rises to approximately 27°C (80°F) and the weather conditions become ideal for the formation of tropical cyclones. Most of the hurricanes form during these periods. Out of the 26 hurricanes found in this study, 19 (73%) made landfall during these months. We can, therefore, define two annual hurricane seasons for Bangladesh, pre-monsoon and post-monsoon.

Gray (1968) in his seminal paper indicated the influence of the location of the Equatorial Trough for the two maxima of seasonal storm development (associated with the onset and retreat of monsoon) in the Bay of Bengal. He mentioned that frequency of development is largest when the Equatorial Trough is displaced farthest from the equator, i.e., in the months of May-June and October-November.

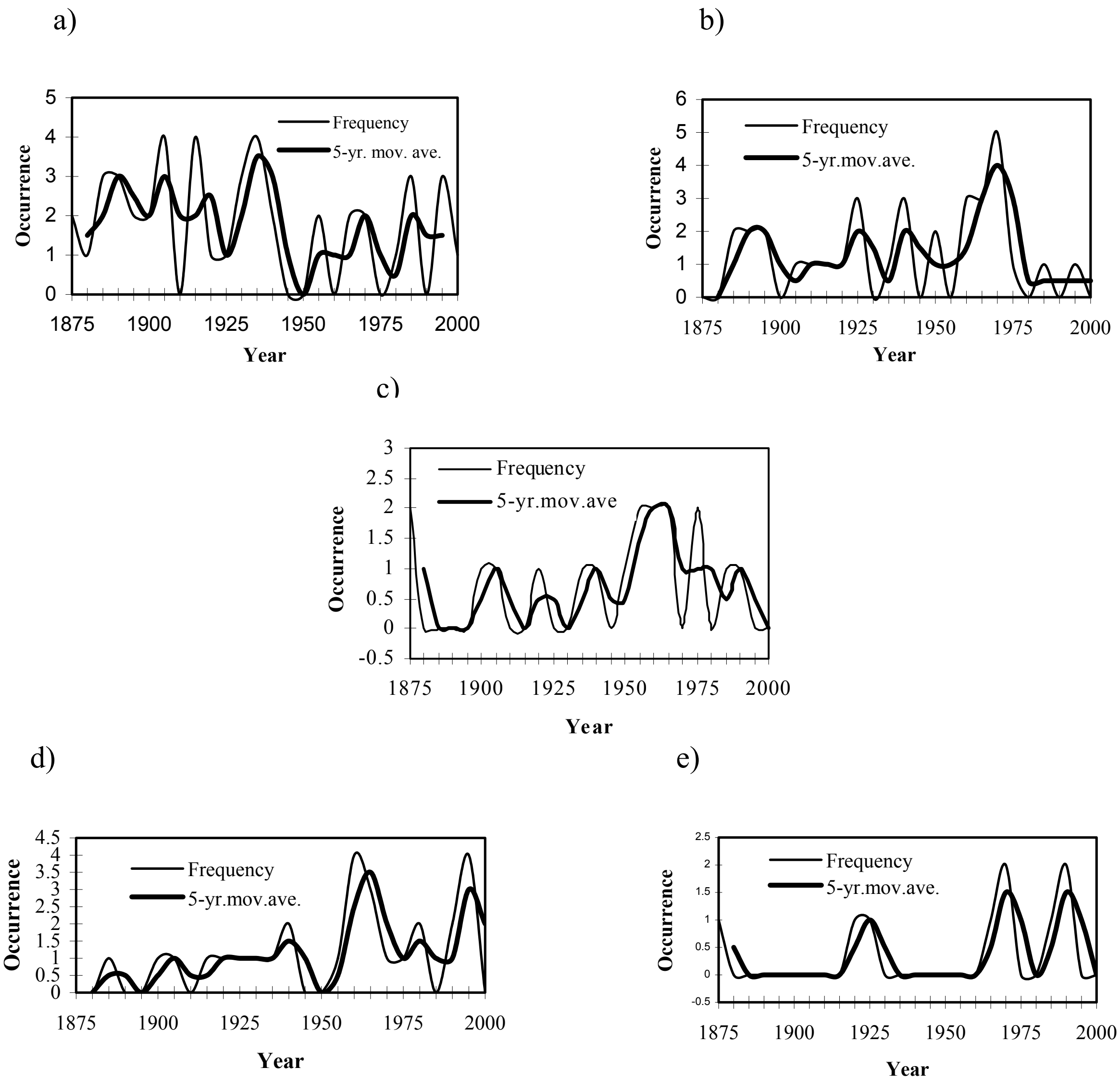

Figure 3.21. Frequencies and 5- year moving average of landfalling tropical cyclones of different coastal segments: a) Khulna, b) Barisal, c) Noakhali, d) Chittagong, e) Cox's Bazar

The frequency of tropical cyclones and 5-year moving averages for different coastal segments are presented in Figure 3.21. There is not much difference between the frequency and 5-year moving average for all the coastal segments.

3.6 Summary

A climatological database for landfalling tropical storms has been established for the Bangladesh coast. The trend of tropical cyclones hitting the Bangladesh coast is not steady. It has vacillated in the past century. Presently, there is an increasing trend again.

Khulna coast is the most vulnerable in terms of cyclone hit. Barisal and Chittagong coasts are the most vulnerable in terms of cyclone casualties. Cyclonic disturbances are absent in January, February and March. Most of the tropical cyclones with hurricane winds strike the coast of Bangladesh during the pre- and post-monsoon periods, thus, establishing two annual hurricane seasons for the country.

CHAPTER IV
CYCLONE WIND ANALYSIS

4.1 Selection of test sites

In the present study, five coastal sites have been selected at approximately equal interval of 40-50 miles. The actual sites where the Monte Carlo simulations are performed are depicted by 'X' in Figure 4.1. However, all of these five sites fall within the existing and old district lines of the five popularly known regions. These are Khulna, Barisal, Noakhali, Chittagong and Cox's Bazar (Figure 4.1). In Chapter III, these regional boundaries are used to assign landfall locations in order to develop the landfalling tropical cyclone climatology. Since storm data for a particular coastal spot in Bangladesh is hardly available, it is assumed that the statistics extracted from the cyclone climatology for the five regions would be applicable to these five selected sites. Accordingly, it is also assumed that the results drawn from the Monte Carlo simulations among these five coastal sites would represent respectively the five coastal regions mentioned above. The latitudes and longitudes of the selected sites to carry out the Monte Carlo simulations are given in Table 4.1.

Table 4.1 Sites with their latitudes and longitudes (NIMA nautical chart)

Site	Latitude (°N)	Longitude (°E)
Khulna	21.48	89.25
Barisal	21.55	90.25
Noakhali	22.35	91.12
Chittagong	22.15	91.45
Cox's Bazar	21.27	92.00

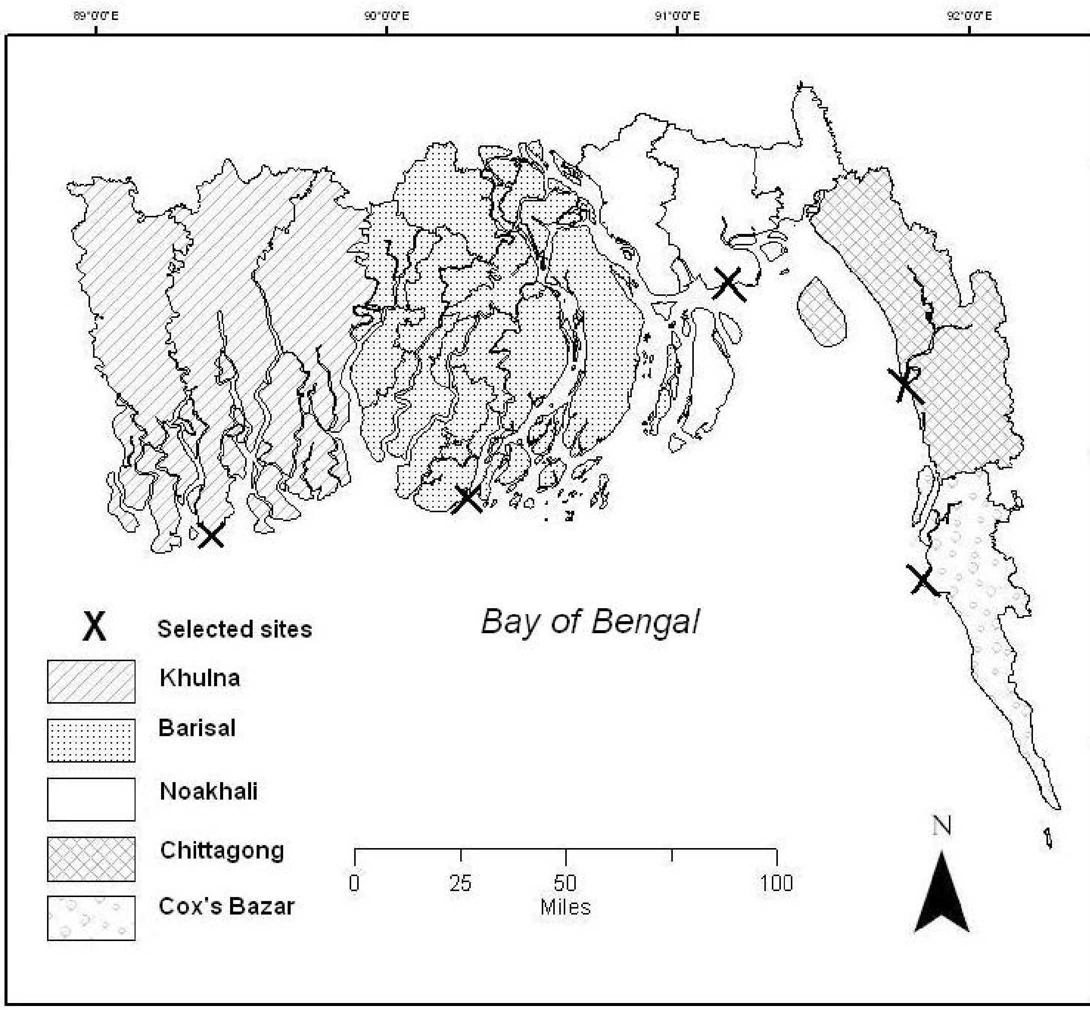

Figure 4.1 Sites used in the simulations

4.2 Wind field parameters

In order to carry out the Monte Carlo simulations, a wind field is needed to represent the landfalling cyclones. The Holland (1991) wind field model which is discussed in Chapter II, is chosen as the required wind field. The parameters needed to generate a hurricane wind field with the Holland model are: central pressure, radius of the maximum wind, storm heading or angle of attack, forward speed, pressure at the storm periphery and latitude of the site to be struck. The pressure at the storm periphery is held constant for all locations and all simulations at 1013.25 hPa (mean sea level pressure). Table 4.1 shows the latitudes and longitudes of the coastal sites read off from the National Imagery and Mapping Agency (NIMA) nautical chart # 63330: Raimangal River to Elephant Point.

Central pressure is the inherent characteristic of a storm and plays a vital role to fluctuate the strength of the storm. Since cyclones or hurricanes are developed in the deep ocean and can hit anywhere within the proximity irrespective of the geographic boundary, the central pressure data of all the hurricanes or major cyclones developed in the Bay of Bengal during 1877-1995 are included in this study.

Forward speed and storm heading can be influenced by the bathymetry or geographic condition of the landfall region. Thus, data for these two parameters are extracted from the landfalling tropical cyclone climatological database developed in Chapter III for Bangladesh during 1877-2003.

Radius of the maximum wind (RMW) is another important characteristic of a cyclone. Unfortunately, the GTCCA database which is the primary source of the climatology does not include the data of radius of the maximum wind of the associated storms. Attempts have been made to obtain the data of RMW of the Bay of Bengal cyclones from both the Indian Meteorological Department (IMD) and the Bangladesh Meteorological Department (BMD), but gone in vain. Finally, the data are collected from the *Statistical Year Book of Bangladesh 2000*, which lists all the major landfalling cyclones in Bangladesh including RMW only since 1981 provided by the Bangladesh

Meteorological Department. The statistical properties of the wind field parameters are discussed in the next section.

4.3 Statistical properties of the wind field parameters

4.3.1 Methodology

In order to use the data in the Monte Carlo simulations, probability density functions of the data of wind field parameters must be specified and a distribution table for each parameter needs to be created based on that. Best Fit 4.5 software found within the Palisade Decision Tools Software Package is used to find a best fit distribution to the collected data of each parameter. The Best Fit 4.5 gives best fit distribution based on three different methods. These are Chi-square, Kolmogorov-Smirnov and Anderson-Darling methods (Best Fit 4.5 help tutorial).

Chi-square: The Chi-Square test is the most common goodness-of-fit test. It can be used with sample input data and any type of distribution function (discrete or continuous). A weakness of the Chi-Square test is that there are no clear guidelines for selecting intervals or bins. In some situations, one can reach different conclusions from the same data depending on how the bins are specified.

Kolmogorov-Smirnov (K-S) Method: The Kolmogorov-Smirnov test does not depend on the number of bins, which makes it more powerful than the Chi-Square test. This test can be used with sample input data but cannot be used with discrete distribution functions. A weakness of the Kolmogorov-Smirnov test is that it does not detect tail discrepancies very well.

Anderson-Darling (A-D) Method: The Anderson-Darling test is very similar to the Kolmogorov-Smirnov test, but it places more emphasis on tail values. It does not depend on the number of intervals. The smaller the value of A-D statistic of a distribution, the more acceptable the distribution is as a best fit.

4.3.2 Distribution of the central pressure data

The data of central pressure are collected for all the major tropical cyclones developed in the Bay of Bengal during 1877-1995. As the central pressure is not influenced by the landfall region, it is assumed that the distribution would be applicable to all the five sites in Monte Carlo simulation. A logistic distribution curve is found the best fit in the A-D method (Figure 4.2).

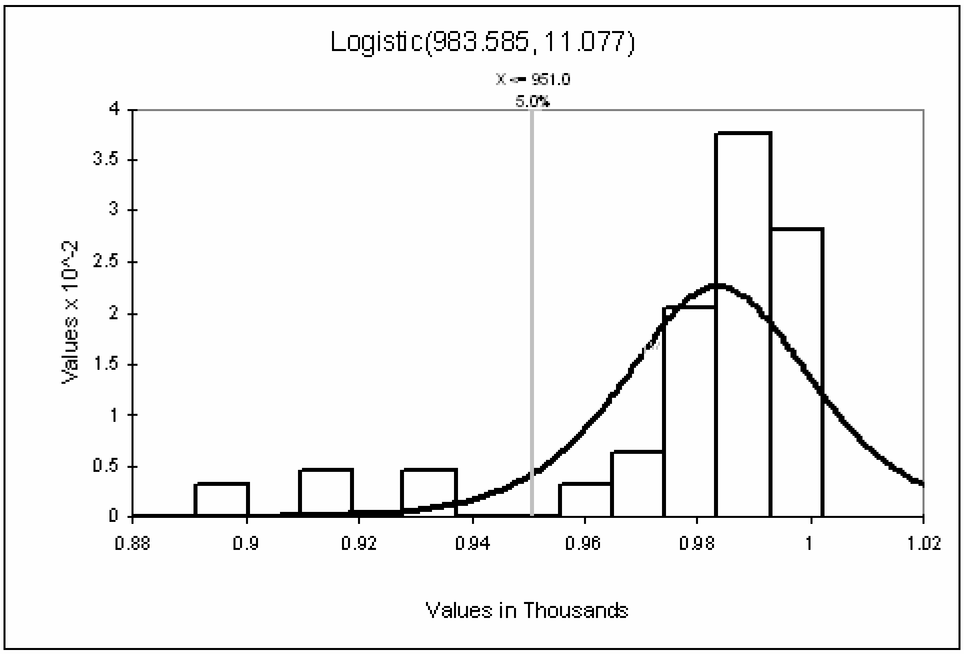

Figure 4.2 Probability distribution of central pressure data

The distribution of the central pressure data according to the best fit is given in the Table 4.2 in order to use it as input to generate simulated data.

Table 4.2 Central pressure distributions. Units are in millibars. The percentages represent the probability the central pressure will be less than the given value.

All Sites	**90%**	**70%**	**50%**	**30%**	**15%**	**5%**	**1%**	**lower bound**
C.P.	1002	994	983	975	965	933	916	890

From Table 4.2 at all sites, the central pressure is sampled such that there is a 10% chance of selecting a central pressure of 1002 mb, a 20% chance of selecting central pressure of 994, 983 or 975 mb, a 15% chance of selecting a central pressure of 965 mb, a 10% chance of selecting a pressure of 933 mb, a 4% chance of selecting a pressure of 916 mb, and only a 1% chance that a central pressure of 890 mb will be selected for any simulation.

4.3.3 Distribution of the storm heading data

The storm heading or the angle of attack data are collected for each of the five sites from 1877-2003. A beta distribution curve is the best fit for the storm heading data of Khulna in the K-S method (Figure 4.3). For Barisal, a Weibull distribution curve is found the best fit in both A-D and K-S methods (Figure 4.4). Again, the Weibull curve is the best fit for Noakhali in the K-S method (Figure 4.5). A logistic distribution curve is found the best fit for Chittagong in the Chi-square and A-D methods (Figure 4.6). The same curve is also found the best fit for Cox's Bazar in the K-S method (Figure 4.7).

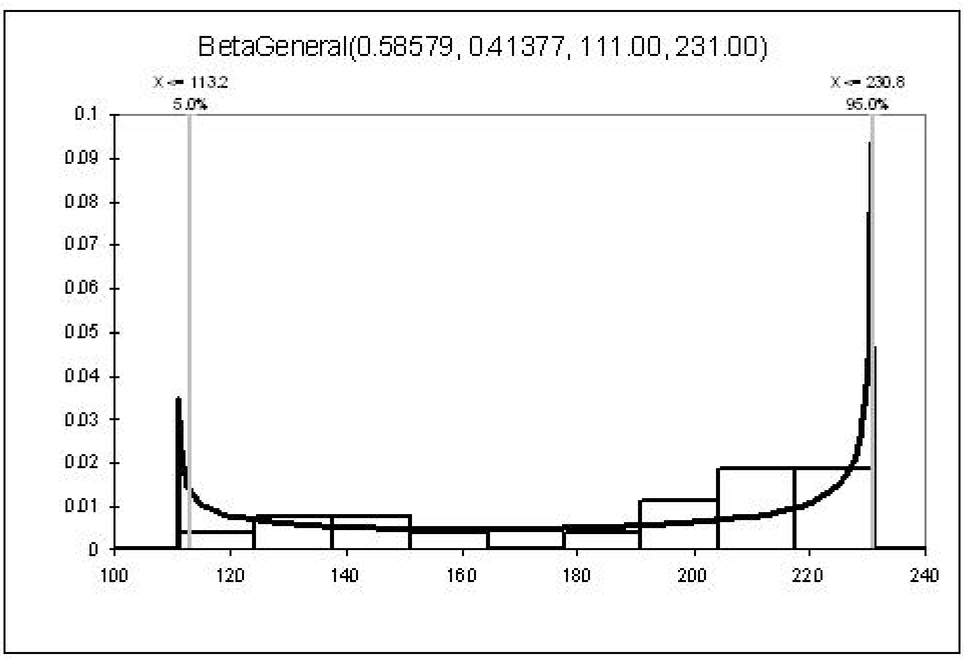

Figure 4.3 Probability distribution of storm heading data for Khulna

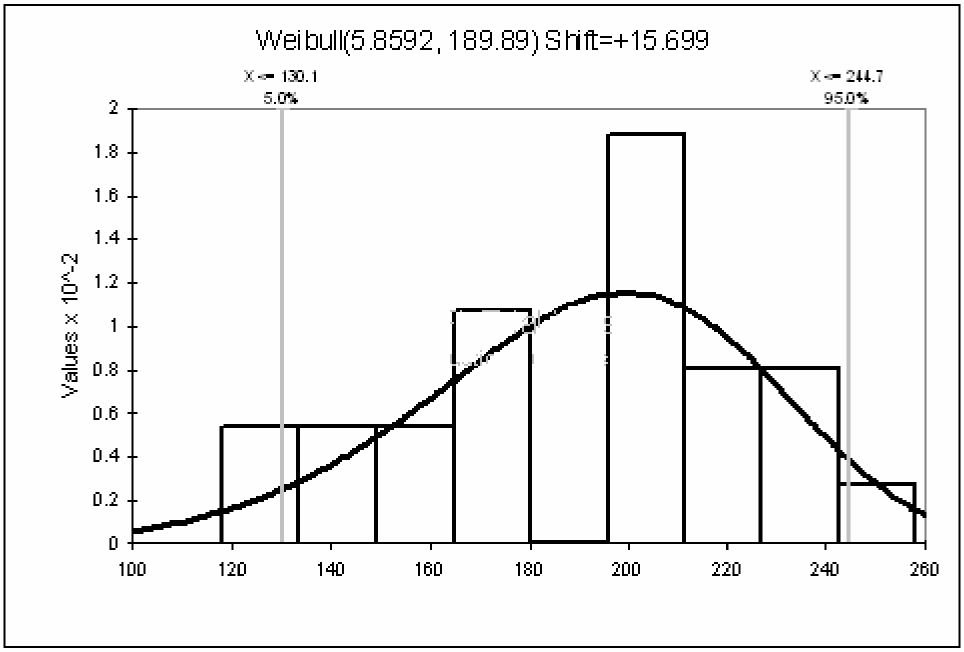

Figure 4.4 Probability distribution of storm heading data for Barisal

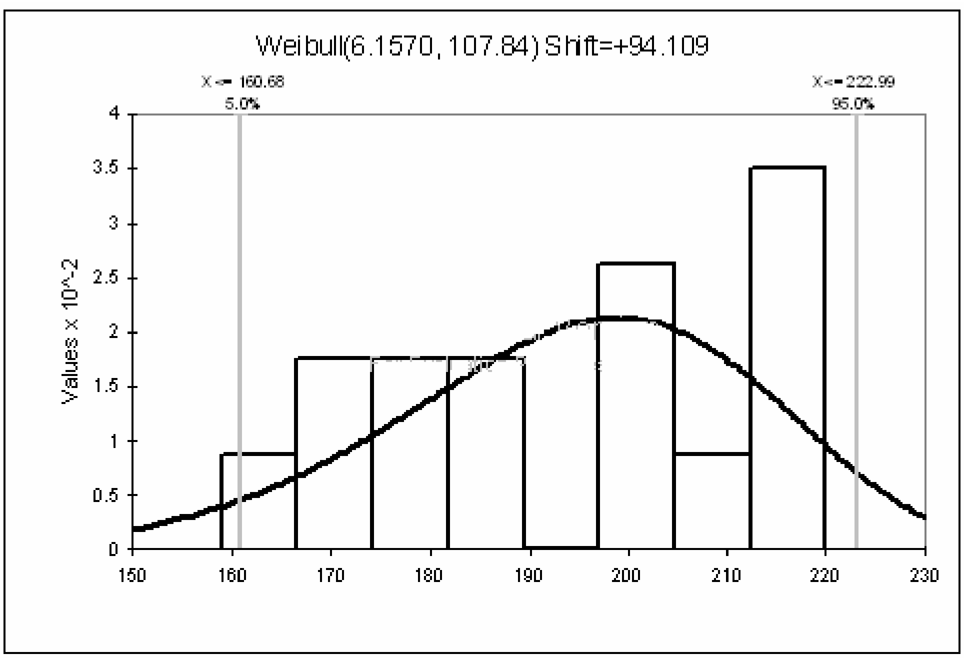

Figure 4.5 Probability distribution of storm heading data for Noakhali

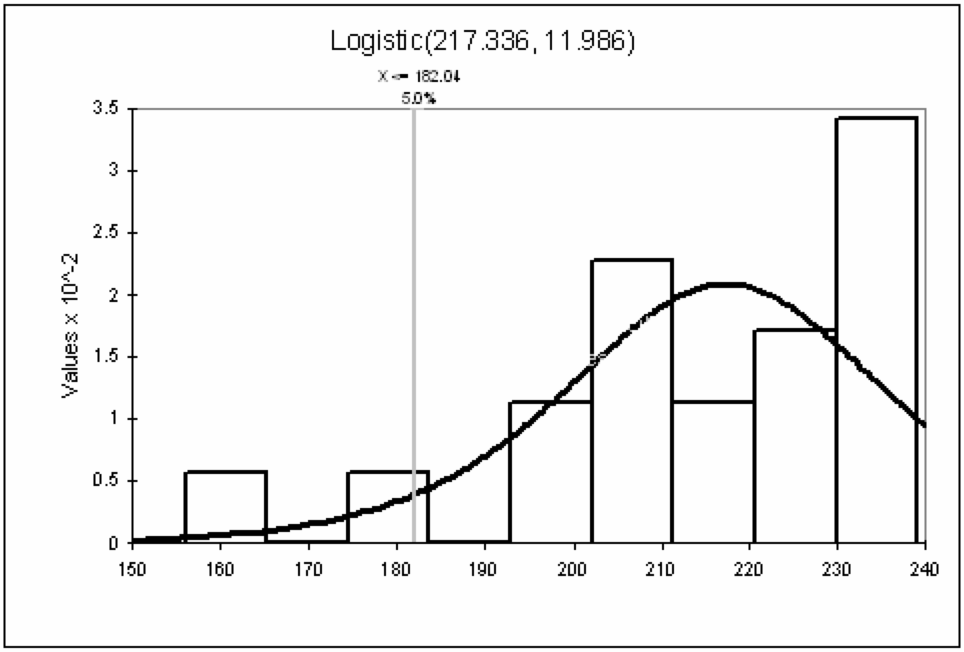

Figure 4.6 Probability distribution of storm heading data for Chittagong

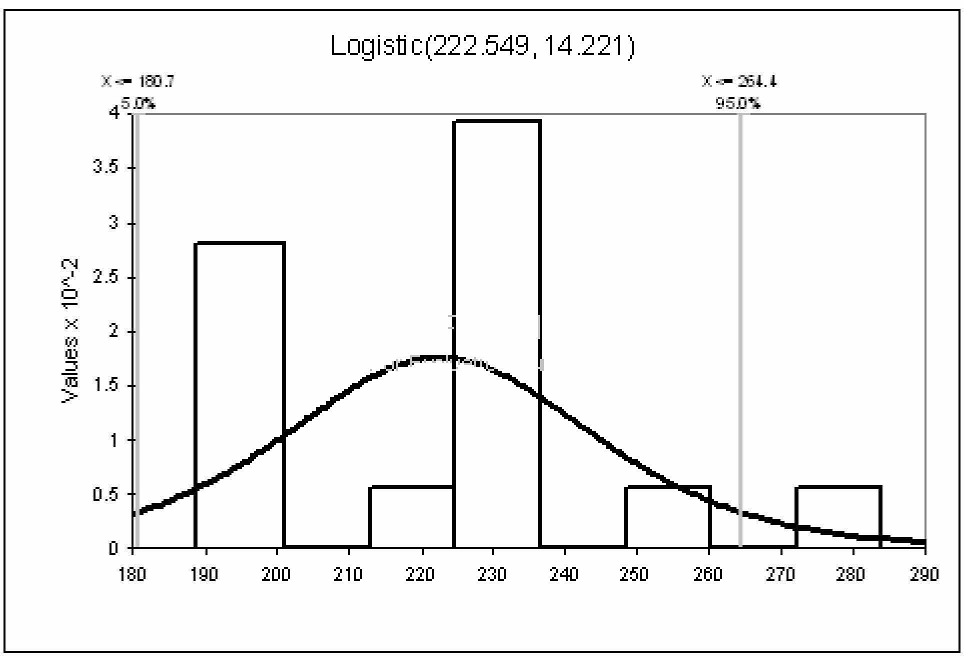

Figure 4.7 Probability distribution of storm heading data for Cox's Bazar

The distribution of the storm heading data for each of the five sites according to the best fits is given in Table 4.3.

