JOURNAL OF ENGINEERING AND TECHNOLOGY , **Vol. 8 No. 1** June 2010 ISSN 1684-4114
http://www.iutoic-dhaka.edu/jet

# Assessing Cyclone Wind Hazard in Coastal Regions of Bangladesh

**Shakila Kayum*, Kazi Nusrat Jahan* and Syed Rokanuzzaman***

Received 08 November 2009; Accepted after revision 06 July 2010

## ABSTRACT

***One of the most dangerous Cyclone basins of the world located in the Bay of Bengal and the population most affected lives in coastal regions of Bangladesh. Bangladesh often suffers from many climate induced disasters such as flood, drought, Cyclone etc. among which the Cyclone is the most catastrophic one. The coastal morphology of Bangladesh influences the impact of Cyclone hazards on the area. Especially in the south-western area, Cyclone hazards increase the vulnerability of the coastal dwellers and slow down the process of social and economic development. This includes districts like Chittagong, Noakhali, Khulna, Patuakhali and Barisal where the Cyclones strike most in Bangladesh. Cyclone continues to pose a dangerous threat to the coastal populations of Bangladesh, despite improvements in the disaster control procedures. After 1,38,000 persons died in the April 1991 Cyclones, a rapid epidemiological assessment was carried out to determine factors associated with Cyclone-related mortality and to identify prevention strategies. The present study was aimed at exploring the probability of Cyclone occurrence in Bangladesh coast along with the probable wind speed through***

* *Dept of Urban and Regional Planning, Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh. Email: shakila_kayum_buet@yahoo.com.*

***the possible utilization of GIS. This study was oriented toward wind hazard assessment of the Cyclones that make landfall in the coastal regions of Bangladesh. For these purposes, a digital map of coastal areas is overlaid with a grid of approximately 5 km in size and a wind field model is used to estimate maximum sustained wind speed in each cell. Finally Cyclone 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 area of Bangladesh. It is hoped that this study will contribute in taking proper disaster planning efforts in Bangladesh especially in the mitigation phase for the reduction of damage from the Cyclone hazard.***

***Keywords:*** *Cyclone Hazards, epidemiological assessment, GIS, digital map, Cyclone risk, landfall.*

## 1 INTRODUCTION

Bangladesh suffers from many climate induced disasters like flood, drought, Cyclone among these natural hazards Cyclone, a tropical storm or atmospheric turbulence involving circular motion of winds, occurs in Bangladesh almost every year. Tropical Cyclones generally occur in the belt, lying between $5^o$ to $30^o$ latitude on either side of the equator. Since Bangladesh lies within this range, the country in general is considered as the Cyclone prone area [1]. About one-tenth of the global total of tropical Cyclones occurs in the Bay of Bengal and about one-sixth of tropical Cyclones born in the Bay of Bengal had landfall on the Bangladesh coast [2]. Tropical storms which develops in the Bay of Bengal (commonly known as Cyclones) moves towards two directions. If not weaken along its way, it either moves west wardley towards the coastal belts of Orissa and West Bengal of India or north-easterly towards the coastal areas of Bangladesh, a stretch of 750 *km* from Teknaf river in the south-east to the mouth of Raimangal river in the south-west. The Bay Cyclones also move towards the eastern coast of India, towards Myanmar and occasionally into Sri Lanka. But they cause the maximum damage when they come into Bangladesh, west Bengal and Orissa of India. This is because of the low flat terrain, high density of population and poorly built houses. Also the coastal morphology of Bangladesh influences the impact of natural hazards in these areas. In the south-western area, natural hazards increase the vulnerability of the coastal dwellers and slow down the process of social and economic development.

This study is oriented towards wind hazard assessment of the Cyclones that make landfall in the coastal regions of Bangladesh. This study aims to understand the land falling tropical Cyclones of Bangladesh and the associated risk and vulnerability in coastal areas. It is expected that this study will contribute to taking proper disaster planning efforts in Bangladesh especially in the preparation and mitigation phase for the reduction of damage from the Cyclone hazard. The present study aims to understand the land falling tropical Cyclones of Bangladesh and the associated risk and vulnerability in coastal areas with the following objectives:

(i) To determine the probability of Cyclone occurrence in different regions of Bangladesh coast.

(ii) To compute the maximum wind speed for Cyclone of particular return period.

(iii) To simulate maximum wind speed in different regions of Bangladesh coast.

In the present study several methodologies and models have been developed for the successful completion of task. It is the sequential process that includes every part of the study that was conducted during the completion of the project. Gradient wind model and Holland wind field model is discussed briefly here and relevant equations were set to develop the simulation model. In order to achieve the above mentioned objectives, there were four particular parameters i.e. pressure drop, radius of maximum winds, the track speed and the angle of track (measured clockwise in degrees from the north). Data were collected from the different sources and then the data were processed and analyzed. The first and second objectives were achieved through the calculation from particular mathematical equations and a simulation model was run for the third objective. The obtained result is then analyzed and the salient features of the output were analyzed. It is found that some pocket regions comprises of part of Sundarban, off-shore islands of Bhola and Patuakhali, Hatiya (Noakhali) and some regions of Cox's Bazar are highly vulnerable to Cyclones with probable highest maximum sustained wind speed of 55 to 57 meters per second (*m/s)* and outside the coastal region has the lowest (43 to 47 *m/s*) maximum wind speed. The lowest speed of 4 *m/s* is observed in most of the part of Satkhira, northern part of Khulna and southern part of Cox's Bazar. The average maximum sustained wind speed is found in the southern part of Bagerhat, large portion of greater Barisal, greater Noakhali, Chittagong and a small portion of Cox's Bazar. From the zonal analysis, it is found that the average maximum sustained wind speeds are highest in Barisal.