Table 4.3 Storm heading distributions. Units are in degrees clockwise from north with 180º being a heading from the south. The percentages represent the probability the storm heading will be less than the given value.

Site	95%	83.33%	50%	16.67%	5%	lower bound
Khulna (Beta)	222	213	204	135	120	111
Barisal (Weibull)	244	226	194	157	130	118
Noakhali (Weibull)	222	212	196	176	159	94
Chittagong (Logistic)	252	236	217	198	182	130
Cox'sBazar (Logistic)	264	245	222.5	199	180	95

From Table 4.3 at Khulna, the storm heading is sampled such that there is a 5% chance of selecting a storm heading of 222º, a 11.67% chance of selecting a storm heading of 213º, a 33.33% chance of selecting a storm heading of 204º, a 33.34% chance of selecting a storm heading of 135º, a 11.66% chance of selecting a storm heading of 120º, and a 5% chance that a storm heading of 111º will be selected for any simulation. (The directions are in the meteorological system, where 0º is a storm that moves out of the true north, 90º is a storm moves from east to west, 180º is a storm which moves from south to north, etc.) The same process is used in selecting the storm heading for all of the other sites.

In the Table 4.4, the orientation of the sites along with the Bangladesh coastline is given. The units are in degrees clockwise from north with 180º being a heading from the south. The values in the table represent the direction of a storm approaching to impact the site normally, i.e., perpendicular to the shore.

Table 4.4 Orientation of the sites

Sites	Orientation (degrees)
Khulna	185
Barisal	195
Noakhali	165
Chittagong	235
Cox’s Bazar	240

In the simulations, once the storm heading for each storm is determined using Table 4.3 as input data, the approach angle to the shoreline is calculated using the orientation of the sites given in Table 4.4. The difference between the site orientation and the selected storm heading results in the angle of the storm is from making a normal landfall.

4.3.4 Distribution of the forward speed data

The forward speed data are also collected for each of the five sites from 1877 to 2003. A Weibull distribution curve is the best fit for the forward speed data of Khulna in the Chi-square method (Figure 4.8). For Barisal, a normal distribution curve is found the best fit in both Chi-square and A-D methods (Figure 4.9). Again, the normal distribution curve is the best fit for Noakhali in the A-D method (Figure 4.10). A loglogistic distribution curve is found the best fit for Chittagong in both A-D and K-S methods (Figure 4.11) and the Weibull curve is found the best fit for Cox’s Bazar in the K-S method (Figure 4.12).

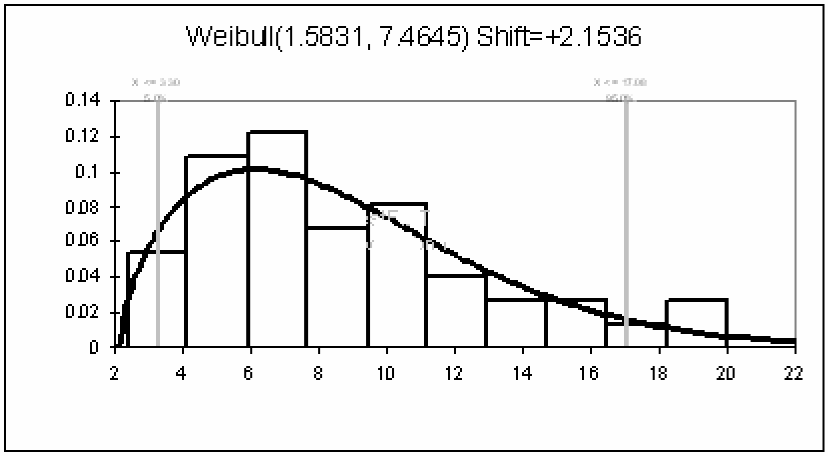

Figure 4.8 Probability distribution of forward speed data for Khulna

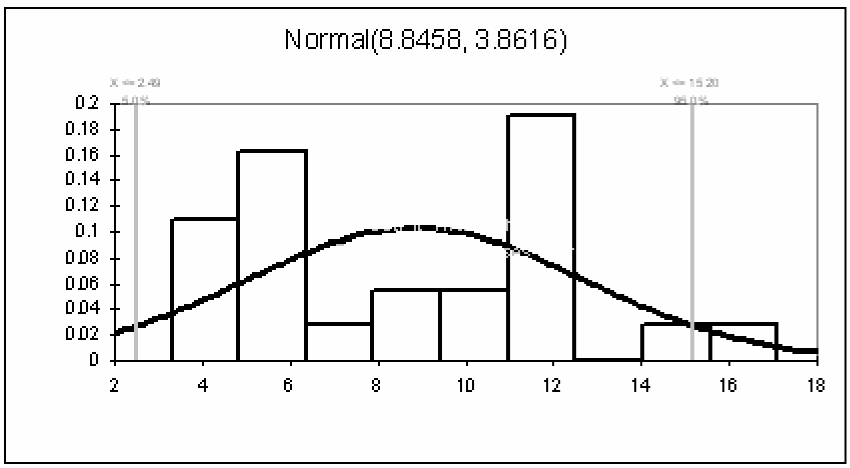

Figure 4.9 Probability distribution of forward speed data for Barisal

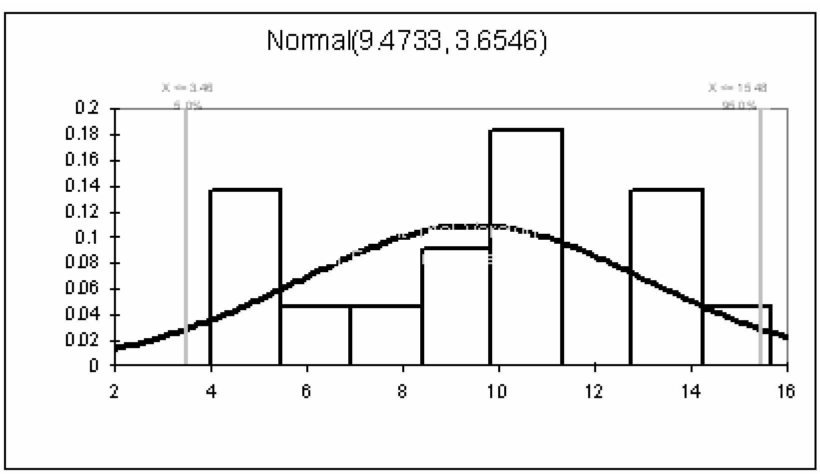

Figure 4.10 Probability distribution of forward speed data for Noakhali

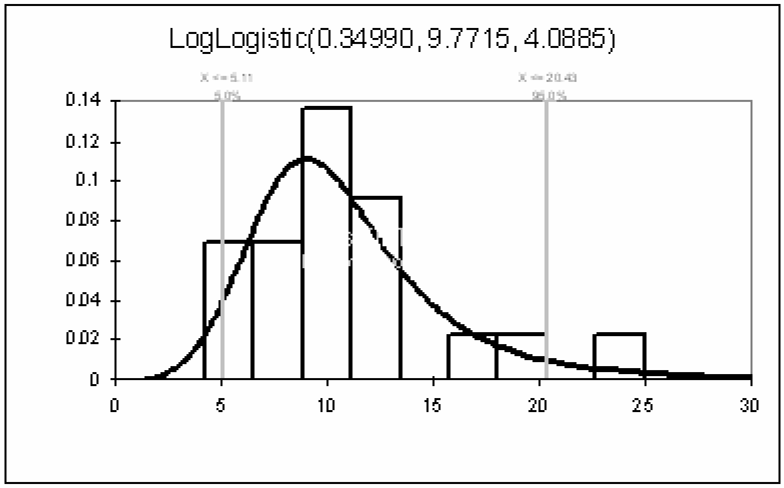

Figure 4.11 Probability distribution of forward speed data for Chittagong

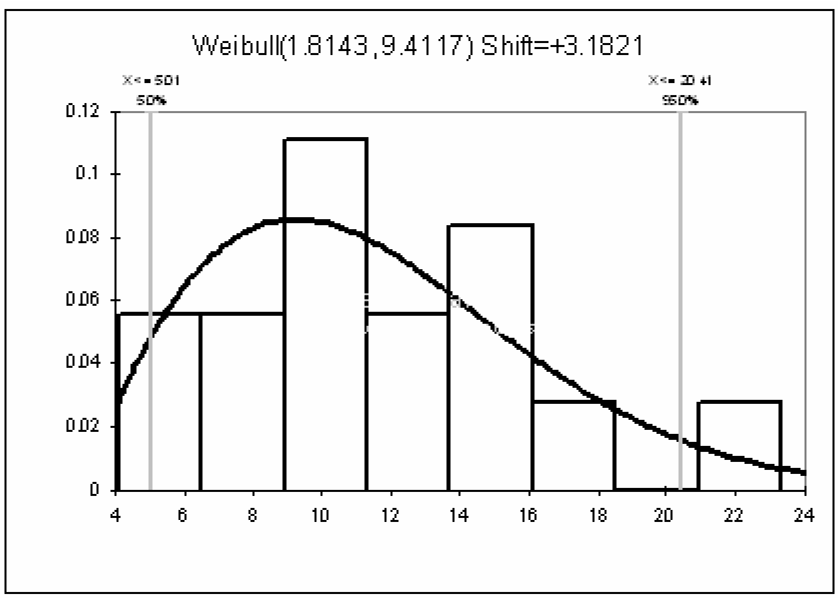

Figure 4.12 Probability distribution of forward speed data for Cox's Bazar

The distribution of forward speed data of each of the five sites is shown in Table 4.5.

Table 4.5 Forward speed distributions of five locations. Units are in nautical miles per hour (knots). The percentages represent the probability the forward speed will be less than the given value.

Site	95%	80%	60%	40%	20%	5%	Lower bound
Khulna	14.93	10.08	7.06	4.88	2.89	1.14	1
Barisal	15.19	12.09	9.82	7.87	5.59	2.49	2
Noakhali	15.48	12.55	10.39	8.55	6.39	3.46	2
Chittagong	24.47	18.25	15.35	13.41	11.51	9.27	4.2
Cox's Bazar	19.85	15.66	12.61	10.08	7.34	4.17	2

From Table 4.5, at Khulna the forward speed is selected so that there is a 5% chance of selecting a speed of 14.93 knots, a 15% chance of selecting a speed of 10.08, a 20% chance of selecting a speed of 7.06, 4.88 and 2.89 knots, a 15% chance of selecting a speed of 1.14 knots, and a 5% chance that a forward speed of 1.0 knots is selected for any simulation. This same set of steps is used in selecting the forward speed for all other sites.

4.3.5 Distribution of the radius of the maximum wind data

Since each site individually has too few data for the radius of the maximum wind, it is difficult to get any distribution from the data for each site. For the convenience, data of the sites located in the western side, i.e., Khulna, Barisal and Noakhali are grouped together to get a better a distribution and the same is adapted for the sites located in the eastern side which are Chittagong and Cox's Bazar.

For Khulna, Barisal and Noakhali, a normal distribution curve is found the best fit by the A-D and by K-S method as well (Figure 4.13).

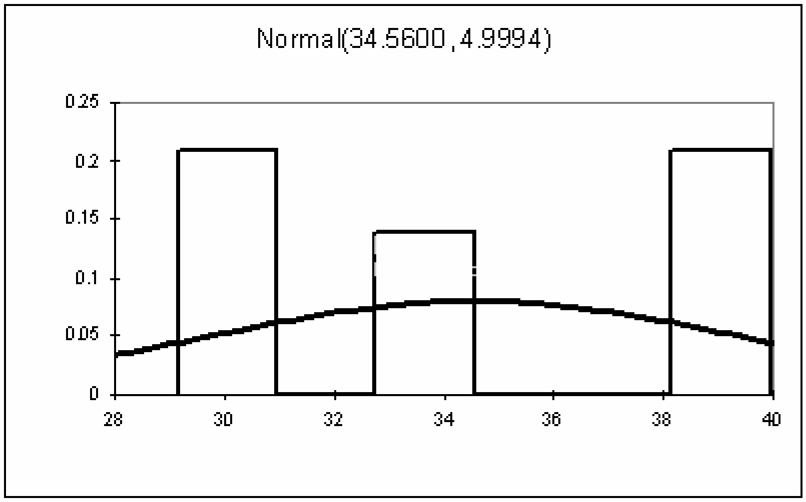

Figure 4.13 Probability distribution of RMW data for Khulna, Barisal and Noakhali

For Chittagong and Cox's Bazar, a logistic distribution curve is found the best fit by the A-D and K-S methods (Figure 4.14).

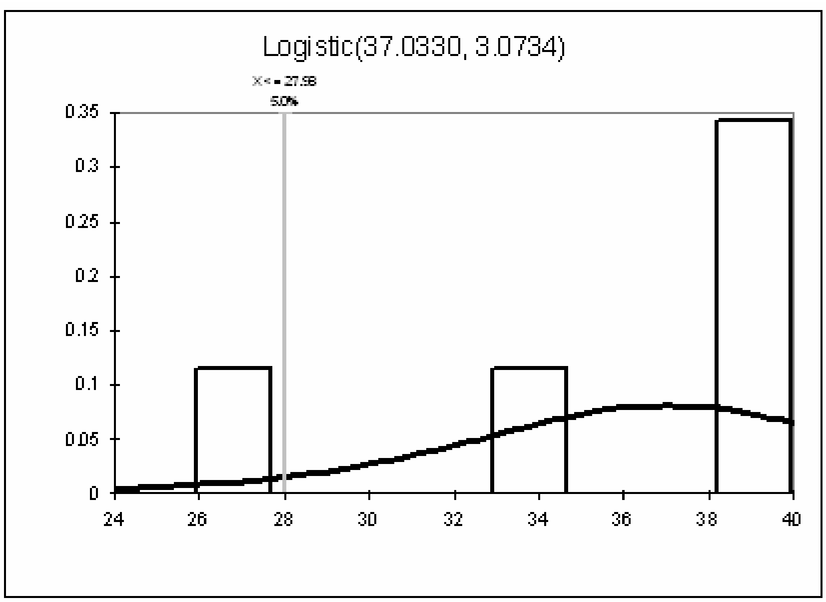

Figure 4.14 Probability distribution of RMW data for Chittagong and Cox's Bazar

The distribution of data for the radius of the maximum wind are given in Table 4.6.

Table 4.6 RMW data distributions. Units are in nautical miles. The percentages represent the probability the RMW will be less than the given value.

Site	95%	83.33%	50%	16.67%	5%	lower bound
Khulna, Barisal, Noakhali	42.78	39.39	34.56	29.72	26.34	10.0
Chittagong, Cox's Bazar	46.08	41.98	37.03	32.08	27.98	10.0

From Table 4.6, at Khulna the sample is such that there was a 5% chance of selecting radius of maximum wind of 42.78 nmi, a 11.67% chance of selecting a radius of maximum wind of 39.39 nmi, a 33.33% chance of selecting a radius of maximum wind of 34.56 nmi and 29.72 nmi, a 11.67% chance of selecting a radius of maximum wind of 26.34 nmi and a 5% chance that a radius of maximum wind of 12.30 nmi will be selected for any simulation. The same set of procedure is used in selecting the radius of maximum winds for all of the other sites.

From the distributions of the wind field parameters, central pressure may have a significant effect since it will control the maximum wind speed in the storm. Storm heading or the angle of attack are slightly different for the sites in the eastern side (Chittagong and Cox's Bazar) than from the western sites (Khulna, Barisal and Noakhali). The differences in forward speed are not critical even though at 50% it varies from 6 to 14 knots; its difference on vulnerability would be insignificant. The radius of the maximum wind speed is the same way; at 50% it varies from 34.5 to 37 nmi; its impact on vulnerability would be negligible.

4.4 Bathymetry of the Bay of Bengal along the coastal sites

The Holland (1991) wind field model is installed into a simple bathystrophic storm surge model. The surge model requires the bathymetry of the Bay of Bengal perpendicular to each site as input. The bathymetry of the Bay of Bengal along the coasts of the five selected sites are given in Table 4.7 – Table 4.11. The data are read off the nautical chart # 63330: Raimangal River to Elephant Point (scale 1: 300,000), produced by the National Imagery and Mapping Agency (NIMA). The depths are estimated every nautical mile as moving out perpendicular to the coast at each site and cut off when the water gets to a significant depth.

Table 4.7 Bathymetry along the Khulna coast (row-wise).Units are in feet.

6	7	10	11	16	19	22	24	25	26
27	33	44	66	72	82	98	125	131	164
203	262	302	328	341	354	361	377	390	420
433	479	564	594	659	804	1030	1224		

Table 4.8 Bathymetry along the Barisal coast (row-wise). Units are in feet.

9	10	10	15	16	17	19	20	21	23
42	49	66	72	89	98	102	125	164	246
282	289	295	312	328	358	384	407	420	436
443	459	492	515	600	666				

Table 4.9 Bathymetry along the Noakhali coast (row-wise). Units are in feet.

6	9	10	18	19	20	21	24	26	27
28	29	30	31	33	34	35	37	37	42
44	48	54	58	66	72	82	151	157	180
210	226	233	240	249	272	276	285	312	358
394	410	515	686	702					

Table 4.10 Bathymetry along the Chittagong coast (row-wise). Units are in feet.

6	7	9	10	16	20	23	23	23	23
23	23	23	26	26	26	30	33	59	72
89	102	121	131	194	269	276	288	295	328
341	358	364	436						

Table 4.11 Bathymetry along the Cox's Bazar coast (row-wise). Units are in feet.

6	9	10	13	20	23	26	30	33	49
62	72	82	95	121	131	161	180	187	203
217	226	230	249	259	272	276	285	312	348
358	394	443	459	515	600	686			

4.5 Monte Carlo simulation procedure

Two computer programs written in FORTRAN are used to perform the Monte Carlo simulations for each site. Using the distributions of historical data of storm parameters given in section 4.3 as input, the first program generates 1000 randomly selected variables for each of the four parameters for each site. These randomly generated variables of storm parameters are stored in a separate file for each site.

The second program generates 1000 landfalling storms for a selected site using the output file of the first program and the bathymetry information of the selected site given in section 4.4. Two output files are produced which contain the maximum wind speed and maximum surge height at landfall location. The simulation is run for a total of 30 hours for each of the storms; 20 hours over the sea when the storm approaches to the site and 10 hours more after landfall to allow the storm enter well inland.

During the period the storm approaches the site, central pressure, radius of the maximum wind, storm heading and forward speed all are held constant. Once the storm makes landfall, the central pressure is allowed to decrease at a rate of 3% of the original value for the first six hours the storm over land. After that, the central pressure is held constant at 82% of the original central pressure. The other parameters are not allowed to change any time during the simulation (Kriebel et al., 1996).

In the simulations, friction is also taken into account at the land/water interface. Over land, the winds are reduced to 70% of their value over the ocean due to the roughness of land. At the shoreline, the winds are reduced to 89% of their strength over the open ocean if the winds are onshore, and 70% for offshore. Also, for the offshore winds, the wind speeds are reduced to 90% of their value over open ocean within less than one nautical mile from shore (Kriebel et al., 1996). Considering all these factors, the wind speed is then reduced by a factor of 0.7 to adjust it to a 10- minute mean wind speed at 10 meter (Hubbert et al., 1991).

4.6 Results and analysis

4.6.1 Wind analysis

At each of the five sites 1000 simulated storms are generated through Monte Carlo simulations. The mean maximum wind speeds of these storms at each site are shown in Figure 4.15. These are steady for Khulna, Barisal and Noakhali, which are located to the western side of the coastline. The mean wind speeds are slightly higher for Chittagong and Cox's Bazar located along the eastern part of the coasts.

The combination of the four storm parameters, i.e., central pressure, radius of maximum wind, storm heading and forward speed, are mainly responsible for this variation of mean wind speed. The mean central pressure that is created for each site from the simulations is almost identical as the same central pressure distribution (Table 4.2) is applied to all the five sites. The mean radius of the maximum wind is higher for Chittagong (34.06 nmi) and Cox's Bazar (33.81) than the other three coastal sites. The mean forward speeds are also higher for Chittagong (13.35 knots) and Cox's Bazar (9.72 knots) than Khulna (5.28 knots), Barisal (7.48 knots) and Noakhali (8.11 knots). Thus, the variation of the mean wind speeds is certainly influenced by the radius of maximum wind and forward speed of the storms.

In terms of storm heading, the mean angles of attack for Khulna (195), Barisal (197) and Noakhali (162) are closer to normal (180º being a heading from the south and normal to coastline) than for Chittagong (208) and Cox's Bazar (210.2). In reality, storms gain more strength during re-curvature than just approaching straight. The location of Chittagong and Cox's Bazar along the coastline is as such that most of the storms have to re-curve to strike unlike the sites located on the western side. Thus, the storm heading might play a role for higher mean wind speeds at Chittagong and Cox's Bazar.

To make a comparison, the mean wind speeds from the Monte Carlo simulations performed by Skwira (1998) at 11 sites of the United States coastline is shown in Figure 4.16. The range and pattern of the mean wind speeds look similar in both the cases.

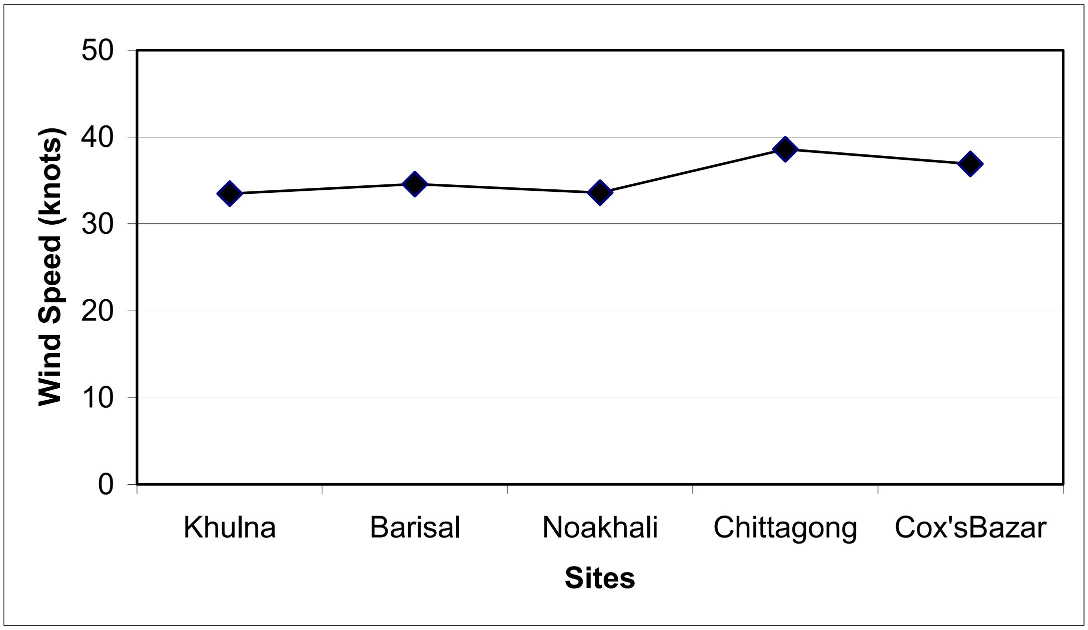

Figure 4.15 The mean wind speed obtained from the Monte Carlo simulations at each of the five sites along the Bangladesh coastline.

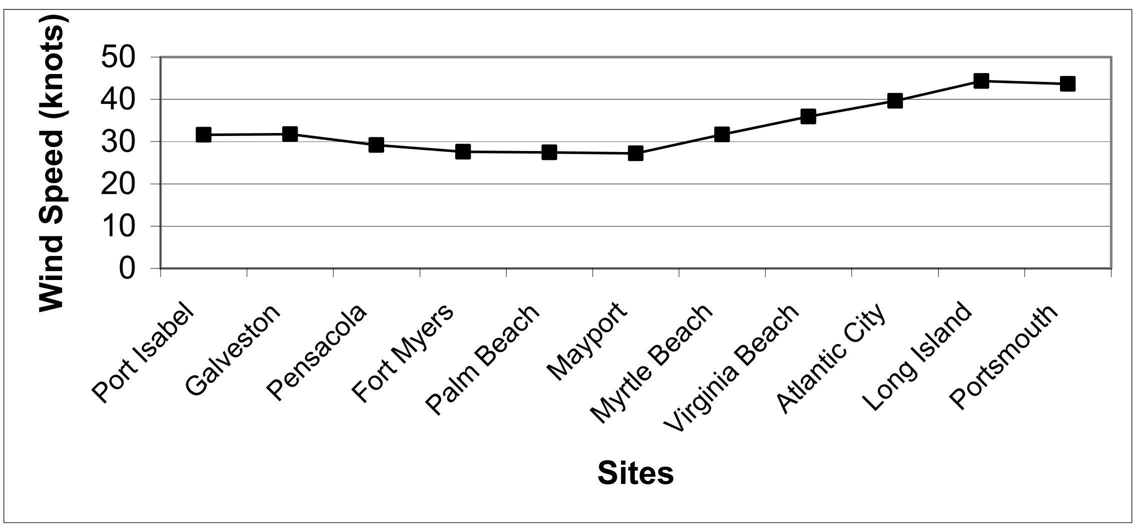

Figure 4.16 The mean wind speed at 11 sites of the United States coastline obtained from the Monte Carlo simulations (Skwira, 1998).

Figure 4.17 to Figure 4.21 show the frequency of storms in different wind speed categories for a total of 1000 simulated storms at each of the five sites. At Khulna, the highest reached wind speed is 85.5 knots. At Barisal, the maximum wind speed is 86.88 knots. At Noakhali, the maximum wind speed is obtained 88.91 knots. At Chittagong, wind speed reached at maximum 94.56 knots. The highest wind speed among all the five locations is found at Cox's Bazar, which is 102.07 knots.

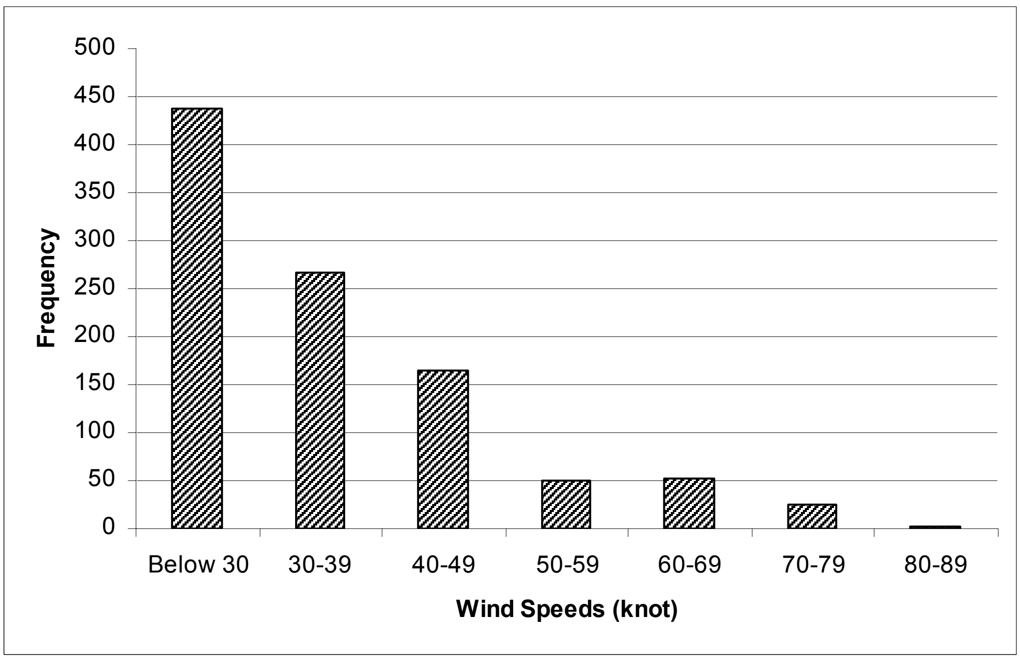

Figure 4.17 Frequency of simulated storms in different wind speed categories at Khulna

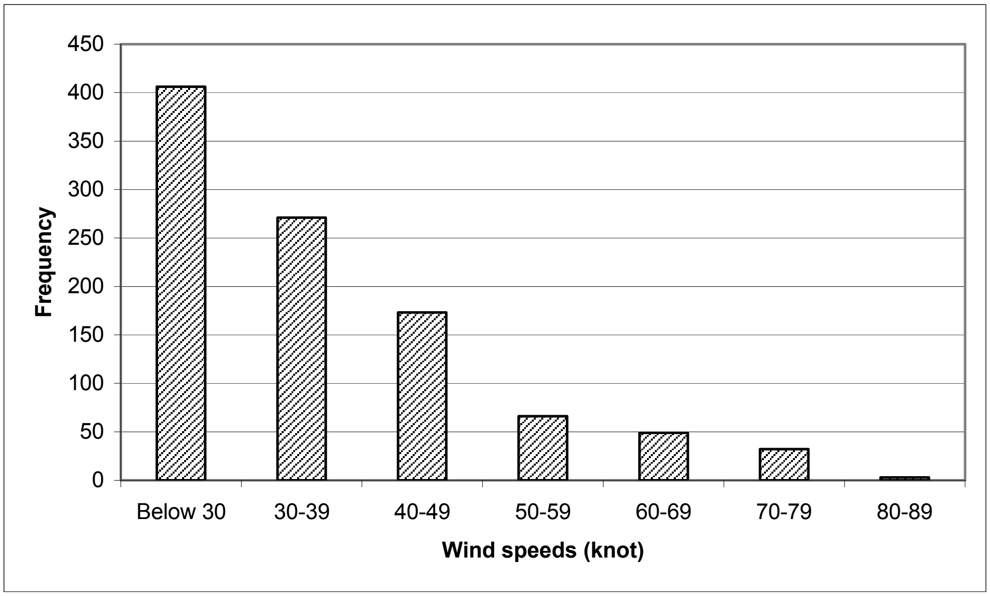

Figure 4.18 Frequency of simulated storms in different wind speed categories at Barisal

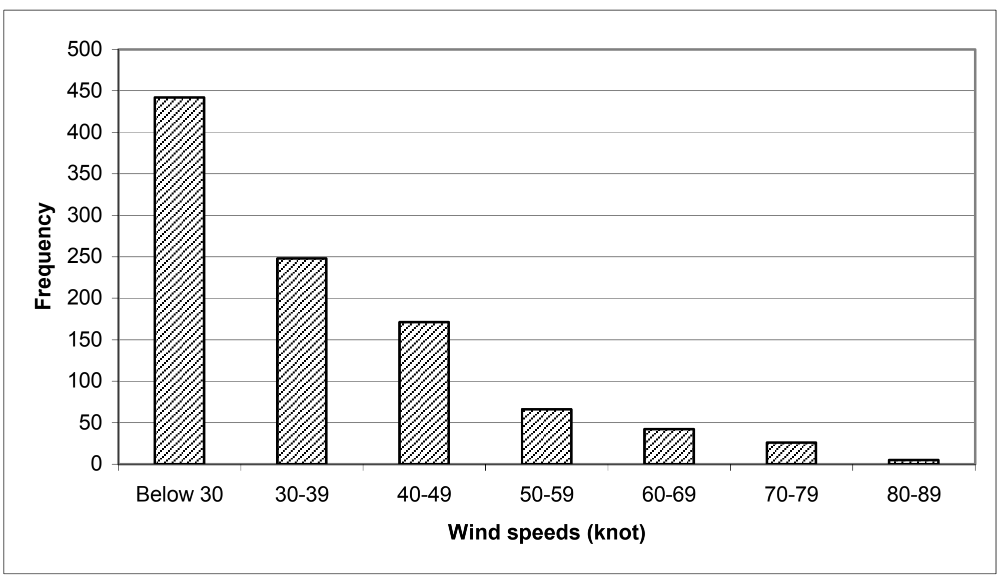

Figure 4.19 Frequency of simulated storms in different wind speed categories at Noakhali

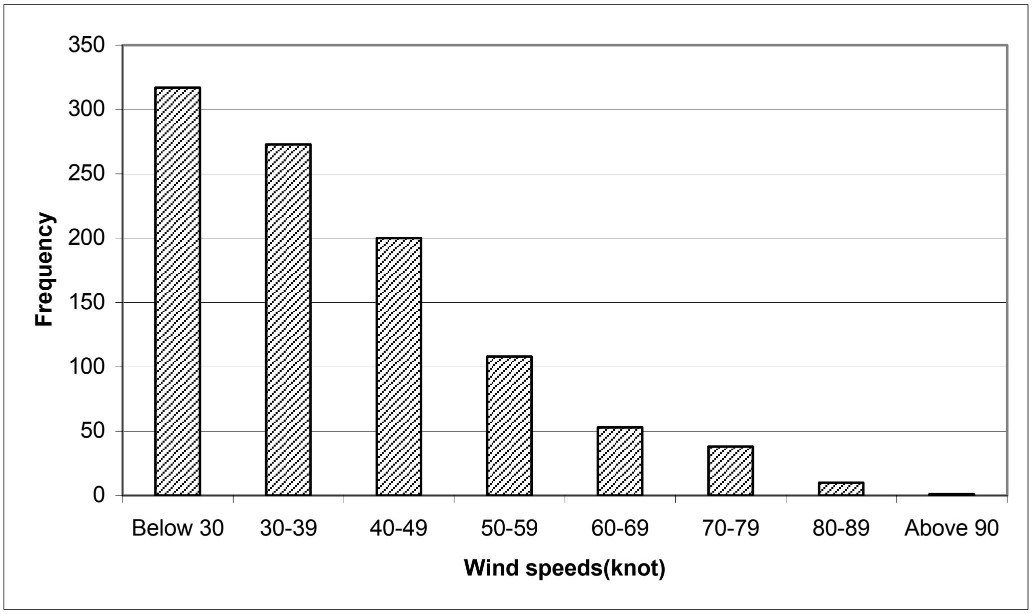

Figure 4.20 Frequency of simulated storms in different wind speed categories at Chittagong

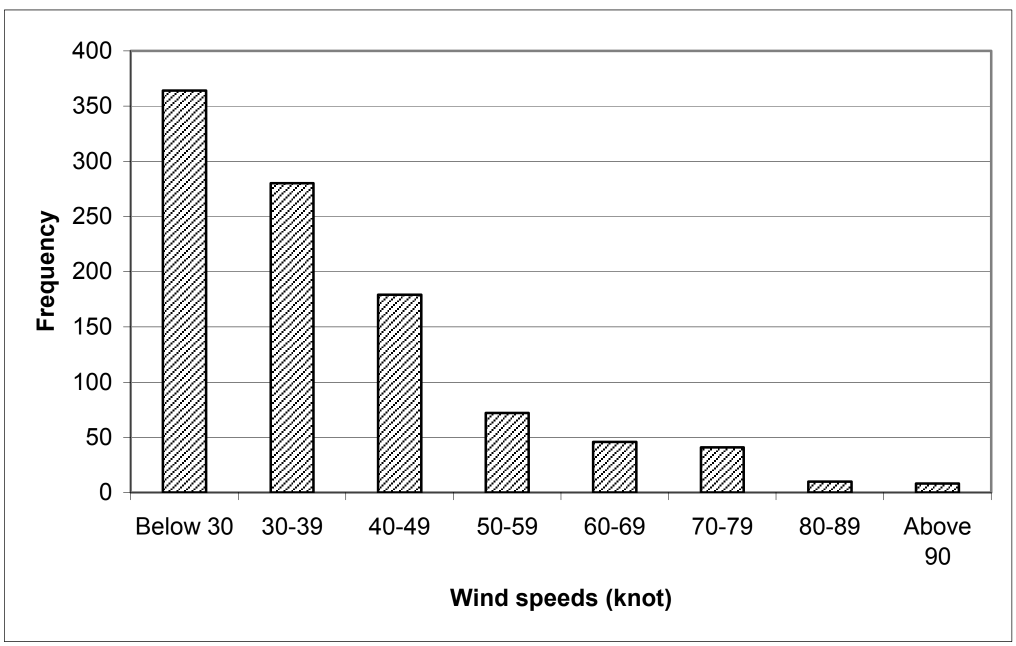

Figure 4.21 Frequency of simulated storms in different wind speed categories at Cox's Bazar

One useful method to interpret the results for each site individually is to determine the wind speed for a given return period. This is very important from the structural engineering standpoint as the engineers can determine the appropriate wind speed strength or the design wind speed for a given certain life of a structure. The ASCE 7 wind speed map for the United States is based upon a 50-year recurrence level, which presumes that 50 years is the useful life expectancy of a facility (ASCE Standard No. 7-98, 2000).

The winds for specified return periods are calculated by the following procedure developed by Batts et al. (1980). First, the wind speeds are ranked by their magnitude as W_i, where i=1 is the smallest through i=1000, the largest. Then, the cumulative probability of occurrence of wind is obtained based on the assumption that the storm occurrences follow a Poisson distribution with a mean annual rate of occurrence as given in Table 4.12.

Table 4.12 Frequency of occurrence of landfalling cyclones (1877-2003)

Location	**Frequency (number per year)**
Khulna	0.28
Barisal	0.24
Noakhali	0.07
Chittagong	0.17
Cox's Bazar	0.16

The annual probability of occurrence is then determined as:

$$P\,(X < x_i) = \exp\left(-n\left(1 - \frac{i}{I+1}\right)\right) \qquad (4.1)$$

and the associated mean return period (mean recurrence interval) in years is given by:

$$T_R\ (x_i) = \frac{1}{1 - P\,(X < x_i)} \tag{4.2}$$

where,

X	=	Variable of interest, which is the wind speed W;
x_i	=	Ranked value of the wind speed W ;
i	=	Rank of event with i=1 smallest and i=I largest;
I	=	Total number of events in simulation = 1000;
n	=	Mean number of storms per year, from Table 4.12;
$P(X<x_i)$	=	Annual probability that variable X is less than ranked value x_i; and
$T_R\ (x_i)$	=	Mean recurrence interval in years for events equaling or exceeding value x_i.

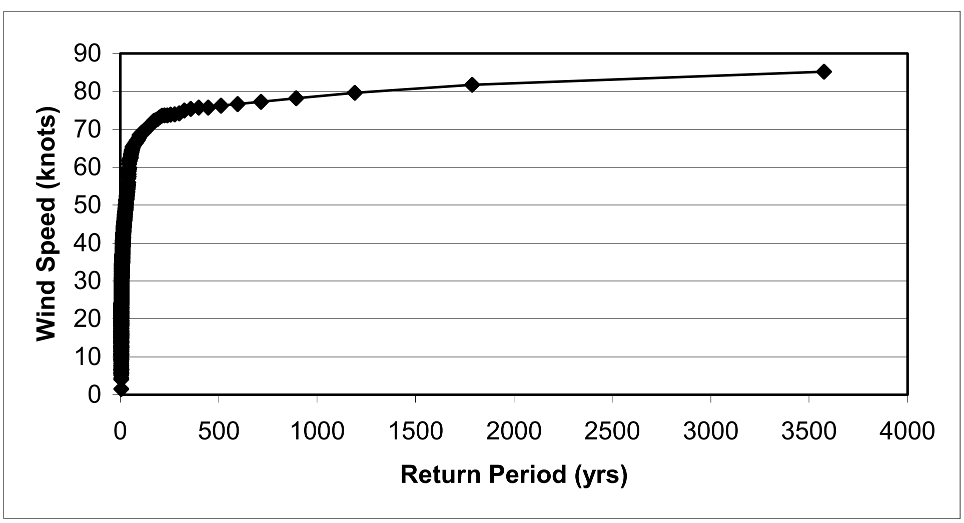

Figure 4.22 Wind speed return period for Khulna

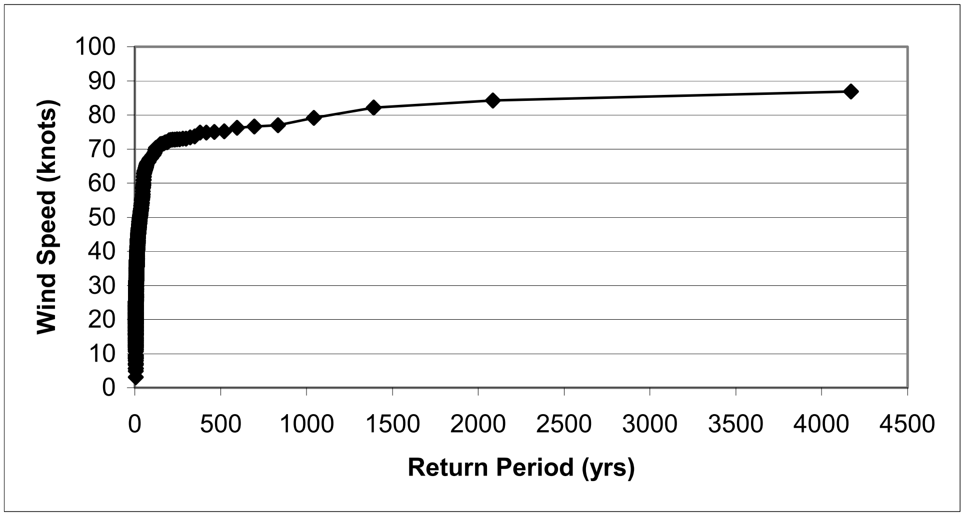

Figure 4.23 Wind speed return period for Barisal

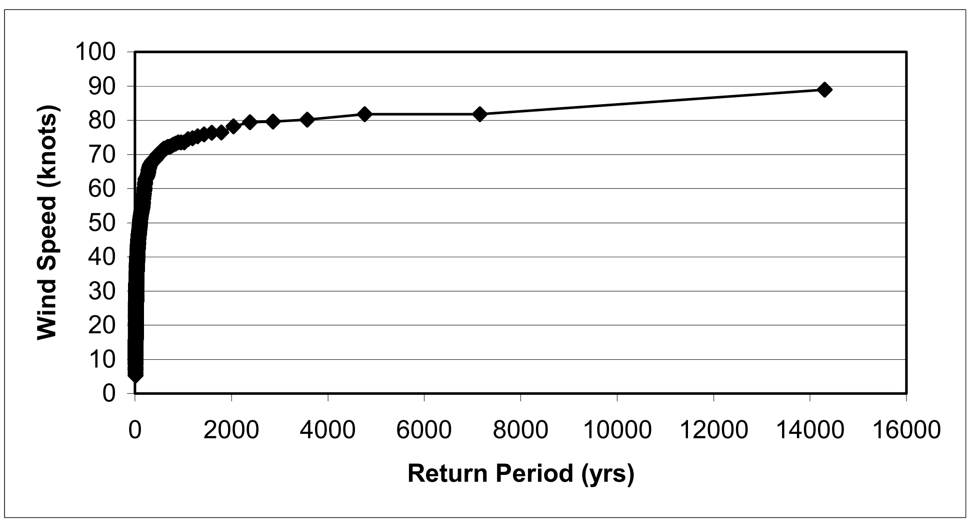

Figure 4.24 Wind speed return period for Noakhali

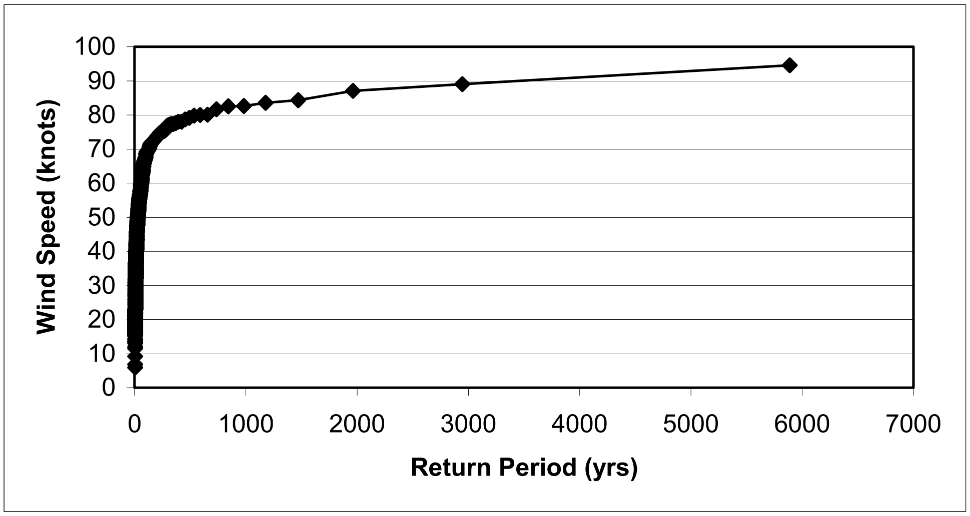

Figure 4.25 Wind speed return period for Chittagong

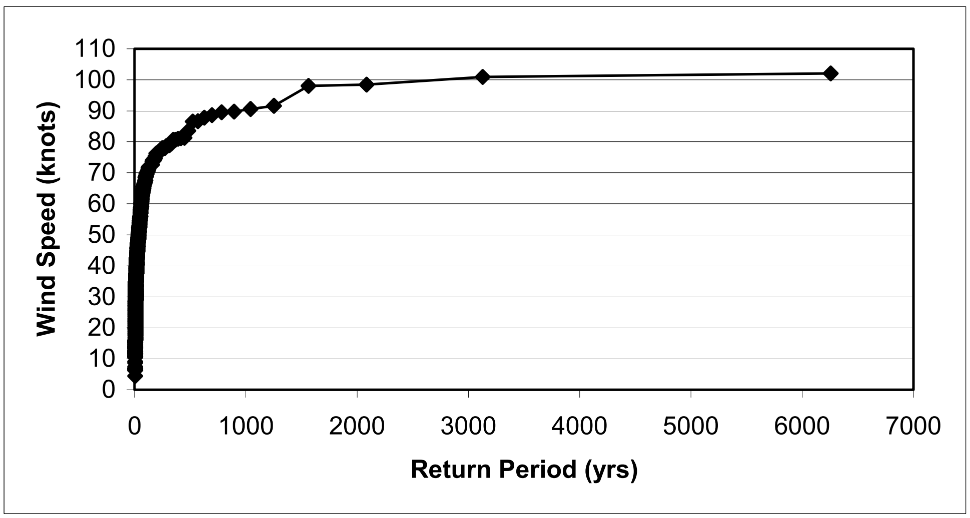

Figure 4.26 Wind speed return period for Cox's Bazar

The procedure described above effectively converts the 1000 storms simulated for each coastal location into an annual series with a different record length based on the mean rate of storm occurrence (Kriebel et al., 1996). For example, the lowest mean rate of occurrence is at Noakhali, where n=0.07. Therefore, the largest of the 1000 storms simulated at this location corresponds to a 14,300 year return period. At the other extreme, the highest rate of occurrence is at Khulna, where n=0.28. The most severe storm simulated at this location is assigned a return period of 3575 years.

4.6.2 Surge analysis

The mean surge heights from the simulated storms at each of the five sites are shown in Figure 4.27. At Khulna, Barisal and Cox's Bazar the mean surge heights are relatively low, whereas at Chittagong the mean surge height is the maximum.

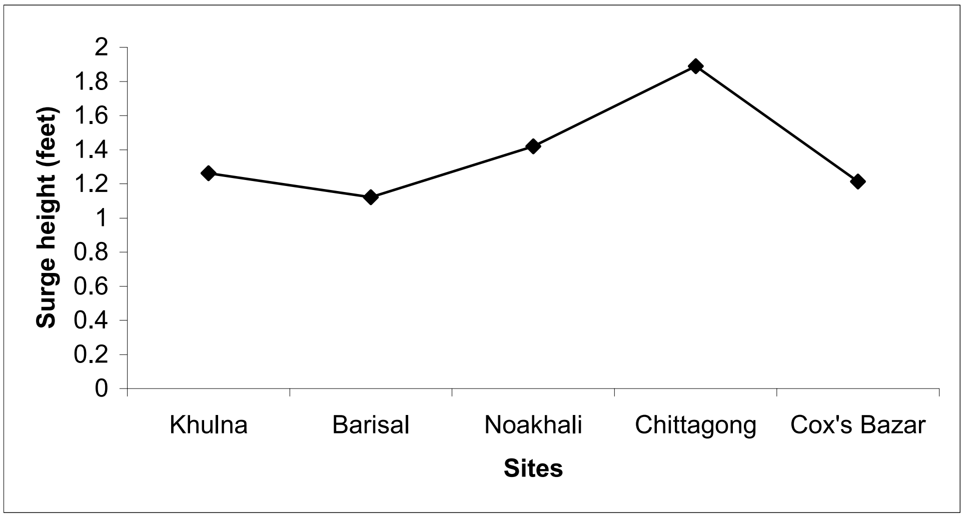

Figure 4.27 The mean surge height (in feet) obtained from the Monte Carlo simulations at each of the five sites along the Bangladesh coastline.

Mandal (1991) prepared the probable maximum storm surge for the Indian and Bangladesh coastlines using the pre-computed nomograms (Figure 4.28). Pre-computed nomograms have been used by the India Meteorological Department (IMD) for operational surge predictions in the North Bay of Bengal (Dube et al., 1997). The nomograms have been constructed from modeling studies using the SPLASH model adapted by Ghosh (1977).

According to the nomograms, the highest storm surge along the Bangladesh coastline as well as in the North Bay of Bengal may be expected at Hatia of Noakhali region, 13.2 meters. The maximum surge height obtained from the Monte Carlo simulations at Noakhali is 38.39 feet or 11.7 meters. Among all of the coastal sites, the maximum surge height is the highest at Khulna, which is 41.14 feet or 12.5 meters. In the pre-computed nomograms, the maximum surge height at Khulna is shown also as 12.5 meters, which is well matched with the Monte Carlo simulation results.

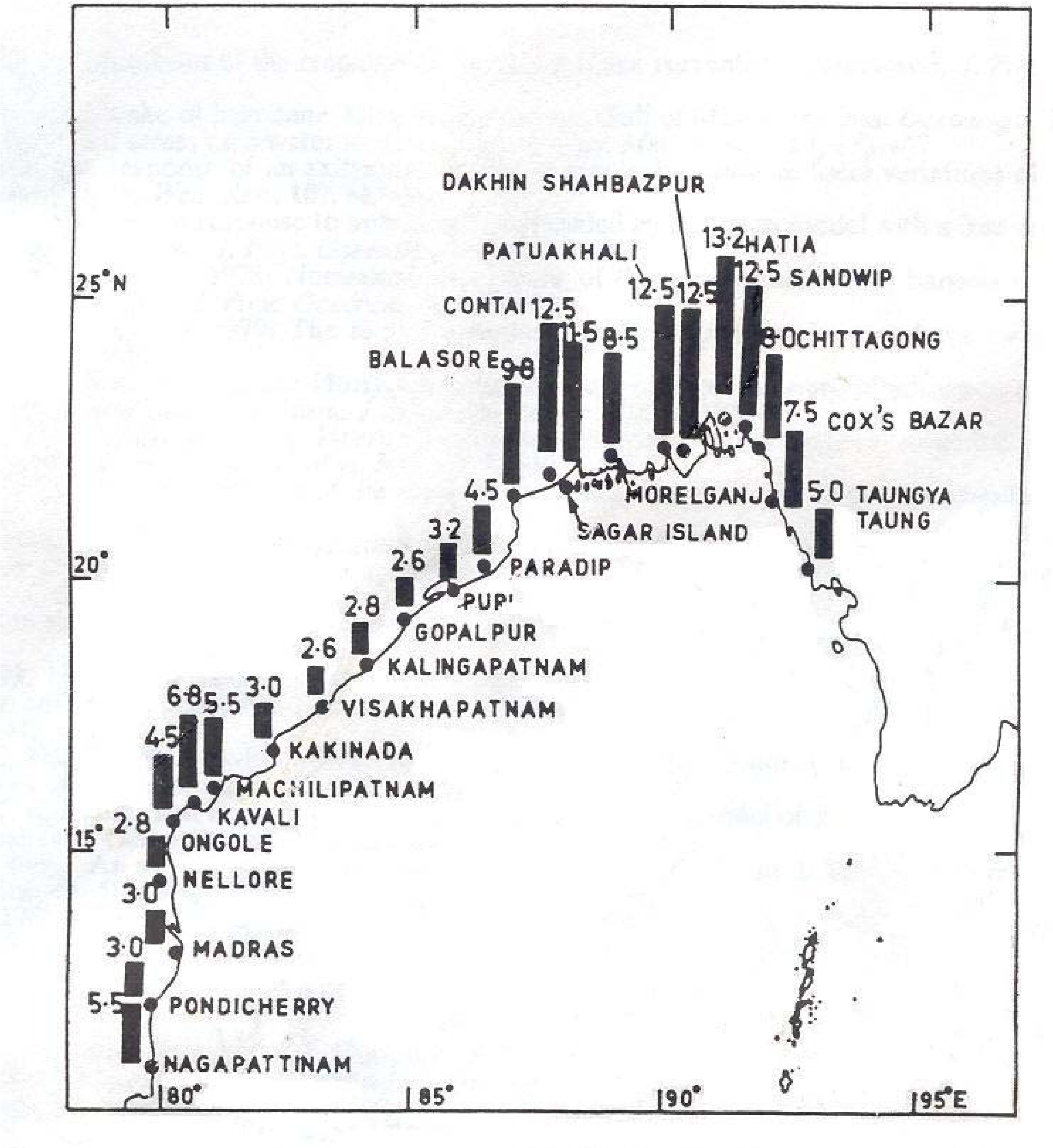

Figure 4.28 Probable maximum storm surge (in meters) for the Indian and Bangladesh coastlines constructed by using pre-computed nomograms (Mandal, 1991)

Figure 4.29 to Figure 4.33 show the histograms of storm surges from the 1000 simulated storms at each of the five sites. At Khulna, most of the surges are within 5 feet height and the highest storm surge is 41.14 feet. At Barisal, most of the surge heights are within 6 feet height and the highest is 27.69 feet. At Noakhali, most of the surges are within 10 feet height with the highest surge is 38.39 feet. At Chittagong, most of the surges are also within10 feet height and the highest surge is obtained as 37.63 feet. In the April 1991 Super cyclone, the storm surge reached around 30 feet height in Chittagong region. The maximum surge height is the lowest at Cox's Bazar, only 10.72 feet.

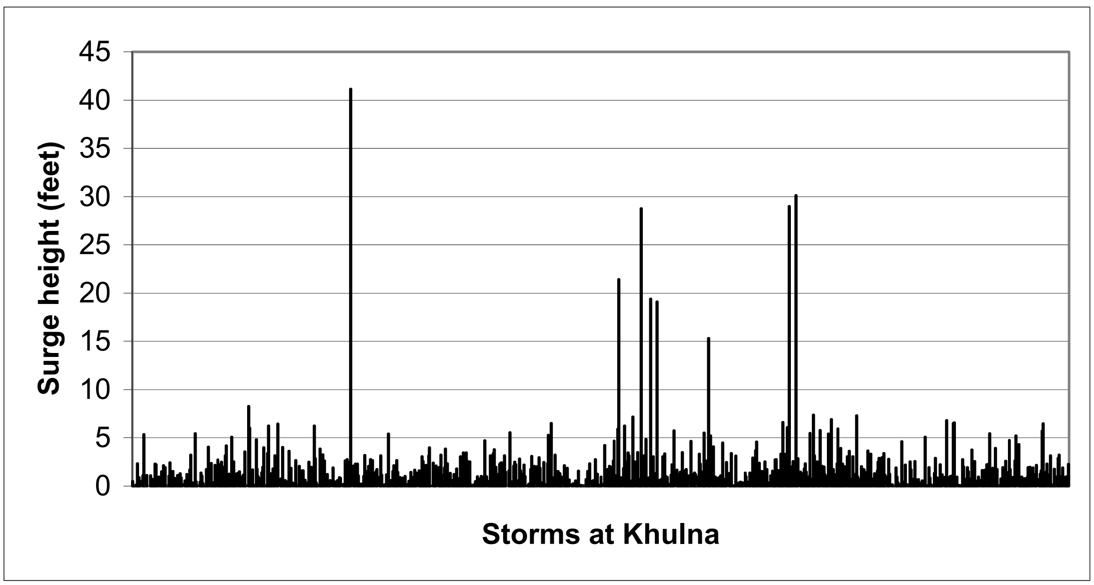

Figure 4.29 Surge height from the simulated storms at Khulna

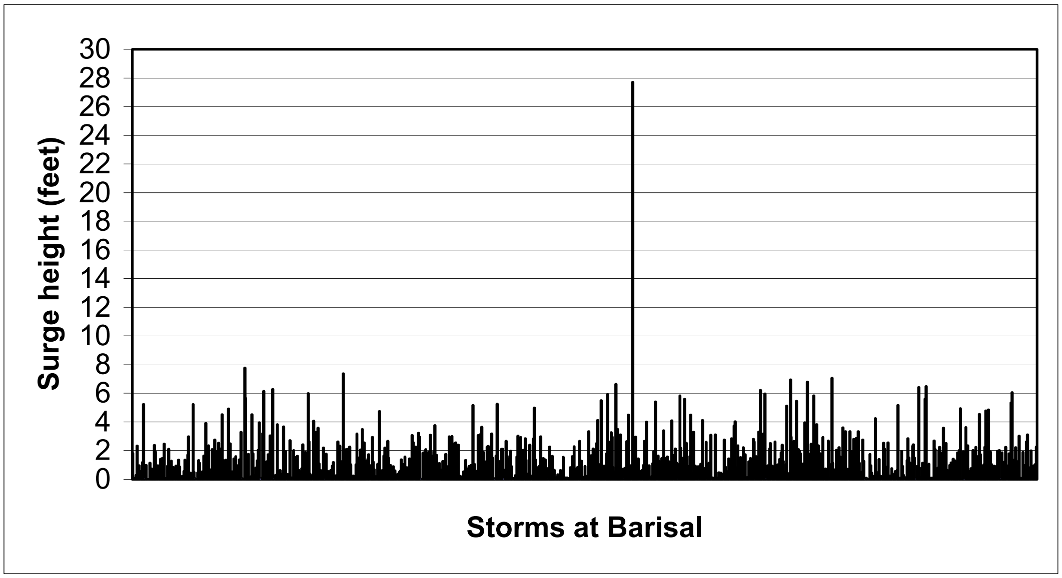

Figure 4.30 Surge height from the simulated storms at Barisal

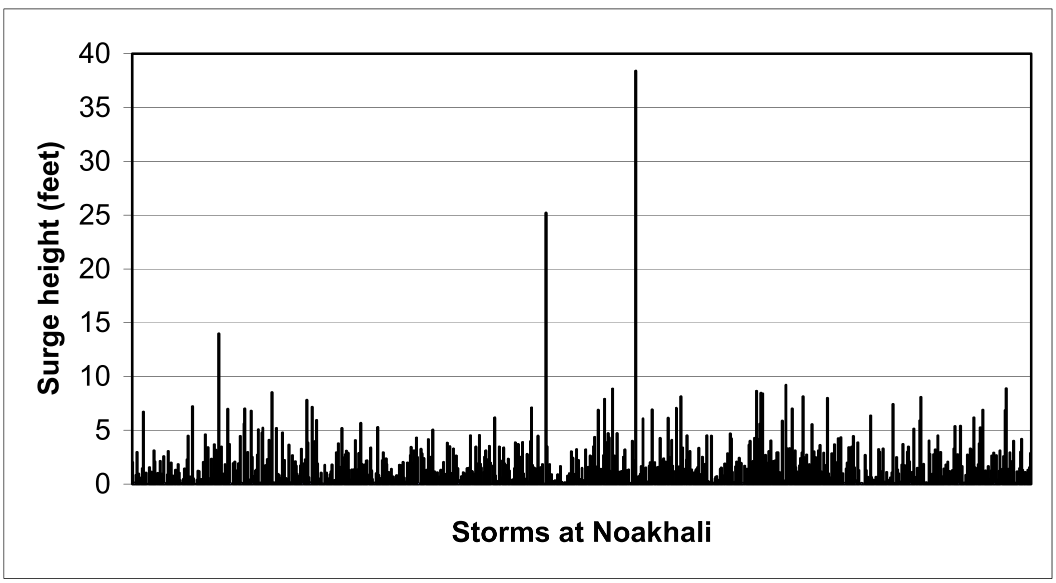

Figure 4.31 Surge height from the simulated storms at Noakhali

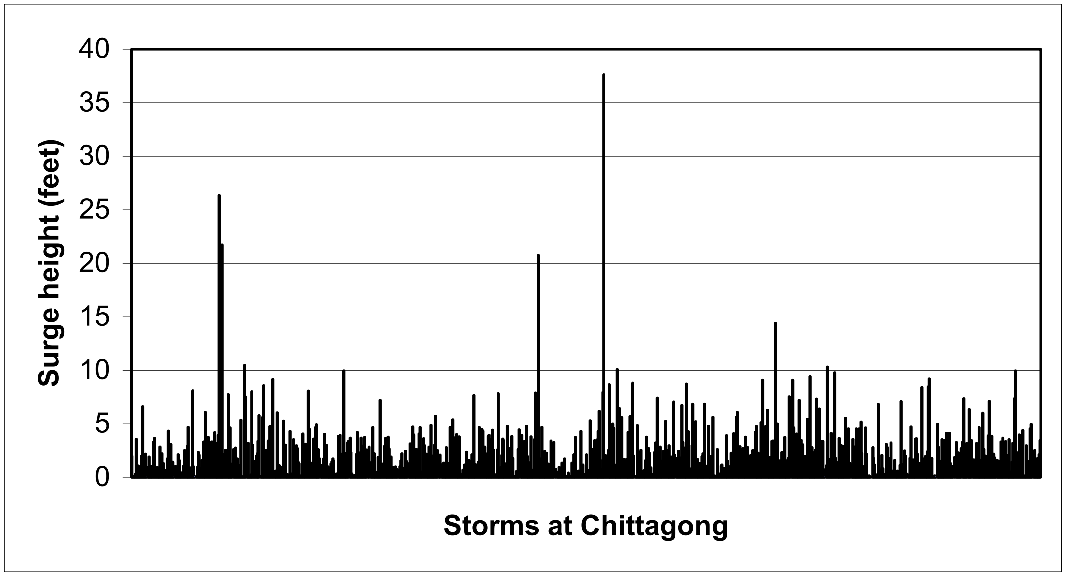

Figure 4.32 Surge height from the simulated storms at Chittagong

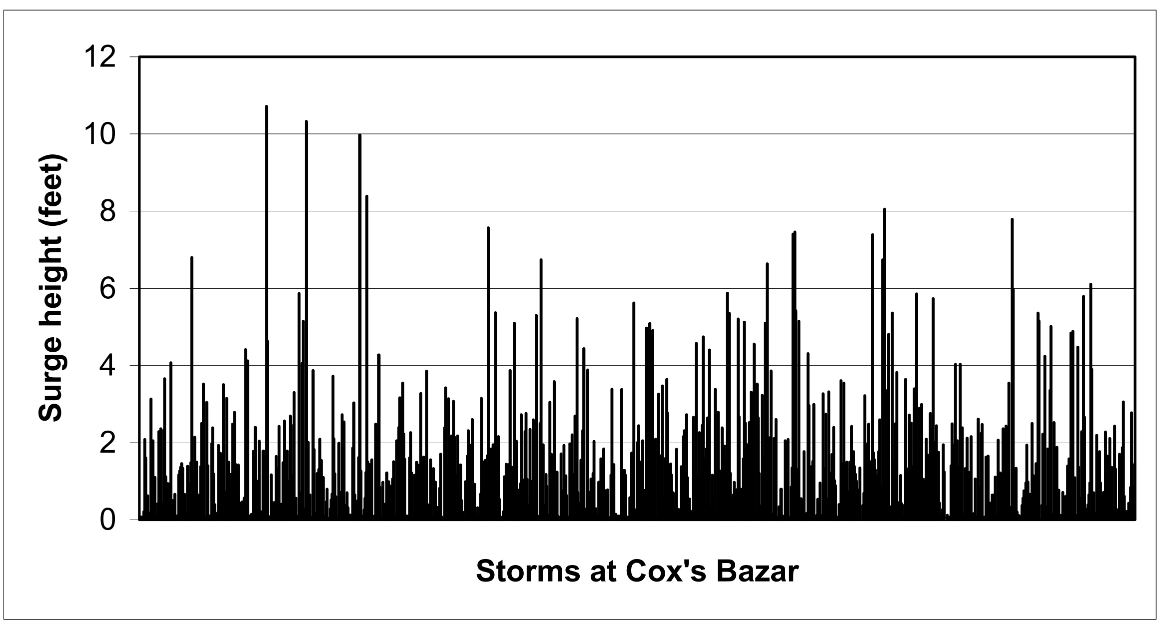

Figure 4.33 Surge height from the simulated storms at Cox's Bazar

CHAPTER V

CYCLONE RISK AND VULNERABILITY ANALYSIS OF THE COASTAL AREAS

5.1 Overview of the coastal areas

The coastal area of Bangladesh is comprised of 14 administrative districts. These are- Satkhira, Khulna, Bagerhat, Pirojpur, Barguna, Patuakhali, Jhalokati, Barisal, Bhola, Lakshmipur, Noakhlai, Feni, Chittagong and Cox's Bazar. Figure 5.1 shows the district lines of Bangladesh with the colored districts represent the coastal districts. The regions used in the cyclone wind analysis are also depicted in the map.

A brief overview of the coastal districts is given in the following. The information and statistics of the districts are provided from the *Statistical Year Book of Bangladesh*, published by the Bangladesh Bureau of Statistics (2003) and from the online edition of the Banglapedia- the national encyclopedia of Bangladesh, published by the Asiatic Society (www.banglapedia.org).

5.1.1 Satkhira

Satkhira is a south-west bordered district of Bangladesh located in the greater Khulna region with an area of 3858 sq. km. The total population of Satkhira is 1,843,194 and per capita income is 22,400 BDT equivalent to 320 USD (@ 1 USD = 70.00 Taka.).

Average literacy in the district is 30.35%; male 39.7% and female 21%. The main occupations are agriculture 36.9%, fishing 1.86%, pisciculture 1.01%, agricultural laborer 26.74%, wage laborer 3.72%, commerce 13.32%, industry 1.49%, transport 2.46%, service 4.37%, and others 8.13%. Of the total land, 140,953.93 hectares are cultivable and 41,220.31 hectares are fallow land. Only 34.03% cultivable land is under irrigation.

5.1.2 Khulna

Khulna city is the largest city and business center of this region located in the Khulna district. Mongla Port, the second largest seaport of Bangladesh is located 48 km south of Khulna city. Many tourists come in Khulna to visit the Sundarbans forest. Sundarbans is the world's largest mangrove forest located in both Bangladesh and India, of which the Bangladesh portion is spread over along the coasts of Satkhira, Khulna and Bagerhat districts.

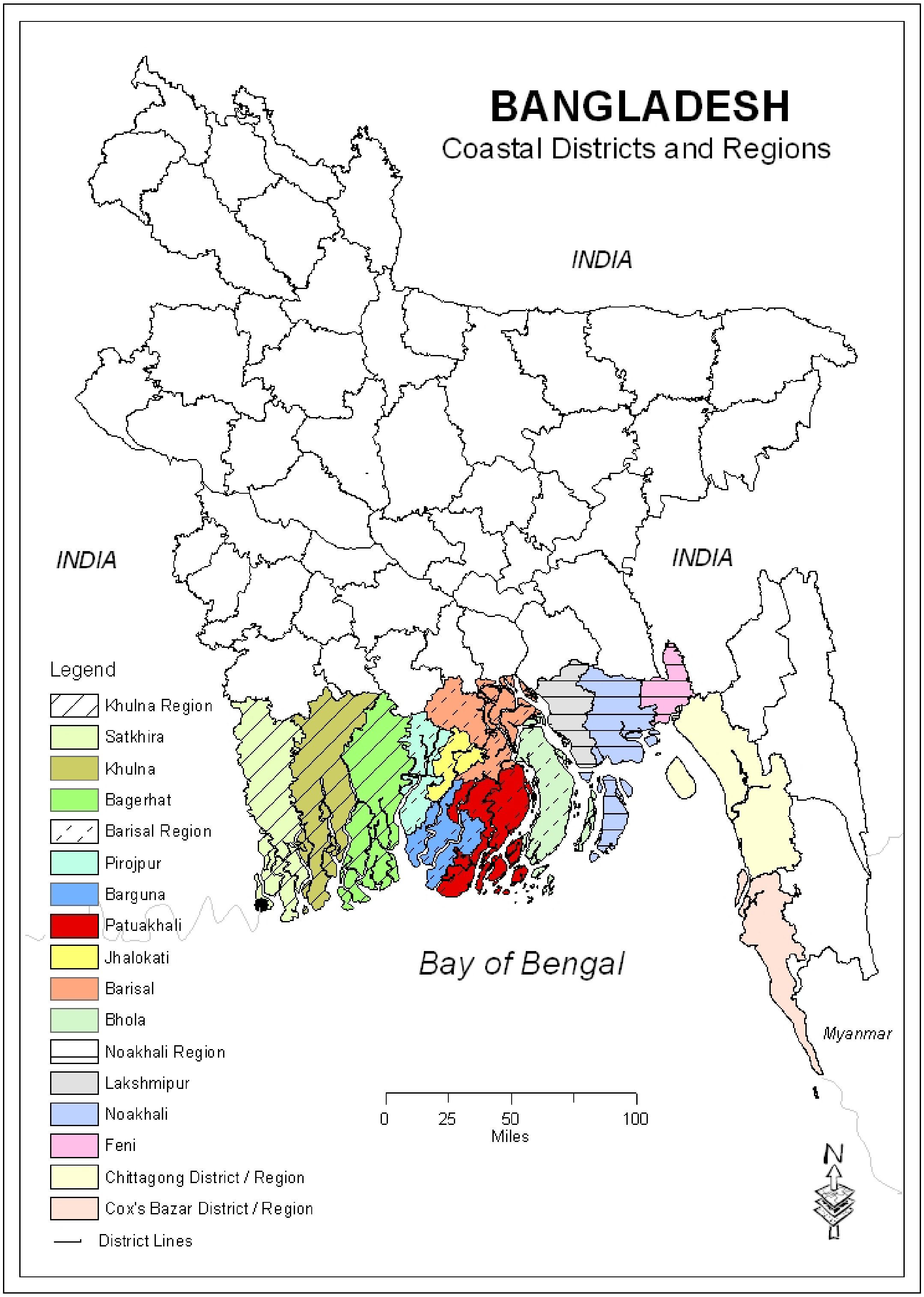

Figure 5.1 Coastal districts and regions

The total area of Khulna district is 4395 sq. km with the total population of 2,334,285. The per capita income of Khulna district is 32,200 BDT, which is equivalent to 460 USD. Average literacy in the district is 43.9%; male 52.2% and female 34.6%. The main occupations are agriculture 25.11%, fishing 1.66%, agricultural laborer 11.3%, wage laborer 7.15%, industry 16.38%, transport 4.09%, constructions 1.53%, service 18.93%, others 12.22%.

5.1.3 Bagerhat

Bagerhat district is also located in the Khulna region. The area of Bagerhat district is 3959 sq. km. The total population of Bagerhat is 1,515,815 and per capita income is 23,450 BDT equivalent to 335 USD.

Average literacy in the district is 44.33%; male 49.54% and female 34.33%. The main occupations are agriculture 36.24%, fishing 3.06%, agricultural laborer 18.31%, wage laborer 6.7%, commerce 12.86%, transport 2.27%, service 7.58%, and others 12.95%. Of the total land, 179,401.05 hectares are cultivable and 687.98 hectares are fallow land.

5.1.4 Pirojpur

The area of Pirojpur district is 1308 sq. km and the total population is 1126,525. The per capita income of Pirojpur district is 18,970 BDT equivalent to 271 USD. The district is located in the Barisal region.

Average literacy in the district is 55.8%; male 63.5% and female 48.1%. The main occupations are agriculture 35.3%, fishing 1.86%, agricultural laborer 17.05%, wage laborer 5.71%, commerce 16.2%, service 7.25%, fishing 2.68%, transport 1.64%, construction 1.28%, and others 12.89%. Of the total land, 87,051.8 hectares are cultivable and 520.53 hectares are fallow land.

5.1.5 Barguna

Barguna is located in the Barisal region with an area of 1832 sq km. The total population of Barguna is 837,955 and per capita income is 23,520 BDT equivalent to 336 USD.

Average literacy in the district is 40.14%; male 45.15% and female 35.05%. The main occupations are agriculture 50.53%, fishing 3.96%, agricultural laborer 15.27%, wage laborer 3.81%, commerce 10.01%, construction 1.29%, service 4.86%, and others 10.27%. Of the total land, 150,533.79 hectares are cultivable and 4,609.88 hectares are fallow land.

5.1.6 Patuakhali

Patuakhali is an exposed coastal district in the Barisal region. The area of the Patuakhali district is 3205 sq. km. The total population of Patuakhali is 1,444,340 and per capita income is 25,270 BDT equivalent to 361 USD.

Average literacy in the district is 36.4%; male 42.7% and female 30%. The main occupations are agriculture 45.84%, fishing 3.32%, commerce 9.94%, service 6.12%, agricultural laborer 16.72%, wage laborer 4.53%, construction 1.31%, others 12.22%.

Of the total land, 222,899 hectares are cultivable and 3,694 hectares are fallow land. Only 3.8% cultivable land is under irrigation.

5.1.7 Jhalokati

The area of Jhalokati district is 758 sq. km. Total population is 696,055 and per capita income is 17,920 BDT equivalent to 256 USD. Jhalokati district is also located in the Barisal region.

Average literacy in the district is 51.2%; male 55.9% and female 46.5%. The main occupations are agriculture 40.07%, agricultural laborer 15.68%, wage laborer 4.66%, commerce 12.43%, service 11.03%, fishing 1.1%, and others 11.42%. Of the total land, 112,388 hectares are cultivable. Only 40% cultivable land is under irrigation.

5.1.8 Barisal

Barisal city located in the Barisal district is the largest city and business center of this region. The area of Barisal district is 2791 sq. km. The total population of Barisal is 2,330,960 and per capita income is 20,020 BDT equivalent to 286 USD.

Average literacy in the district is 42.9%; male 47.9% and female 37.9%. The main occupations are agriculture 35.28%, agricultural laborer 18.76%, wage laborer 4.16%, commerce 13.89%, service 10.64%, fishing 3.45%, construction 1.25%, transport

1.72% and others 10.85%. Of the total land, 178,601 hectares are cultivable and 5785.4 hectares are fallow land.

5.1.9 Bhola

Bhola is an offshore island with an area of 3403 sq km, The total population of Bhola is 1,676,600 and per capita income is 22,400 BDT equivalent to 320 USD.

Average literacy in the district is 21.47%; male 25.60% and female 17.05%. The main occupations are agriculture 38.74%, fishing 5.9%, agricultural laborer 24.52%, wage laborer 4.67%, business 9%, service 4.47%, construction 1.11%, others 11.59%.. Of the total land, 158923 hectares are cultivable. Only 8.53% cultivable land is under irrigation.

5.1.10 Lakshmipur

The area of Lakshmipur district is 1456 sq. km and the population is 1,479,371. The per capita income of Lakshmipur district is 21,560 BDT equivalent to 308 USD. It is located in the Noakhali region.

Average literacy in the district is 34.3%; male 38.8% and female 29.7%. The main occupations are agriculture 35.19%, fishing 2.7%, agricultural laborer 19.86%, wage laborer 3.16%, commerce 12.10%, service 12.21%, transport 2.04%, construction 1.27%, others 11.47%. Of the total land, 125,466 hectares are cultivable and 9,704 hectares are fallow land.

5.1.11 Noakhali

The area of Noakhali district is 3601 sq. km. Noakhali city located in the district is the largest city and business center of the Noakhali region. The total population of Noakhali district is 2,533,394 and per capita income is 19,390 BDT equivalent to 277 USD.

Average literacy in the district is 37.11%; male 42.9% and female 31.5%. The main occupations are agriculture 30.27%, agricultural laborer 16.99%, wage laborer 2.86%, commerce 12.23%, service 19.39%, transport 2.46%, fishing 1.4% and others 14.4%. Of the total land, 229,385 hectares are cultivable and 17,136 hectares are fallow land.

5.1.12 Feni

The area of Feni district is 928 sq. km. The total population of Feni is 1,196,219 and per capita income is 17,640 BDT equivalent to 252 USD. Feni district is located in the Noakhali region.

Average literacy in the district is 40.7%; male 48.2% and female 33.1%. The main occupations are agriculture 36.67%, agricultural laborer 11.54%, wage laborer 2.1%, commerce 12.29%, industry 1.13%, service 18.86%, transport 3.31%, construction 1.12% and others 12.98%. Of the total land, 74824 hectares are cultivable and 772 hectares are fallow land.

5.1.13 Chittagong

Chittagong city, located in the Chittagong district, is the second largest city and the business capital of Bangladesh. It is the largest of all the cities located in the coastal region. Chittagong seaport is the largest seaport of Bangladesh and plays a vital role in the economy of Bangladesh as well as for the whole region. The port was badly damaged in 1991, when the Super cyclone hit the coast of Chittagong on April 29. More than 138,000 people died from that tropical cyclone.

The area of Chittagong district is 5283 sq. km. The total population of Chittagong is 6,545,078 and per capita income is 39,130 BDT equivalent to 559 USD. Average literacy in the district is 43.2%; male 50.3% and female 35%. The main occupations are agriculture 18.71%, fishing 1.16%, agricultural laborer 12.13%, wage laborer 3.54%, industry 1.72%, commerce 16.58%, transport 4.52%, construction 1.43%, service 24.09% and others 16.12%. Of the total land, 223,782.40 hectares are cultivable and 115,901.25 hectares are fallow land. Only 34.18% cultivable land is under irrigation.

5.1.14 Cox's Bazar

Cox's Bazar is famous for its world's longest sea beach and it is a tourist city which is still underdeveloped. The area of Cox's Bazar district is 2492 sq. km. The total population of Cox's Bazar is 1,757,321 and per capita income is 27,370 BDT equivalent to 391 USD.

Average literacy in the district is 21.9%; male 28.2% and female 14.9%. The main occupations are agriculture 25.64%, forestry 1.85%, fishing 4.01%, agricultural laborer 21.2%, wage laborer 7.64%, service 4.68%, commerce 15.14%, transport 1.86%, others 17.98%. Of the total land, 79,500 hectares are cultivable and 8,620 hectares are fallow land. Only 64% cultivable land is under irrigation.

5.2 Selection of variables and methodology

As described in Chapter II, cyclone risk means exposure of an area to the chance or threat of cyclone hazard. Tropical cyclones are always accompanied by storm surges and high storm surge is a common phenomenon during the tropical cyclone landfall in Bangladesh. The effect of high winds and storm surges in coastal areas also depends on the location of the particular district from the coastline. Thus, in this study, the variables that are considered in terms of cyclone risk analysis include distribution of historical landfalling cyclones, maximum cyclone wind speed, maximum surge height and average distance of coastal districts from the coastline.

Vulnerability is related to the coping capacity of the people. Coping means ability to withstand risks at a particular point of time. It could be money, deployment of technology, infrastructure or emergency response system. The variables that are chosen to analyze the coping capacity of the Bangladesh coastal areas include population density, per capita income, quantity and distribution of cyclone shelters, road network and finally the distribution of casualties from the past tropical cyclones. Whereas the parameters of cyclone risk are comprised of natural features, cyclone vulnerability is conceptualized as a combination of cyclone risk and coping capacity of the people. Hence, all the factors in combination are evaluated to analyze the cyclone vulnerability.

The z-score formula discussed in Chapter II (Eq. 2.19) is used to testify the values of corresponding districts regarding a particular variable to determine the conditions of the district. Value of z-score close to zero represents the mean or average condition among the coastal districts. Here, z-score values ranging from -0.1 to +0.1 is selected to represent the average condition. Values higher or lower than this range represent better or worse condition respectively. The categories with corresponding z-score range used in this study are shown in Table 5.1.

Table 5.1 Category based on z-score

z-score	Cyclone risk/vulnerability	Coping capacity
>= 0.5	Low risk/vulnerability	High coping capacity
0.11 – 0.49	Above average	Above average
-0.1 - +0.1	Average/Medium risk/vulnerability	Average
-0.49 - -0.11	Below average	Below Average
=< -0.5	High risk/vulnerability	Low coping capacity

Based on Table 5.1, the coastal districts are categorized, and using GIS the distribution of a selected variable among the coastal districts is shown on the map. A composite cyclone risk map for the coastal areas of Bangladesh is produced combining all the selected variables of cyclone risk. Similarly, a composite coping capacity map is created showing the socio-economic vulnerability of the coastal districts. Finally, a cyclone vulnerability map for Bangladesh is produced combining all the variables of cyclone risk and coping capacity.

Here, an example is given to illustrate the application of z-score to determine the condition of the districts in terms of selected variables. Suppose, it is desired to determine the condition of cyclone shelter distribution in Satkhira district compared to other coastal districts. There are only 60 cyclone shelters in the Satkhira district. The total population of Satkhira district is 1,843,000 and the number of cyclone shelter per thousand population is 0.0326. The modified z-score formula used for regional comparison in this study is as follows.

$$z = \frac{K - \frac{\sum K}{N}}{\sqrt{\frac{\sum \left[K - \left(\frac{\sum K}{N} \right) \right]^2}{N}}}$$

Where, N is the number of coastal districts, N = 14

K is the weighted value of a district in terms of a variable/variables in a scale 0-1.

Cox's Bazar has 402 cyclone shelters in the district. Although it is not the highest number of cyclone shelters for a district (Chittagong has the highest number of cyclone shelters, 407), in terms of cyclone shelter per thousand population Cox's Bazar is ranked on top with a value of 0.2054. Hence, the weighted value of Cox's Bazar in terms of cyclone shelters is 1.00. Accordingly, the weighted value of Satkhira in terms of cyclone shelters is 0.16. Similarly, the weighted values for all other districts are calculated against the weighted value of Cox' Bazar. Thus, we can calculate the total of all the weighted values and find the mean, which is 0.32. Now for Satkhira in terms of cyclone shelter, by putting its weighted value K=0.16, N=14 and the mean value 0.32, we get the z-score of Satkhira -0.642. Z-score values ranging from -0.1 to +0.1 represent the average condition among the study districts. So, the z-score value for Satkhira certainly does not represent the average condition but a worse condition. Based on the Table 5.1, it represents extremely poor distribution among the coastal districts since the value is below -0.5.

Similarly, the condition for all other districts can be determined and using GIS the result can be shown on a map. In terms of more than one variables for a district such as for the composite cyclone risk, the mean of the weighted values of all the respective variables for a particular district is taken as the composite weighted value.

5.3 Cyclone risk analysis

The variables considered for cyclone risk analysis are: distribution of the past landfalling cyclones, maximum cyclone wind speed, maximum possible surge height and the average distance of the districts from the open sea.

5.3.1 Distribution of landfalling cyclones (1877-2003)

Table 5.2 shows the z-score values of different districts based on the frequency of past cyclones landfall during 1877-2003. The data are obtained from the landfalling cyclone climatology developed in Chapter III, which is based on the coastal regions. It is assumed that the data for the coastal regions would also be applicable to the corresponding districts, thus the frequency for the coastal districts under a particular region is the same all through the region.

Table 5.2 z-score of storm distribution

Sl. No	Districts	No. of Storms	Ki	z-score
1	Satkhira	36	0.25	-0.706
2	Khulna	36	0.25	-0.706
3	Bagerhat	36	0.25	-0.706
4	Barguna	31	0.29	-0.567
5	Barisal	31	0.29	-0.567
6	Bhola	31	0.29	-0.567
7	Jhalokati	31	0.29	-0.567
8	Pirojpur	31	0.29	-0.567
9	Patuakhali	31	0.29	-0.567
10	Lakshmipur	9	1.00	1.877
11	Noakhali	9	1.00	1.877
12	Feni	9	1.00	1.877
13	Chittagong	21	0.43	-0.091
14	Cox's Bazar	20	0.45	-0.017

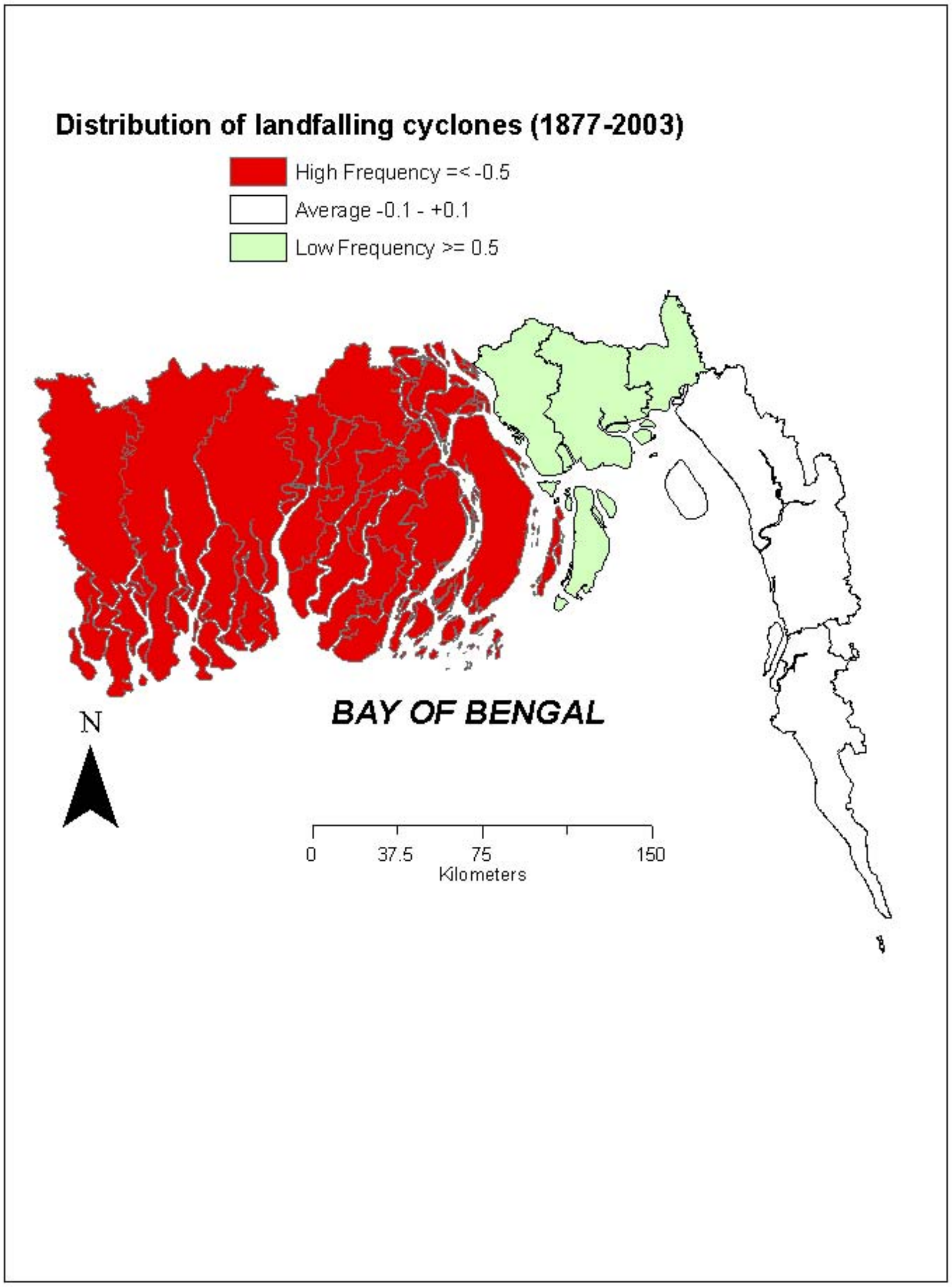

Figure 5.2 Distribution of landfalling cyclones (1877-2003)

Figure 5.2 shows the distribution of cyclone frequencies in the coastal areas of Bangladesh. The red area shows the high frequency area, where z-score value is less than -0.5. The districts under Khulna and Barisal region fall in this category. The districts under Noakhali region are in the low frequency area with z-score value greater than 0.5. Chittagong and Cox's Bazar are in average situation with z-score values -0.091 and -0.017, respectively, which is within the range of -0.1 - +0.1. Table 5.3 shows the grouping of the districts under different category.

Table 5.3 Grouping of districts (storm distribution)

Categories and Range	Districts
High frequency (=< -0.5)	Satkhira, Khulna, Bagerhat, Pirojpur, Barguna, Patuakhali, Jhalokati, Barisal, Bhola,
Average (-0.1 - +0.1)	Chittagong, Cox's Bazar
Low frequency (>= 0.5)	Lakshmipur, Noakhali, Feni

5.3.2 Maximum cyclone wind speed

Table 5.4 shows the z-score values of different districts based on the maximum cyclone wind speed experienced in the five coastal regions from the landfalling tropical cyclones during 1877-2003 and also from the simulations performed on the five coastal sites.

Table 5.4 z-score of maximum wind speed

Sl. No	Districts	Max. wind speed (knots)	Ki	z-score
1	Satkhira	110	0.81	0.249
2	Khulna	110	0.81	0.249
3	Bagerhat	110	0.81	0.249
4	Barguna	130	0.68	-0.727
5	Barisal	130	0.68	-0.727
6	Bhola	130	0.68	-0.727
7	Jhalokati	130	0.68	-0.727
8	Pirojpur	130	0.68	-0.727
9	Patuakhali	130	0.68	-0.727
10	Lakshmipur	89	1.00	1.746
11	Noakhali	89	1.00	1.746
12	Feni	89	1.00	1.746
13	Chittagong	140	0.64	-1.111
14	Cox's Bazar	125	0.71	-0.512

Figure 5.3 shows the distribution of maximum cyclone wind speed in the coastal areas. The red areas showing maximum wind speed greater than 125 knots, where the z-score values are =<-0.5. The green hatched areas have maximum wind speed between 90-110 knots (z-score values 0.11 – 0.49) and the light green area represents wind speed less than 90 knots (z-score values >=0.5).

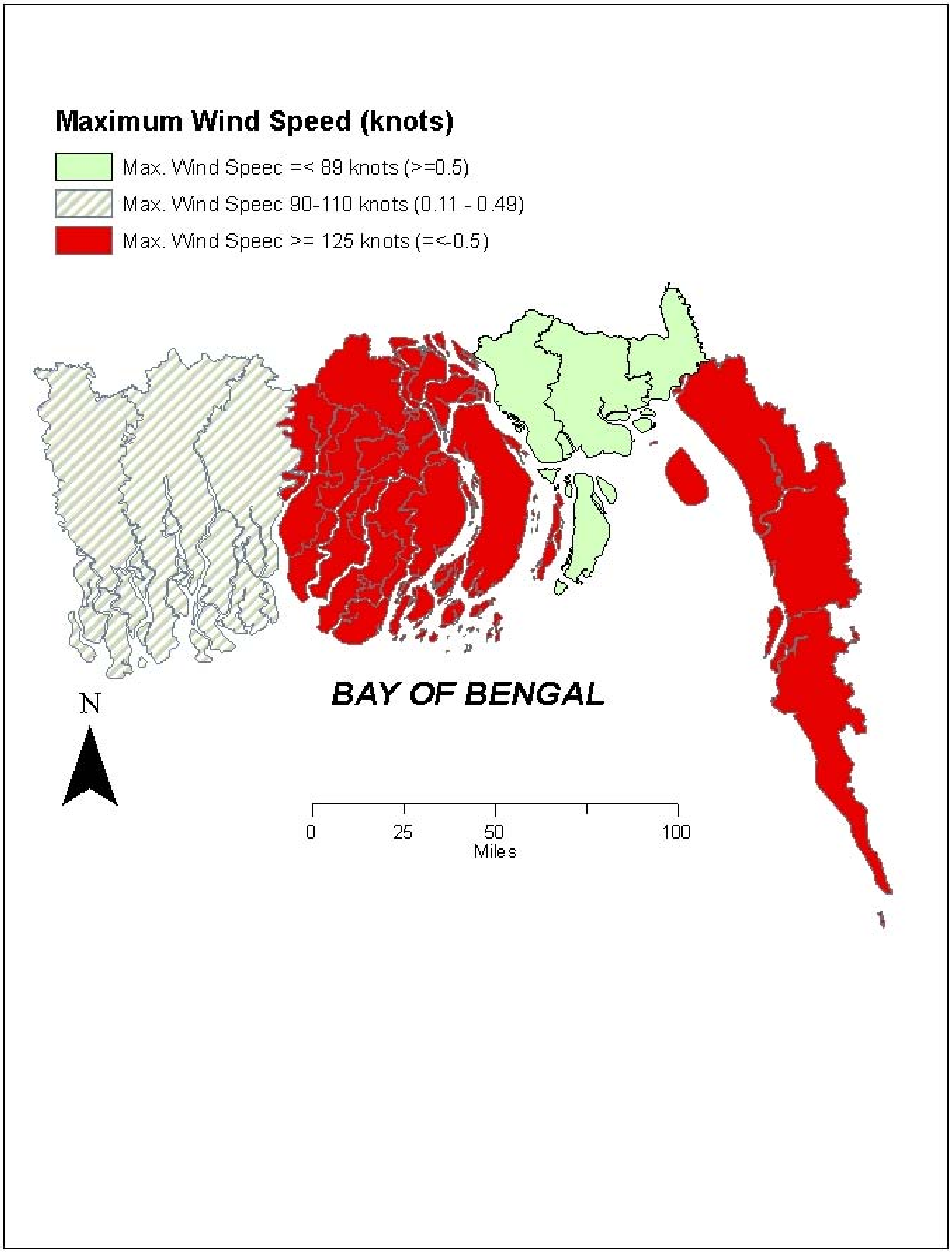

Figure 5.3 Maximum cyclone wind speed in coastal areas

Table 5.5 showing the grouping of coastal districts under different categories based on the z-score values of maximum cyclone wind speed.

Table 5.5 Grouping of districts (maximum wind speed)

Categories and Range	Districts
Max. wind speed >= 125 knots (=< -0.5)	Pirojpur, Barguna, Patuakhali, Jhalokati, Barisal, Bhola, Chittagong, Cox's Bazar
Max. wind speed 90-110 knots (0.11 - 0.49)	Satkhira, Khulna, Bagerhat
Max. wind speed =< 89 knots (>= 0.5)	Lakshmipur, Noakhali, Feni

5.3.3 Maximum storm surge height

Table 5.6 shows the z-score values of different districts based on maximum surge height obtained from the Monte Carlo simulations.

Table 5.6 z-score of maximum surge height

Sl. No	Districts	Max. Surge Height (feet)	Ki	z-score
1	Satkhira	41.14	0.26	-0.618
2	Khulna	41.14	0.26	-0.618
3	Bagerhat	41.14	0.26	-0.618
4	Barguna	27.69	0.39	0.075
5	Barisal	27.69	0.39	0.075
6	Bhola	27.69	0.39	0.075
7	Jhalokati	27.69	0.39	0.075
8	Pirojpur	27.69	0.39	0.075
9	Patuakhali	27.69	0.39	0.075
10	Lakshmipur	38.39	0.28	-0.516
11	Noakhali	38.39	0.28	-0.516
12	Feni	38.39	0.28	-0.516
13	Chittagong	37.63	0.28	-0.485
14	Cox's Bazar	10.72	1.00	2.433

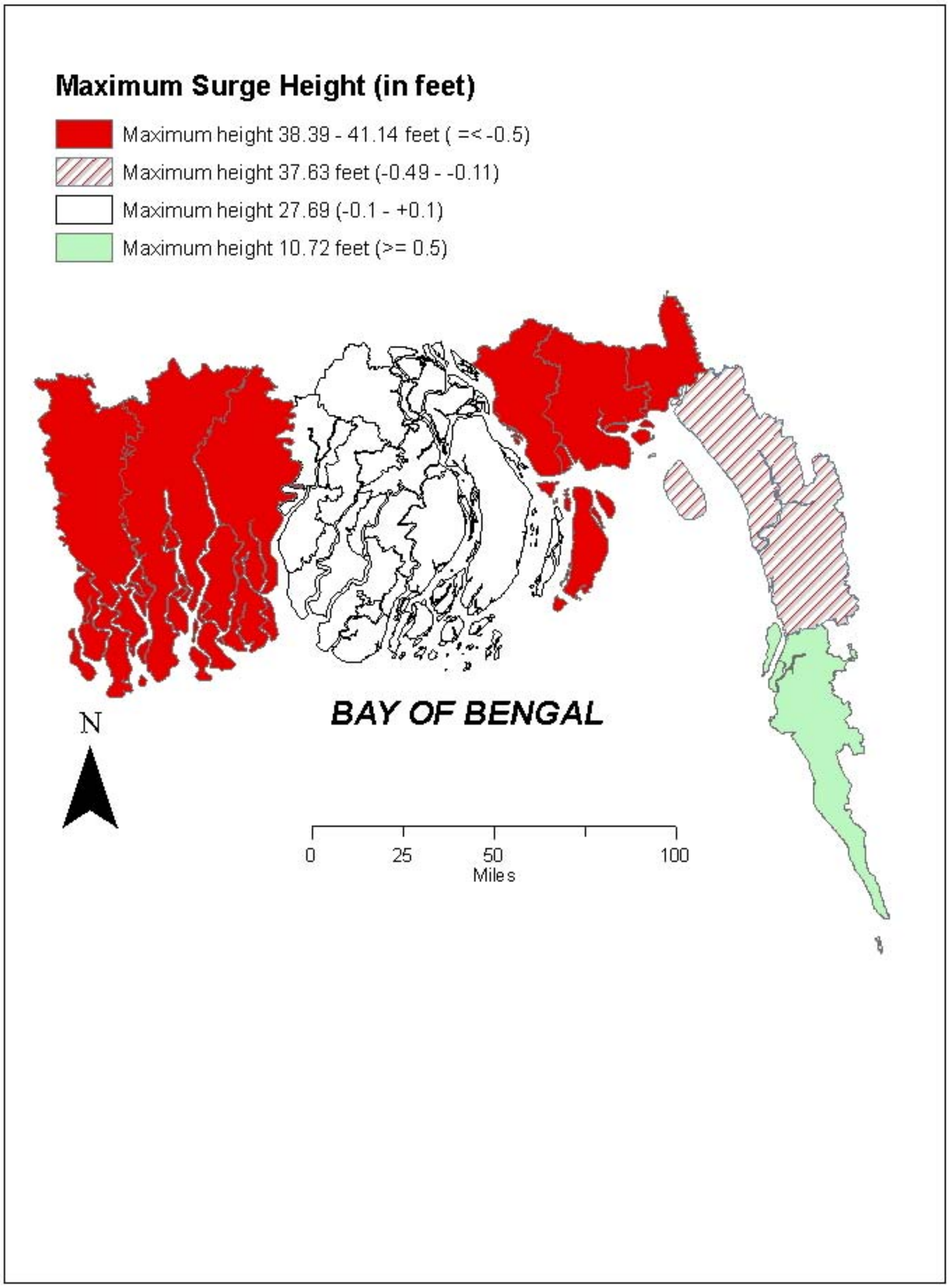

Figure 5.4 Maximum surge height in coastal areas

Figure 5.4 shows the distribution of maximum surge height in the coastal areas of Bangladesh. Noakhali and Khulna may experience possible maximum surge height between 38.39-41.14 feet (z-score values =<-0.5). Mandal (1991) calculated maximum surge height for the India and Bangladesh coast based on pre-computed nomograms and in that study the highest possible surge can be experienced at Hatia of Noakhali district which is 13.2 meters or 42.3 feet.

The red hatched area shows the maximum possible surge height of 37.63 feet (z-score values -0.49 - -0.11) which is at Chittagong district. In the 1991 Super cyclone that hit the coast of Chittagong, the maximum surge height was more than 30 feet and many people died because of that. The Barisal coast, which was hit by another super cyclone in 1970 may experienced maximum surge height of 27.69 feet (z-score values -0.1 - +0.1). It is suspected that in the 1970 Super cyclone, the surge height was not less than 25 feet as many people died from storm surges. Cox's Bazar, in the light green color, shows the lowest maximum surge height of all regions, which is 10.72 feet (z-score value >=0.5).

Table 5.7 shows the grouping of coastal districts under different categories based on the z-score values of maximum surge height.

Table 5.7 Grouping of districts (maximum surge height)

Categories and Range	Districts
Max. surge height 38.39-41.14 feet (=< -0.5)	Satkhira, Khulna, Bagerhat, Lakshmipur, Noakhali, Feni
Max. surge height 37.63 feet (-0.49 - -0.11)	Chittagong
Max. surge height 27.69 feet (-0.1 – +0.1)	Pirojpur, Barguna, Patuakhali, Jhalokati, Barisal, Bhola
Max. surge height 10.72 feet (>= 0.5)	Cox's Bazar

5.3.4 Average distance from the open sea

The z-score values of different districts based on their average distances from the open sea are shown in Table 5.8. The distance is calculated from the center point of each district to the open sea assuming the shape of the districts as rectangular form.

Table 5.8 z-score of distance from open sea

Sl. No	Districts	Average distance from open sea (km)	Ki	z-score
1	Satkhira	64	0.89	1.178
2	Khulna	64	0.89	1.178
3	Bagerhat	56	0.78	0.820
4	Barguna	24	0.33	-0.615
5	Barisal	72	1.00	1.537
6	Bhola	8	0.11	-1.332
7	Jhalokati	48	0.67	0.461
8	Pirojpur	48	0.67	0.461
9	Patuakhali	8	0.11	-1.332
10	Lakshmipur	48	0.67	0.461
11	Noakhali	32	0.44	-0.256
12	Feni	40	0.56	0.102
13	Chittagong	8	0.11	-1.332
14	Cox's Bazar	8	0.11	-1.332

Figure 5.5 illustrates the comparison of different districts on their average distances from the open sea. The red area depicts the area closest to the open sea, and the light green area represents the farthest distance among all the coastal districts. The grouping of the districts based on z-score value is given in Table 5.9.

Table 5.9 Grouping of districts (average distance)

Categories and Range	Districts
Near to the sea <30 km (=< -0.5)	Chittagong, Cox'sBazar, Barguna, Bhola, Patuakhali
Below average 30-39 km(-.49- -.11)	Noakhali
Average distance 40 km(-0.1– +0.1)	Feni
Above average 41-50 km(.11–.49)	Lakshmipur, Pirojpur, Jhalokati
Distant from sea>50km (>= 0.5)	Khulna, Satkhira, Bagerhat, Barisal

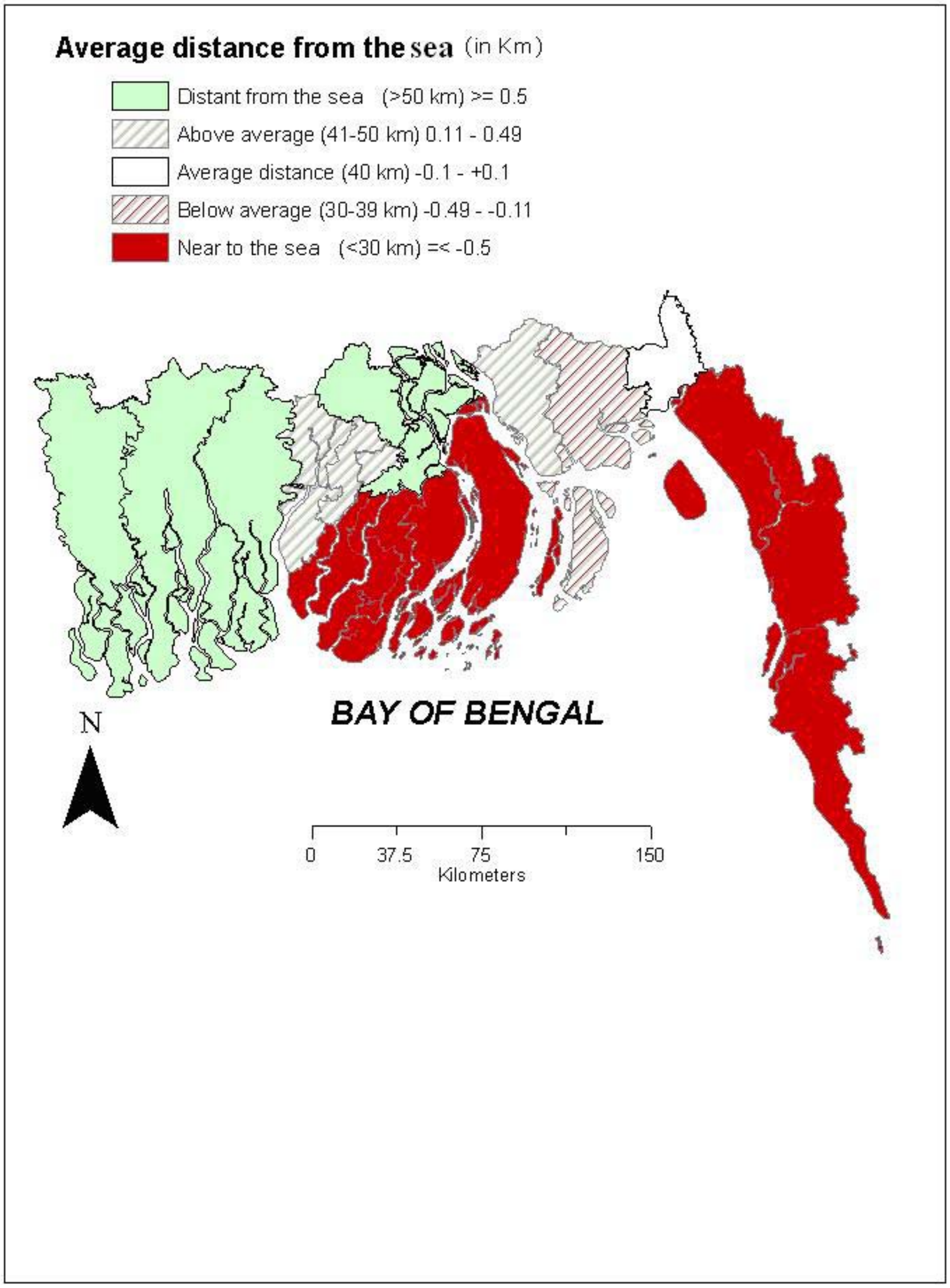

Figure 5.5 Average distance from the open sea

5.3.5 Composite cyclone risk map

To perceive the cyclone risk in the coastal areas of Bangladesh, factors such as distribution of historical landfalling cyclones, maximum cyclone wind speed, maximum surge height and average distance of coastal districts from the coastline are considered all together. In the previous sections, we get individual weighted values for all districts for each of the variable were obtained. Here, for each district all the four weighted values are combined and a mean weighted value is obtained, which is used to calculate the z-score for each district to compare the cyclone risk. Table 5.10 shows the z-score values of different districts based on the mean Ki values, which represent the composite weighted value of all the parameters concerned.

Table 5.10 z-score of composite cyclone risk variables

Sl. No	Districts	Weighted Value for No. of Storms	Weighted Value for Max. Wind Speed	Weighted Value for Surge Height	Weighted Value for Avg. distance from the coast	Mean Ki value	z-score
1	Satkhira	0.25	0.81	0.26	0.89	0.55	0.167
2	Khulna	0.25	0.81	0.26	0.89	0.55	0.167
3	Bagerhat	0.25	0.81	0.26	0.78	0.52	-0.068
4	Barguna	0.29	0.68	0.39	0.33	0.42	-0.919
5	Barisal	0.29	0.68	0.39	1.00	0.59	0.490
6	Bhola	0.29	0.68	0.39	0.11	0.37	-1.390
7	Jhalokati	0.29	0.68	0.39	0.67	0.51	-0.213
8	Pirojpur	0.29	0.68	0.39	0.67	0.51	-0.213
9	Patuakhali	0.29	0.68	0.39	0.11	0.37	-1.390
10	Lakshmipur	1.00	1.00	0.28	0.67	0.74	1.728
11	Noakhali	1.00	1.00	0.28	0.44	0.68	1.258
12	Feni	1.00	1.00	0.28	0.56	0.71	1.493
13	Chittagong	0.43	0.64	0.28	0.11	0.37	-1.417
14	Cox’s Bazar	0.45	0.71	1.00	0.11	0.57	0.304

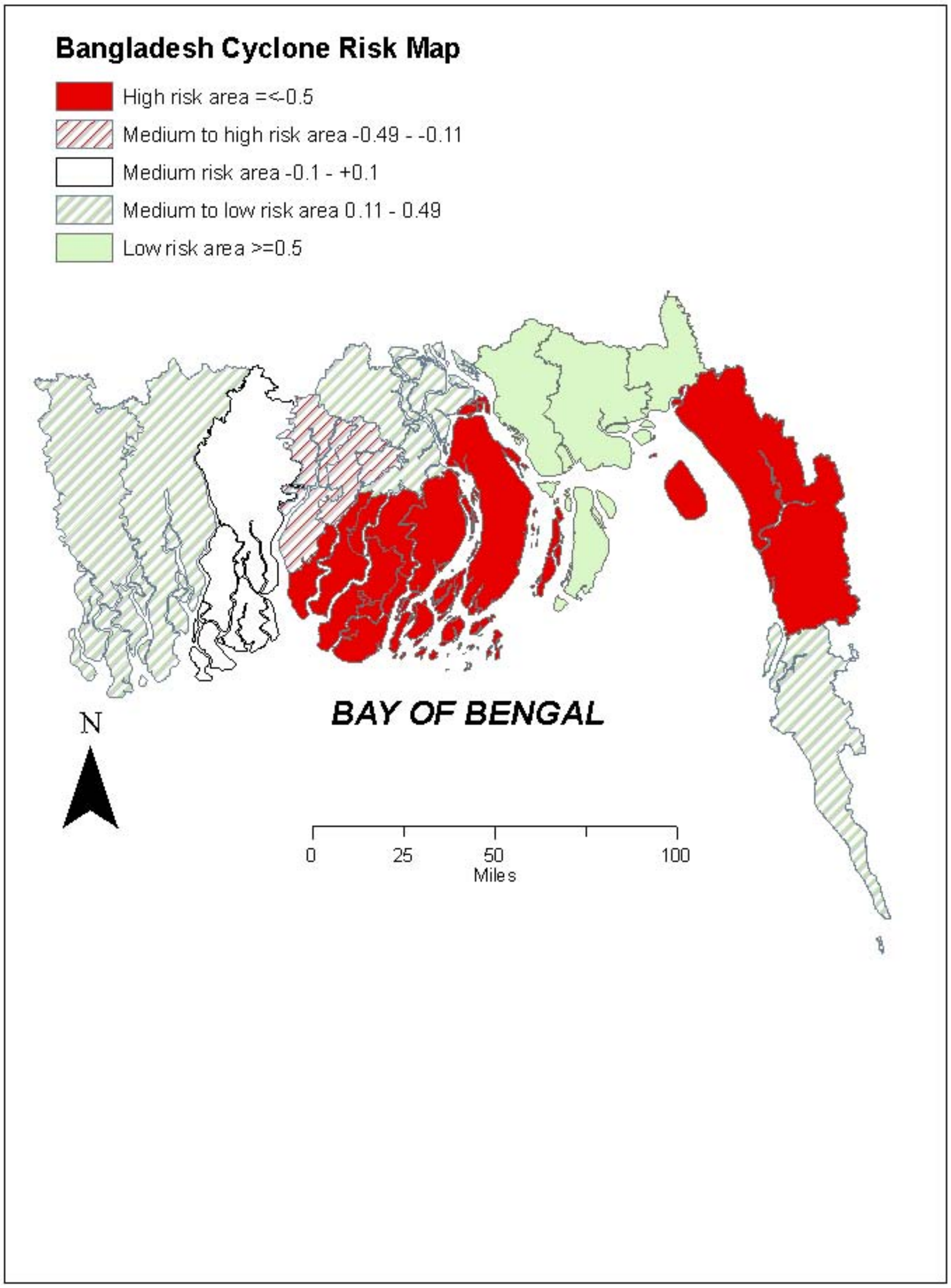

Figure 5.6 Cyclone risk map

Figure 5.6 illustrates the cyclone risk map of Bangladesh depicting the high and low risk areas to cyclone hazard. The red areas represent the high risk area with z-score values =<-0.5. The white area represents the medium risk area, and the light green area represents low risk to cyclone. The grouping of the coastal districts under different categories based on z-score values is given in Table 5.11.

Table 5.11 grouping of districts (composite cyclone risk)

Categories and range	Districts
Low risk area (>= 0.5)	Lakshmipur, Noakhali, Feni
Medium to low risk area (0.11 – 0.49)	Satkhira, Khulna, Barisal, Cox's Bazar
Medium risk area (-0.1 - +0.1)	Bagerhat
Medium to high risk area (-0.49 - -0.11)	Jhalokati, Pirojpur
High risk area (=< -0.5)	Chittagong, Bhola, Patuakhali, Barguna

5.3.5.1 Low risk area to cyclone

Lakshmipur, Noakhali and Feni districts are placed in this area. The main reason for placing these districts in this area is because historically they faced the lowest number of cyclones among all the coastal districts. Also, the maximum wind speed is the lowest in this region compared to other districts. But, in terms of surge height, the region can be at high risk and the districts are not far away from the coastline. Thus, even though the districts are placed in the low risk area, careful attention should be given regarding storm surge.

5.3.5.2 Medium to low risk area

Satkhira, Khulna, Barisal and Cox's Bazar districts comprise this area. For Satkhira, Khulna and Barisal, the distribution of landfalling storms is higher as well as the maximum wind speed and surge height compared to other districts. But due to their average distance from the coastline, these districts are placed in a comparatively low risk area. The Sundarbans forest is located along the coast of Satkhira and Khulna and it works as a shield against high wind and surge during cyclone landfall thus protecting the inland. Barisal district is also located behind the offshore islands and other districts along the coastline, which usually get the hardest hit during landfall. Cox's Bazar is placed in this area because of its low surge height and comparatively low frequency of cyclone landfall although it is located very close to the coastline and the maximum wind speed during the past cyclones is high (125 knots).

5.3.5.3 Medium risk area

Bagerhat is the only district located in the medium risk area. This is due to its average distance from the coastline, which is comparatively less than Satkhira and Khulna.

5.3.5.4 Medium to high risk area

Jhalokati and Pirojpur are placed in this category. The weighted values of all the four parameters are comparatively higher for these two districts, thus, based on the Z-score values these two districts are placed in this comparatively high risk area.

5.3.5.5 High risk area

Chittagong, Bhola, Patuakhali and Barguna districts are in the high risk area. All of these districts are located very close to the coastline and have a history of high cyclone frequency with high maximum wind speed and surge height during landfall.

5.4 Analysis of socio-economic vulnerability (coping capacity)

5.4.1 Distribution of population density

Table 5.12 shows the z-score values of the coastal districts based on the population density. The density is calculated by dividing per thousand population in per square kilometer of the district. The area and population data are obtained from the *Statistical Year Book of Bangladesh (2003)*. Bagerhat has the lowest density of population among all the districts, thus, given the weighted value of 1.00 in the scale of 0-1. The weighted value of other districts are calculated against the weighted value of Bagerhat.

Table 5.12 z-score of population density

Sl. No	Districts	Population (in 000)	Area (sq km)	Population(000) /sq km	Ki	z-score
1	Satkhira	1843	3858	0.4777	0.80	0.937
2	Khulna	2334	4395	0.5311	0.72	0.573
3	Bagerhat	1516	3959	0.3829	1.00	1.834
4	Barguna	838	1832	0.4574	0.84	1.098
5	Barisal	2331	2791	0.8352	0.46	-0.615
6	Bhola	1677	3403	0.4928	0.78	0.826
7	Jhalokati	696	758	0.9182	0.42	-0.802
8	Pirojpur	1127	1308	0.8616	0.44	-0.678
9	Patuakhali	1444	3205	0.4505	0.85	1.156
10	Lakshmipur	1479	1456	1.0158	0.38	-0.984
11	Noakhali	2533	3601	0.7034	0.54	-0.226
12	Feni	1196	928	1.2888	0.30	-1.344
13	Chittagong	6545	5283	1.2389	0.31	-1.291
14	Cox’s Bazar	1957	2492	0.7853	0.49	-0.483

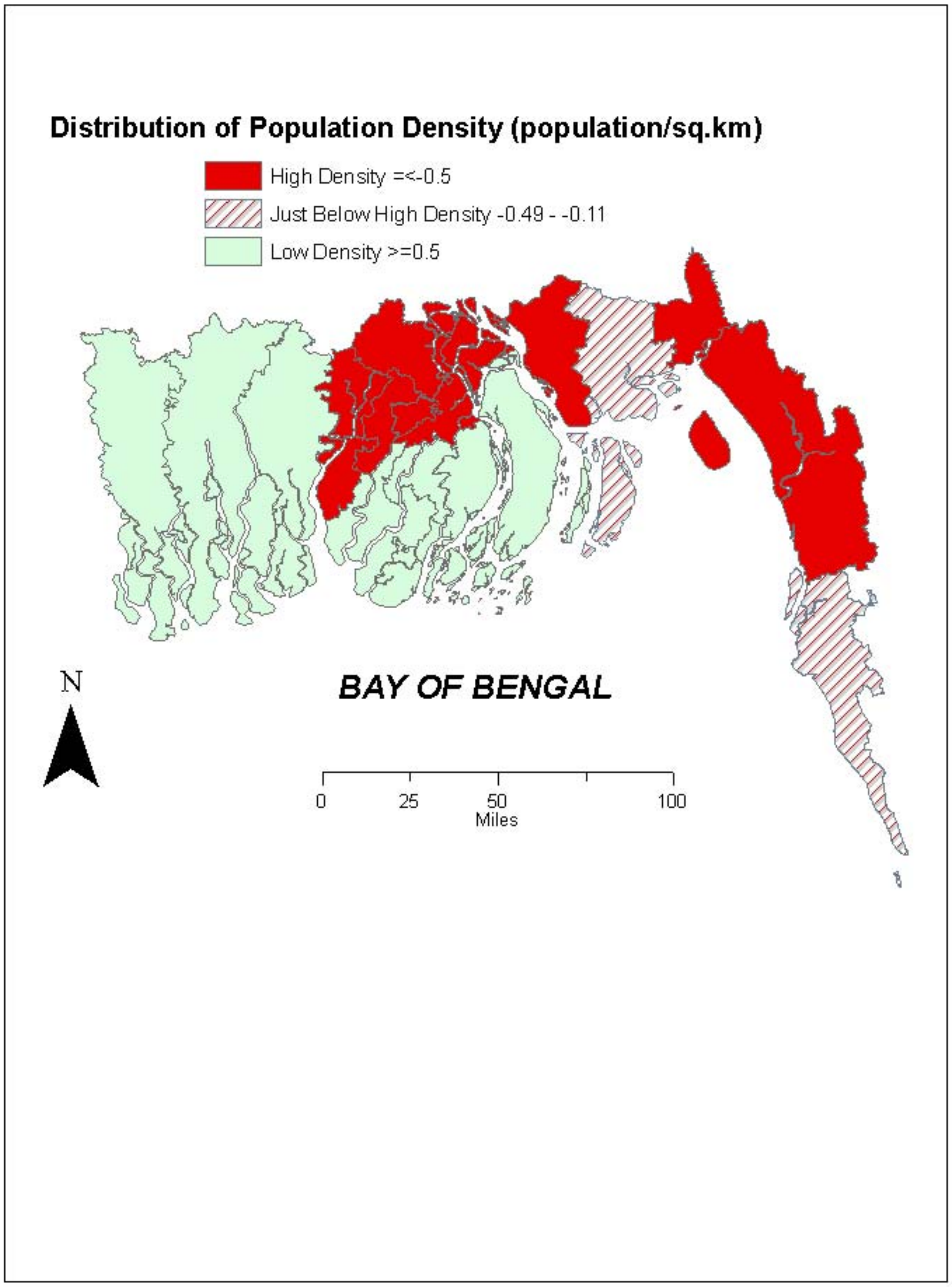

Figure 5.7 Distribution of population density

Figure 5.7 shows the distribution of population density in the coastal areas of Bangladesh. The red area represents the highest population density compared to other areas with the z-score values =<-0.5. The light green area represents the lowest density with z-score value >=0.5. The red hatched area is also densely populated but just below the highest density with z-score values ranging from -0.49 - -0.11.

The grouping of the coastal districts under different categories based on z-score values is given in Table 5.13.

Table 5.13 Grouping of districts (population density)

Categories and Range	Districts
High density (=< -0.5)	Pirojpur, Jhalokati, Barisal, Chittagong, Feni, Lakshmipur
Just below high denisty (0.11 - 0.49)	Noakhali, Cox’s Bazar
Low density (>= 0.5)	Satkhira, Khulna, Bagerhat, Barguna Patuakhali, Bhola

5.4.2 Distribution of per capita income

Table 5.14 shows the z-score values of the coastal districts based on the per capita income in USD. Chittagong has the highest per capita income among the coastal districts with 559 USD and therefore, given the highest weighted value 1.00 in the scale of 0-1. The weighted values, Ki for other districts are calculated in compare to the weighted value of Chittagong. Feni has the lowest per capita income of 252 USD and the corresponding weighted value is 0.45 with respect to the weighted value of Chittagong.

Table 5.14 z-score of per capita income

Sl. No	Districts	per capita income (USD)	Ki	z-score
1	Satkhira	320	0.57	-0.220
2	Khulna	460	0.82	1.492
3	Bagerhat	335	0.60	-0.037
4	Barguna	336	0.60	-0.024
5	Barisal	286	0.51	-0.636
6	Bhola	320	0.57	-0.220
7	Jhalokati	256	0.46	-1.003
8	Pirojpur	271	0.48	-0.819
9	Patuakhali	361	0.65	0.281
10	Lakshmipur	308	0.55	-0.367
11	Noakhali	277	0.50	-0.746
12	Feni	252	0.45	-1.051
13	Chittagong	559	1.00	2.702
14	Cox's Bazar	391	0.70	0.648

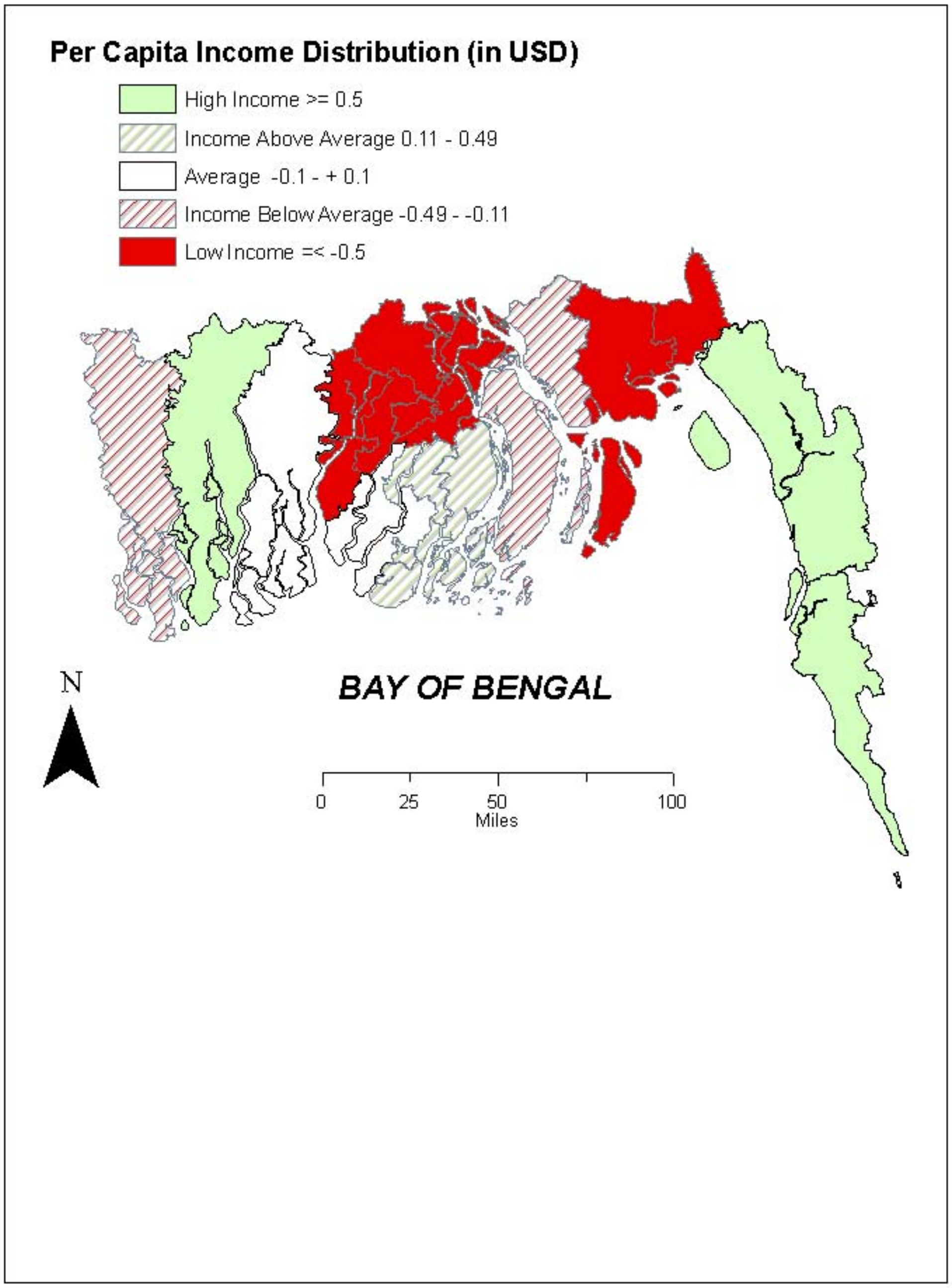

Figure 5.8 Distribution of per capita income

Figure 5.8 shows the distribution of per capita income in the coastal areas of Bangladesh. The red area represents the lowest per capita income among all the coastal districts with z-score values =<-0.5. The light green area represents the highest per capita income with z-score value >=0.5.

The grouping of the coastal districts under different categories based on z-score values is given in Table 5.15.

Table 5.15 Grouping of districts (per capita income)

Categories and Range	Districts
Low income (=< -0.5)	Feni, Noakhali, Jhalokati, Barisal , Pirojpur
Income below average (-0.49- -0.11)	Lakshmipur, Bhola, Satkhira
Average income (-0.1– +0.1)	Bagerhat, Barguna
Income above average (0.11–0.49)	Patuakhali
High income (>= 0.5)	Khulna, Chittagong, Cox’s Bazar

5.4.3 Distribution of cyclone shelters

Since the devastating 1970 cyclone, a number of multi-storied permanent structures have been built intermittently in different coastal districts to provide shelter to the people during emergency. After the 1991 cyclone, Bangladesh government with the support of different foreign agencies, have been building multi-purpose cyclone shelters so that these can be used as primary schools during the normal period of time. But most of the cyclone shelters are in poor condition with minimum or no maintenance at all (Karim, 2001). Table 5.16 shows the district-wise distribution of cyclone shelters in the 14 coastal districts. According to Local Government Engineering Department, there are 2500 cyclone shelters in the country, but the data is available only for 1827 shelters.

Table 5.16 No. of cyclone shelters and percentage of population served in coastal districts.

Sl. No	Districts	No. of Cyclone Shelters	Population served	Total Population	% of Population Served
1	Cox's Bazar	402	247340	1957321	12.64
2	Bhola	227	152390	1676600	9.09
3	Patuakhali	108	91430	1444340	6.33
4	Barguna	74	48190	837955	5.75
5	Noakhali	211	127350	2533394	5.03
6	Lakshmipur	106	69070	1479371	4.67
7	Chittagong	407	272130	6545078	4.16
8	Feni	70	39990	1196219	3.34
9	Satkhira	60	46310	1843194	2.51
10	Bagerhat	49	31340	1515815	2.07
11	Pirojpur	30	18240	1126525	1.62
12	Khulna	47	35900	2334285	1.54
13	Barisal	26	15450	2330960	0.66
14	Jhalokati	10	4000	696055	0.57
	Total	**1827**	**1,199,130**	**27,517,112**	

Source: Local Government Engineering Department (LGED), Compendium of Environment Statistics, Statistical Year Book 2000, Bangladesh Bureau of Statistics.

Figure 5.9 A typical cyclone shelter in the coastal areas of Bangladesh (http://www.uwec.edu/jolhm/EH2/Molnar/images/shelter1.jpg)

The total number of population of the 14 coastal districts is 27,517,112 of which only 1,199,130 people are served from the cyclone shelters which is only 4.36% of the total population. The cyclone shelters in Cox's Bazar serve 12.64% of its population, which is the highest among all the 14 coastal districts. A comparative analysis of cyclone shelter distribution in the coastal districts is carried out ranking Cox's Bazar at the top (Table 5.17).

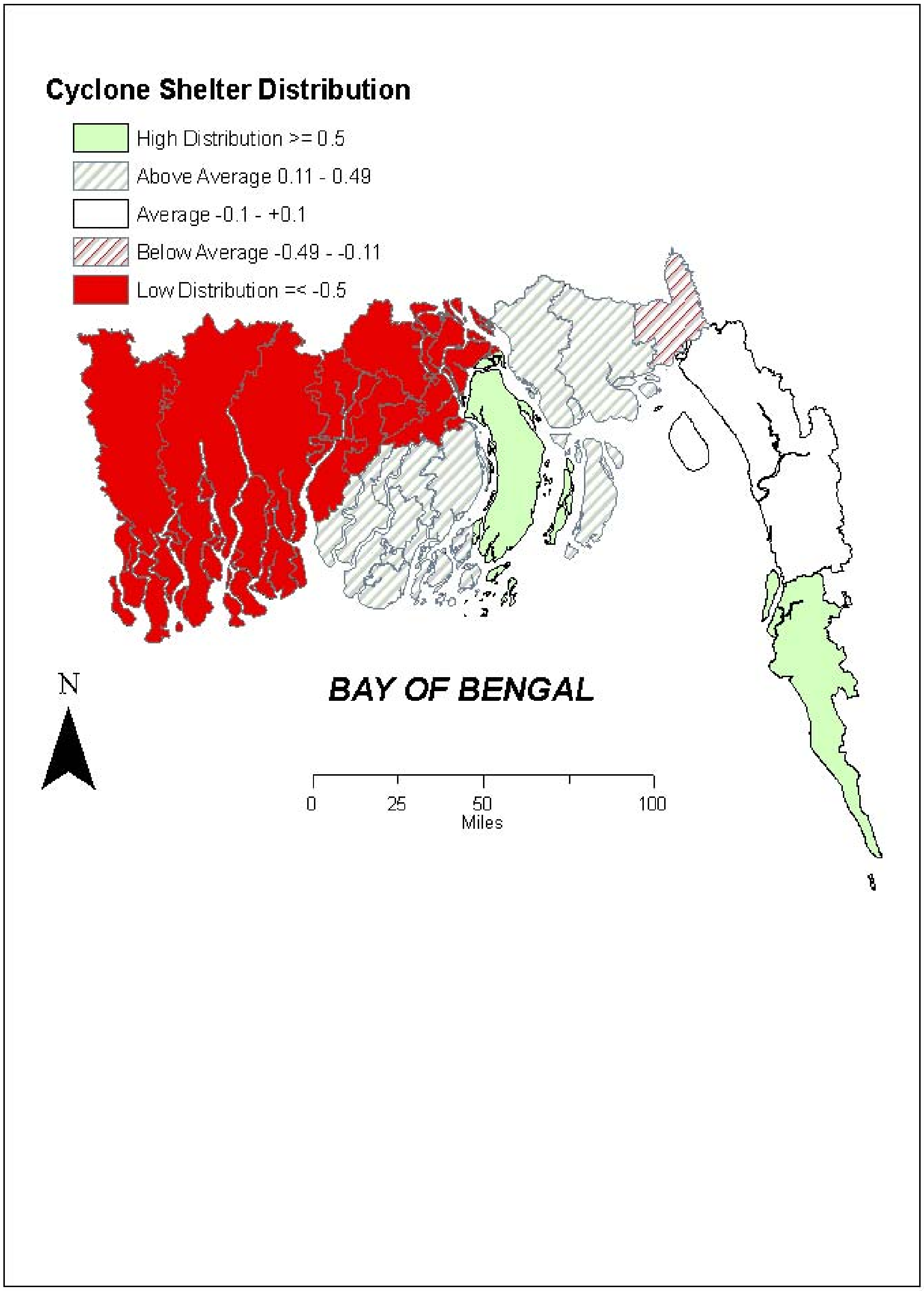

Figure 5.10 Distribution of cyclone shelters

Table 5.17 z-score of cyclone shelters

Sl. No	Districts	No. of Cyclone Shelters	Population (in 000)	Cyclone Shelter / thousand population	Ki	z-score
1	Satkhira	60	1843	0.0326	0.16	-0.642
2	Khulna	47	2334	0.0201	0.10	-0.884
3	Bagerhat	49	1516	0.0323	0.16	-0.647
4	Barguna	74	838	0.0883	0.43	0.445
5	Barisal	26	2331	0.0112	0.05	-1.06
6	Bhola	227	1677	0.1354	0.66	1.363
7	Jhalokati	10	696	0.0144	0.07	-0.997
8	Pirojpur	30	1127	0.0266	0.13	-0.758
9	Patuakhali	108	1444	0.0748	0.36	0.182
10	Lakshmipur	106	1479	0.0717	0.35	0.121
11	Noakhali	211	2533	0.0833	0.41	0.348
12	Feni	70	1196	0.0585	0.28	-0.136
13	Chittagong	407	6545	0.0622	0.30	-0.064
14	Cox's Bazar	402	1957	0.2054	1.00	2.729

Figure 5.9 shows the distribution of cyclone shelters in the coastal areas of Bangladesh. The grouping of the coastal districts under different categories based on z-score values is given in Table 5.18.

Table 5.18 Grouping of districts (cyclone shelters)

Categories and Range	Districts
Low distribution (=< -0.5)	Satkhira, Khulna, Bagerhat, Pirojpur, Barisal, Jhalokati
Below average (-0.49- -0.11)	Feni
Average (-0.1– +0.1)	Chittagong
Above average (0.11–0.49)	Lakshmipur, Noakhali, Patuakhali, Barguna
High distribution (>= 0.5)	Bhola, Cox’s Bazar

5.4.4 Road network distribution

Table 5.19 shows the z-score values of the coastal districts based on the length of road in per square kilometer. The width information also would have been helpful, but are not available. The data of the length of road in each district are provided by the Bangladesh Local Government Engineering Department. The proportion of road network in Jhalokati is better than any other district, thus, given the highest weighted value 1.00. The weighted values for other districts are given based on Jhalokati.

Table 5.19 z-score of road network

Sl. No	Districts	Road network (km)	Area (sq km)	road / sq km	Ki	z-score
1	Satkhira	2562	3858	0.6641	0.34	-0.786
2	Khulna	2180	4395	0.4960	0.25	-1.187
3	Bagerhat	2257	3959	0.5701	0.29	-1.010
4	Barguna	1804	1832	0.9847	0.50	-0.021
5	Barisal	3189	2791	1.1426	0.58	0.355
6	Bhola	2007	3403	0.5898	0.30	-0.963
7	Jhalokati	1481	758	1.9538	1.00	2.290
8	Pirojpur	2136	1308	1.6330	0.84	1.525
9	Patuakhali	3173	3205	0.9900	0.51	-0.009
10	Lakshmipur	1615	1456	1.1092	0.57	0.275
11	Noakhali	3211	3601	0.8917	0.46	-0.243
12	Feni	1330	928	1.4332	0.73	1.048
13	Chittagong	4677	5283	0.8853	0.45	-0.259
14	Cox's Bazar	1416	2492	0.5682	0.29	-1.015

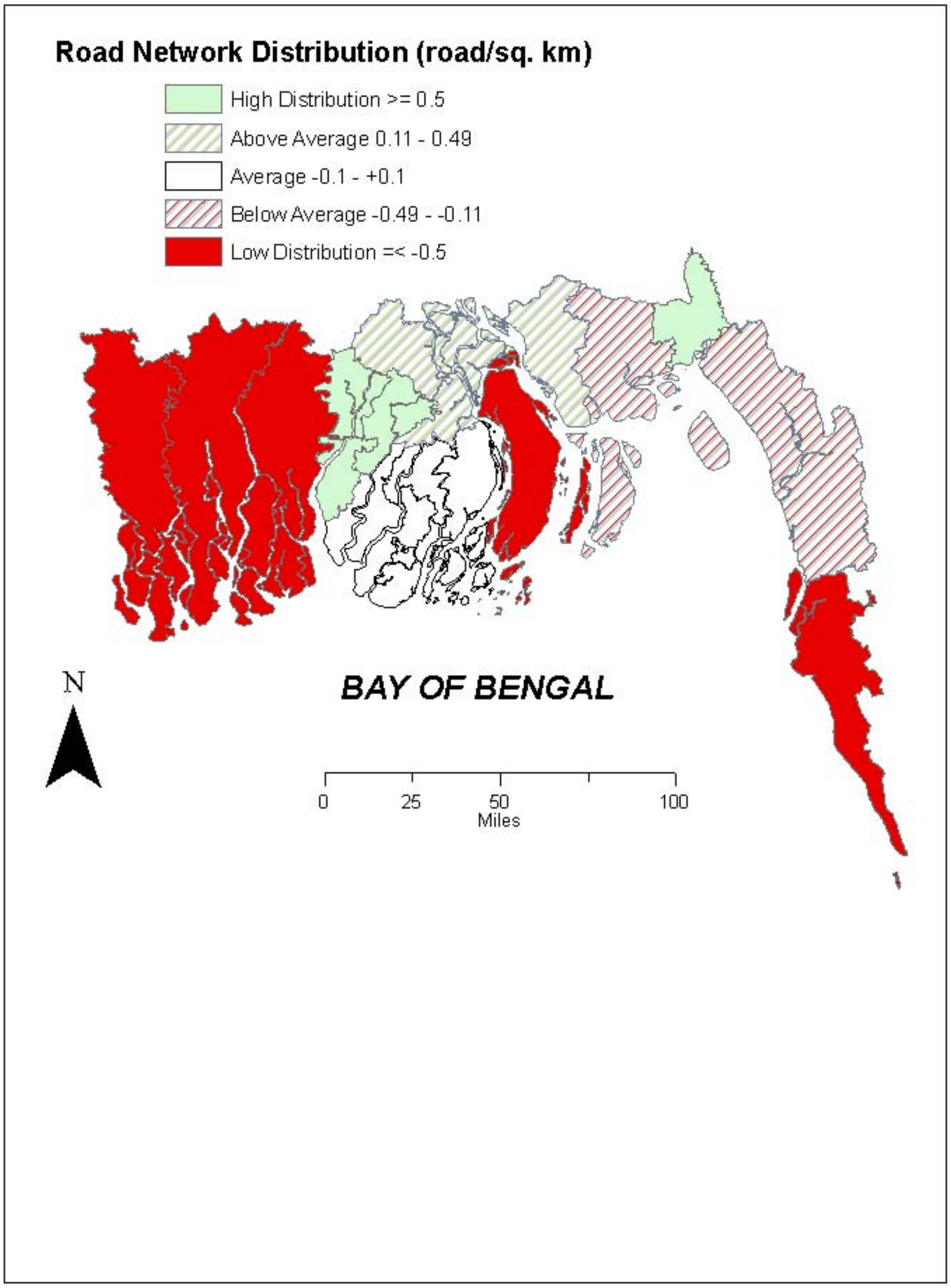

Figure 5.11 Distribution of road network

Figure 5.10 shows the distribution of road network in the coastal areas of Bangladesh. The red area represents the lowest distribution among all the coastal districts with z-score values =<-0.5. The light green area represents the high distribution with z-score value >=0.5.

The grouping of the coastal districts under different categories based on z-score values is given in Table 5.20.

Table 5.20 Grouping of districts (road network)

Categories and Range	Districts
Low distribution (=< -0.5)	Feni, Noakhali, Jhalokati, Barisal , Pirojpur
Below average (-0.49- -0.11)	Lakshmipur, Bhola, Satkhira
Average (-0.1– +0.1)	Bagerhat, Barguna
Above average (0.11–0.49)	Patuakhali
High distribution (>= 0.5)	Khulna, Chittagong, Cox's Bazar

5.4.5 Distribution of deaths from the past landfalling cyclones

Table 5.21 z-score of number of cyclone deaths in different coastal regions

Sl. No	Districts	No. of deaths	Ki	z-score
1	Satkhira	5267	0.07841	-0.055
2	Khulna	5267	0.07841	-0.055
3	Bagerhat	5267	0.07841	-0.055
4	Barguna	354326	0.00117	-0.360
5	Barisal	354326	0.00117	-0.360
6	Bhola	354326	0.00117	-0.360
7	Jhalokati	354326	0.00117	-0.360
8	Pirojpur	354326	0.00117	-0.360
9	Patuakhali	354326	0.00117	-0.360
10	Lakshmipur	25616	0.01612	-0.301
11	Noakhali	25616	0.01612	-0.301
12	Feni	25616	0.01612	-0.301
13	Chittagong	157445	0.00262	-0.354
14	Cox's Bazar	413	1.00000	2.8

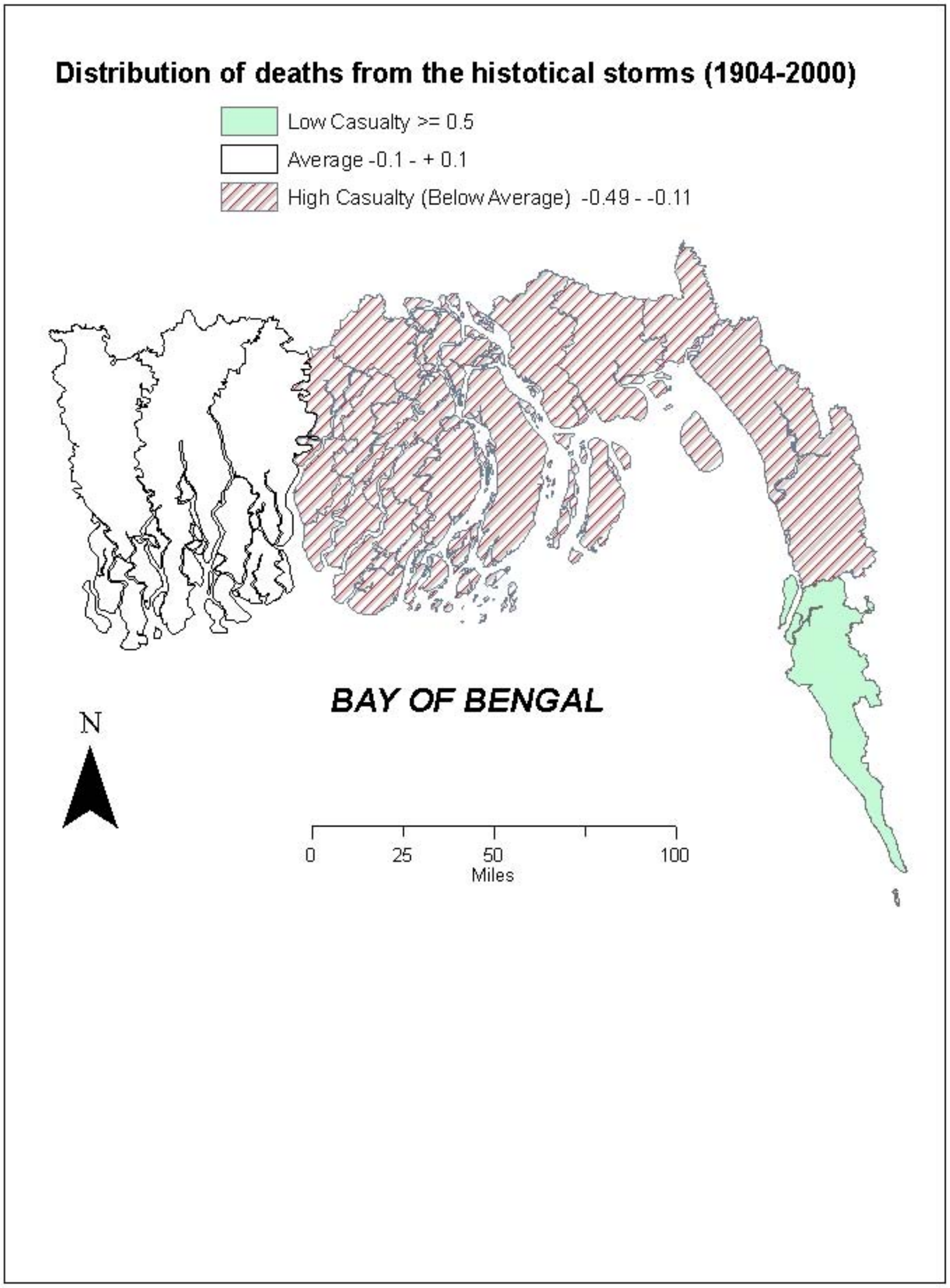

Figure 5.12 Distribution of casualties from the past cyclones

Table 5.21 shows the Z-score values of the coastal districts based on the number of casualties in the coastal regions from the past landfalling cyclones. On 12 November, 1970 more than 300,000 people died when a cyclone hit the coast of Barisal region. More than 138,000 people died from another super cyclone that hit the coast of Chittagong on 29 April, 1991. These two cyclones are primarily responsible for the high number of casualties in these regions.

Figure 5.11 shows the distribution of casualties in the coastal areas of Bangladesh from the past landfalling cyclones during the period of 1877-2003. The red hatched areas represent high casualties among all the coastal districts. The light green area represents low number of casualties.

The grouping of the coastal districts under different categories based on Z-score values is given in Table 5.22.

Table 5.22 Grouping of districts (number of casualties)

Categories and Range	Districts
High casualty (-0.49- -0.11)	Jhalokati, Barisal , Pirojpur, Bhola, Barguna, Patuakhali, Chittagong, Feni, Noakhali, Lakshmipur
Average (-0.1– +0.1)	Satkhira, Khulna, Bagerhat
Low casualty (>= 0.5)	Cox's Bazar

5.4.6 Composite coping capacity

The weighted values of the variables such as population density, per capita income, number of cyclone shelters, length of road network and number of casualties from the past cyclones for each coastal district are combined together to determine the composite coping capacity of the coastal districts of Bangladesh. Based on the mean weighted value z-score value of each district is calculated, which is shown in Table 5.23.

Table 5.23 z-score of composite coping capacity

Sl. No	Districts	Weighted value, Ki					Mean Ki value	z-score
		pop density	per captia income	Cyclone Shelter	road network	Deaths		
1	Satkhira	0.80	0.57	0.16	0.34	0.07841	0.3902	-0.388
2	Khulna	0.72	0.82	0.10	0.25	0.07841	0.3948	-0.334
3	Bagerhat	1.00	0.60	0.16	0.29	0.07841	0.4254	0.019
4	Barguna	0.84	0.60	0.43	0.50	0.00117	0.4746	0.588
5	Barisal	0.46	0.51	0.05	0.58	0.00117	0.3221	-1.175
6	Bhola	0.78	0.57	0.66	0.30	0.00117	0.4623	0.446
7	Jhalokati	0.42	0.46	0.07	1.00	0.00117	0.3892	-0.399
8	Pirojpur	0.44	0.48	0.13	0.84	0.00117	0.3792	-0.515
9	Patuakhali	0.85	0.65	0.36	0.51	0.00117	0.4735	0.575
10	Lakshmipur	0.38	0.55	0.35	0.57	0.01612	0.3721	-0.597
11	Noakhali	0.54	0.50	0.41	0.46	0.01612	0.3836	-0.464
12	Feni	0.30	0.45	0.28	0.73	0.01612	0.3565	-0.777
13	Chittagong	0.31	1.00	0.30	0.45	0.00262	0.4135	-0.119
14	Cox's Bazar	0.49	0.70	1.00	0.29	1.00000	0.6956	2.841

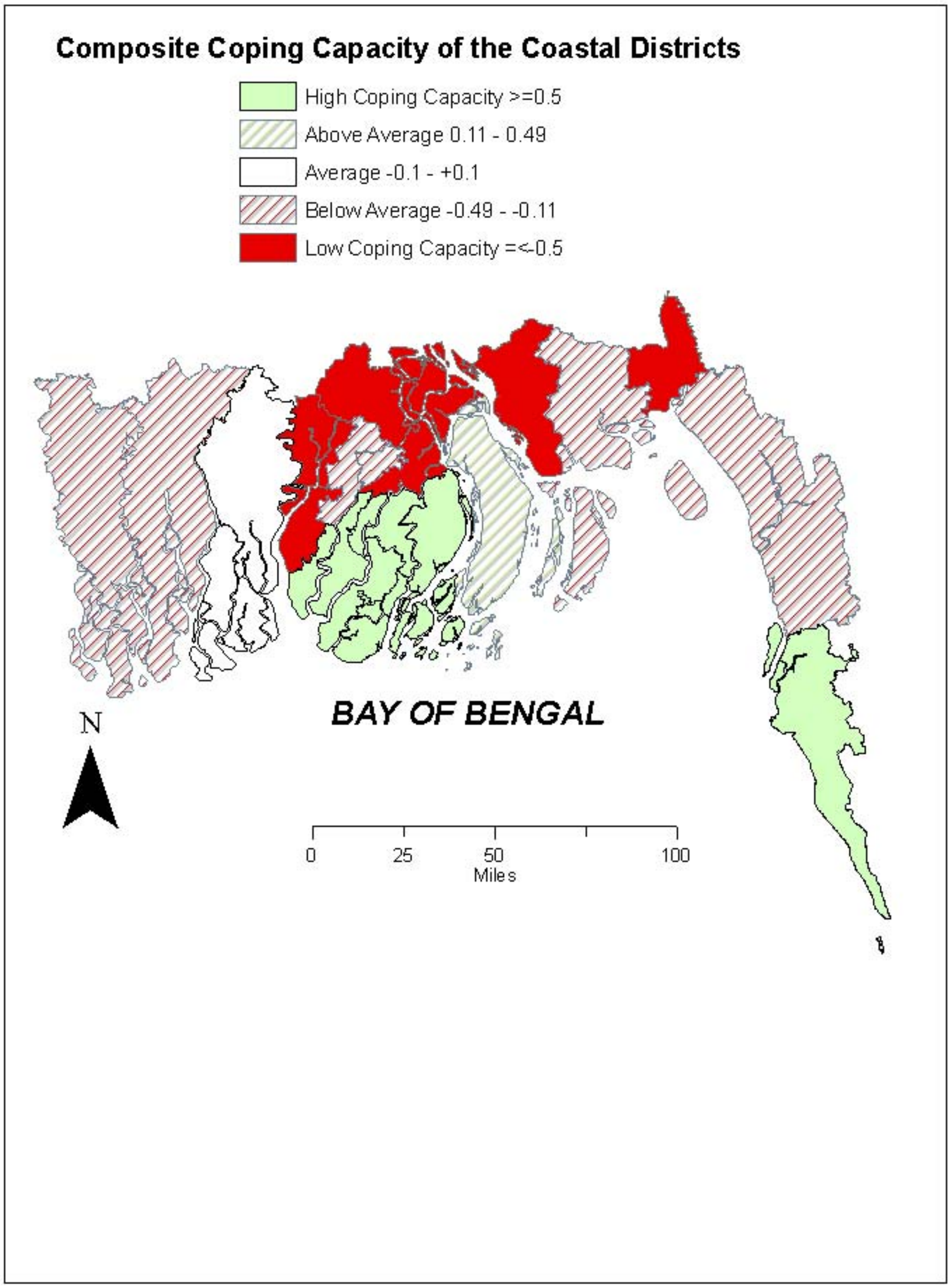

Figure 5.13 Composite coping capacity

Figure 5.12 shows the composite coping capacity or in other words the socio-economic vulnerability in the coastal areas of Bangladesh. The red area represents the least coping capacity compared to other districts in terms of the five variables. The light green area represents high coping capacity or less socio-economic vulnerability with z-score value >=0.5.

The grouping of the coastal districts under different categories based on z-score values is given in Table 5.24.

Table 5.24 Grouping of districts (coping capacity)

Categories and Range	Districts
Low coping capacity (=< -0.5)	Lakshmipur, Feni, Barisal , Pirojpur
Below average (-0.49- -0.11)	Satkhira, Khulna, Jhalokati, Noakhali, Chittagong
Average (-0.1– +0.1)	Bagerhat
Above average (0.11–0.49)	Bhola
High coping capacity (>= 0.5)	Cox’s Bazar, Patuakhali, Barguna

5.5 Cyclone vulnerability map

Cyclone vulnerability is conceptualized as a combination of cyclone risk and the coping capacity of the people. Therefore, all the variables that are analyzed in the previous sections are considered for cyclone vulnerability. The weighted values of all the five variables for each district are combined together to obtain the mean weighted values and based on that the z-score values are calculated to compare the cyclone vulnerability in the coastal areas of Bangladesh. Table 5.25 shows the z-score values of composite cyclone vulnerability for each coastal district.

Table 5.25 z-score of composite cyclone vulnerability in the coastal districts

Sl. No	Districts	Weighted Value for No. of Storms	Weighted Value for Max. Wind Speed	Weighted Value for Surge Height	Weighted Value for Avg. distance from the coast	Weighted Value for no. of deaths	Weighted Value for Cyclone Shelter	Weighted Value for pop density	Weighted Value for road network	Weighted Value for per captia income	Mean Ki value	z-score
1	Satkhira	0.25	0.81	0.26	0.89	0.08	0.16	0.80	0.34	0.57	0.46	-0.165
2	Khulna	0.25	0.81	0.26	0.89	0.08	0.10	0.72	0.25	0.82	0.46	-0.122
3	Bagerhat	0.25	0.81	0.26	0.78	0.08	0.16	1.00	0.29	0.60	0.47	-0.045
4	Barguna	0.29	0.68	0.39	0.33	0.00	0.43	0.84	0.50	0.60	0.45	-0.334
5	Barisal	0.29	0.68	0.39	1.00	0.00	0.05	0.46	0.58	0.51	0.44	-0.512
6	Bhola	0.29	0.68	0.39	0.11	0.00	0.66	0.78	0.30	0.57	0.42	-0.861
7	Jhalokati	0.29	0.68	0.39	0.67	0.00	0.07	0.42	1.00	0.46	0.44	-0.508
8	Pirojpur	0.29	0.68	0.39	0.67	0.00	0.13	0.44	0.84	0.48	0.44	-0.601
9	Patuakhali	0.29	0.68	0.39	0.11	0.00	0.36	0.85	0.51	0.65	0.43	-0.756
10	Lakshmipur	1.00	1.00	0.28	0.67	0.02	0.35	0.38	0.57	0.55	0.53	1.036
11	Noakhali	1.00	1.00	0.28	0.44	0.02	0.41	0.54	0.46	0.50	0.52	0.730
12	Feni	1.00	1.00	0.28	0.56	0.02	0.28	0.30	0.73	0.45	0.51	0.685
13	Chittagong	0.43	0.64	0.28	0.11	0.00	0.30	0.31	0.45	1.00	0.39	-1.338
14	Cox's Bazar	0.45	0.71	1.00	0.11	1.00	1.00	0.49	0.29	0.70	0.64	2.790

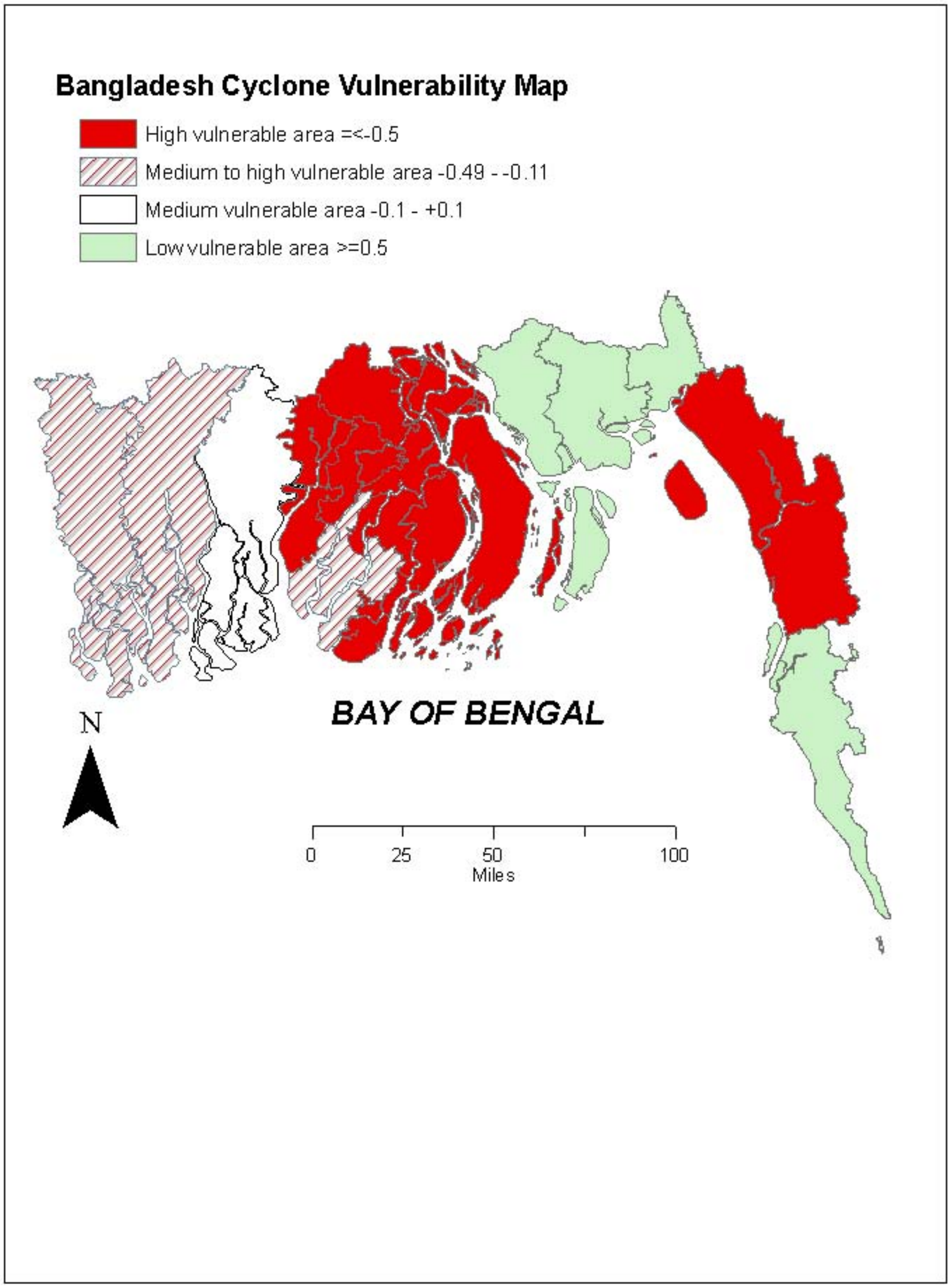

Figure 5.14 Cyclone vulnerability map

Figure 5.13 illustrates the cyclone vulnerability map of Bangladesh depicting the high and low vulnerable areas to cyclone hazard. The red areas represent the high vulnerable areas with z-score values =<-0.5. The white area represents the medium vulnerable area and the light green area represents low vulnerability to cyclone. The grouping of the coastal districts under different categories based on z-score values is given in Table 5.26.

Table 5.26 Grouping of districts (composite cyclone vulnerability)

Categories and range	Districts
Low vulnerable area (>= 0.5)	Lakshmipur, Noakhali, Feni, Cox's Bazar
Medium vulnerable area (-0.1 - +0.1)	Bagerhat
Medium to high vulnerable area (-0.49 - -0.11)	Satkhira, Khulna, Barguna
High vulnerable area (=< -0.5)	Jhalokati, Pirojpur, Barisal, Chittagong, Bhola, Patuakhali,

5.5.1 Low vulnerable areas to cyclone

Lakshmipur, Noakhali, Feni and Cox's Bazar districts are placed in this area. Although in the cyclone risk map, Cox's Bazar is placed one category below the low risk area (medium to low risk area), due to its strong coping capacity Cox's Bazar is placed in the low vulnerable area in the cyclone vulnerability map. However, Lakshmipur, Noakhali and Feni districts are identified as low cyclone risk and vulnerable areas in both the cyclone risk and cyclone vulnerability maps.

5.5.2 Medium vulnerable area

Similar to the cyclone risk map, Bagerhat is the only district located in the medium vulnerable area. Bagerhat has average coping capacity compared to other coastal districts.

5.5.3 Medium to high vulnerable area

Satkhira, Khulna and Barguna districts are placed in this category. In the cyclone risk map, Satkhira and Khulna are in the medium to low risk area. But due to their low coping capacity, these two districts are placed in the comparatively high vulnerable area in the cyclone vulnerability map. On the other hand, Barguna is in the high risk area on the cyclone risk map. But because of its high coping capacity, Barguna is now placed in this category in the cyclone vulnerability map.

5.5.4 High vulnerable area

Jhalokati, Pirojpur, Barisal, Bhola, Patuakhali and Chittagong (Chittagong, Bhola, Patuakhali and Barguna) districts are in the high vulnerable area. In the cyclone risk map, there are less number of districts placed in the high risk area. But due to low coping capacity more districts are added as highly vulnerable in the cyclone vulnerability map. These are Jhalokati, Pirojpur and Barisal districts, which are highly vulnerable to cyclone even though these are not placed in the high risk area in terms of cyclone risk.

The total vulnerable population in this region is 13.82 million which is 50.22% of the total coastal population and 11.22 % of the total population of Bangladesh. The average per capita income of this high vulnerable region is 342.17 USD whereas the average per capita income in Bangladesh is 363 USD (BBS, 2003).

CHAPTER VI
CONCLUSION

A reliable and comprehensive climatological database on the landfalling tropical cyclones, first of its kind for Bangladesh has been established in this study. Based on the climatology, there are two annual cyclone seasons in Bangladesh- the pre-monsoon and the post-monsoon. Tropical cyclone activity is absent from January through March and most active during the months of May and October. Although there is a large variability in the year-to-year occurrence of landfalling cyclones, a trend has been set based on the climatology. Presently, there is an increasing trend of landfalling tropical cyclones in Bangladesh. The number of landfalling tropical cyclones is the highest at the Khulna coast, and the lowest at the Noakhali coast.

Using climatologial information as input, Monte Carlo simulations have been carried out to estimate the maximum wind speeds and maximum surge height at each of the five coastal sites. The Holland (1991) wind field model is used to represent the landfalling storms and a simple bathystrophic storm surge model is used to calculate the storm surge at the landfall locations. The results can be used for taking different mitigation measures in the coastal areas of Bangladesh. The return period of maximum wind speeds for all the coastal sites are calculated in this study, which is important to analyze the vulnerability of structures in this region from the tropical storms. Measures can be taken to improve the existing building code and the basic wind speed map of the country based on this study, which in turn would contribute to minimize the impact of tropical cyclones and other windstorms.

Finally, cyclone risk and vulnerable zones are identified and coastal districts are compared based on the parameters that are responsible for cyclone risk and coping capacity of the people that eventually give the picture of cyclone vulnerability in the coastal areas of Bangladesh. Using GIS, a cyclone risk map and a cyclone vulnerability map are produced for the coastal areas of Bangladesh, which can be very useful towards effective disaster planning. Because of its economic condition, Bangladesh should allocate its resources wisely and on a priority basis. The high vulnerability regions that are identified in this study, should be given the highest priority to take mitigation measures. For instance, it may not be possible for a country like Bangladesh to build levies along of its whole coast, but it can be possible to do so for at least along the coast of the high vulnerability areas. Similarly, more cyclone shelters should be built in areas where the shelter distribution is less and located in the higher vulnerable areas. Efforts should be taken in the high vulnerability areas as well as in other areas in terms of capacity building such as initiating income generating activities, building roads, population control etc., which can help people to cope with cyclones and other natural hazards.

In the cyclone risk analysis four parameters are considered which include distribution of the past landfalling cyclones, maximum cyclone wind speed, maximum possible surge height and the average distance of the districts from the open sea. In terms of the landfalling cyclones distribution, the high frequency area consists of all the districts under Khulna and Barisal regions while the districts under Noakhali region have low frequencies of landfalling cyclones. Maximum cyclone wind speed is the highest in Chittagong and Barisal region and the lowest at Noakhali region along with its corresponding districts. In terms of maximum surge height, the districts under Khulna and Noakhali regions are at high risk with higher possible surge height and Cox's Bazar is found to be at low risk. The location of the districts from the open sea is another crucial factor. Chittagong, Cox's Bazar, Bhola, Barguna and Patuakhali districts are located nearest to the coast while Khulna, Satkhira, Bagerhat and Barisal are the farthest in terms of average distance from the open sea. Combining all these four parameters a cyclone risk map for the coastal districts of Bangladesh is produced using GIS, where Chittagong, Bhola, Barguna and Patuakhali districts are placed in the high risk area and Lakshmipur, Noakhali and Feni districts are placed in the low risk area.

The coping capacity factors that are analyzed in this study to assess the vulnerability of the coastal districts include population density, per capita income, number of cyclone shelters, road network and casualties from the past cyclones.

Chittagong, Barisal, Jhalokati, Pirojpur, Feni and Lakshmipur districts have high density of population compared to other coastal districts whereas Satkhira, Khulna, Bagerhat, Barguna, Patuakhali and Bhola districts have low density of population. In terms of per capita income, Chittagong, Cox's Bazar and Khulna districts are in better position than other districts while the condition is the worst in Feni, Noakhali, Jhalokati, Barisal and Pirojpur districts. The distribution of cyclone shelters is the highest in Cox's Bazar and Bhola districts and is the lowest in Satkhira, Khulna, Bagerhat, Barisal, Pirojpur and Jhalokati districts. Road network distribution is better in Chittagong, Cox's Bazar and Khulna districts but poor in Feni, Noakhali, Barisal, Jhalokati and Pirojpur districts. Except Cox's Bazar and the districts under Khulna region, all the other districts experienced high casualties from the past tropical cyclones. A composite coping capacity map is produced combining all the coping capacity factors, where Cox's Bazar, Patuakhali and Barguna districts are found comparatively better than other coastal districts. In contrast, Lakshmipur, Feni, Barisal and Pirojpur districts are placed in the low coping capacity area.

As cyclone vulnerability is conceptualized in this study as a combination of cyclone risk and coping capacity of the people, a cyclone vulnerability map is produced in GIS combining all the parameters used in the cyclone risk and the coping capacity analyses. In the cyclone vulnerability map, the high vulnerability area is comprised of Chittagong, Barisal, Bhola, Patuakhali, Pirojpur and Jhalokati districts. Cox's Bazar, Feni, Noakhali and Lakshmipur districts are placed in the low cyclone vulnerability area.

The result of the Monte Carlo simulations in this study is very sensitive to the wind field parameters that represent the landfalling storms such as central pressure, radius of the maximum wind, forward speed and storm heading. The data of radius of the maximum wind for the earlier storms are not available which might influence the result somewhat. In future when more data are available, it is recommended to run again the Monte Carlo simulations which would certainly yield improved results.

In any type of planning, participation of people is a very important factor. A plan, which is apparently good may not be useful if it is not appreciated by the majority of people. So, in any disaster planning effort, people's perception should be evaluated to make it more meaningful. Therefore, a social survey is recommended to perform in the coastal areas of Bangladesh as a future work to evaluate the people's perception on risk and vulnerability and to compare it with the findings of this study.

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