## 2 METHODOLOGY OF THE STUDY

The methodology of the present study is described in the flow chart as shown in **Fig.1.**

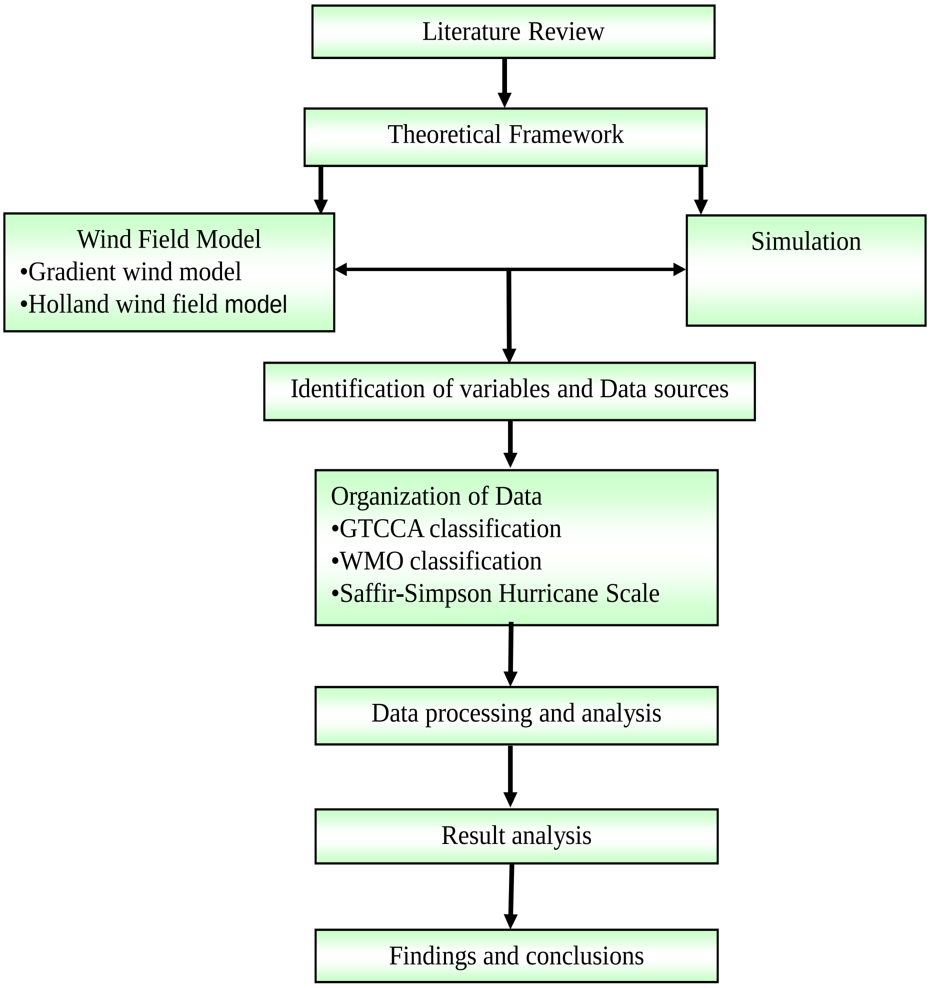



**Figure 1:** Flow chart of the methodology.

### 2.1 Literature Review

There have been numerous studies carried out on the Bay of Bengal Cyclones, but only a few of them have focused on the Bangladesh coast in particular. Previously, climatological analyses on the Bay of Bengal Cyclones are done by Rai Sircar [3], Raghavendra [4], Mooley [5], and Mooley and Mohile [6].

Damage caused by storm surge along the coastal belt is also analyzed which is a considerable factor in a Cyclone. Sim/son and Reihl [7] have defined the storm surge as “the super elevation of the still-water surface that results from the transport and circulation of water induced by wind stresses and pressure gradients in an atmospheric storm.” A simplified scheme was used to estimate the penetration of surge inland. From the estimated wind hazard and storm surge, he proposed the location of disaster related facilities.

Maniruzzaman [8] focus on the application of advances in science and information technology including remote sensing and geographical information system (GIS) for central disaster management personnel in their efforts for emergency pre and post disaster management and mitigation as well as long term disaster preparedness planning. In his thesis a model to estimate the maximum wind speed during a Cyclone in different locations on the coastal areas of southern Bangladesh was implemented on a workstation version of the ARC/INFO GIS software. The Arc Macro Language (AML) was used to implement the model based on Malkin’s model of pressure filling. Damage data collected from the MoDMR was used to analyze the relation between wind speed in a Cyclone and damage caused by it. Considering the relative reliability of damage data, only four Cyclones- those of 1985, 1988, 1991 and 1994- were considered.

The most comprehensive study on the land falling Bay of Bengal Cyclones has been done by the SAARC Meteorological Research Center (SMRC). In that study, the coast of Bangladesh is divided into four segments where landfall locations are assigned for 82 cyclonic storms from 1582 to 1997, Shrestha [9]. Tropical depressions are not included, which should be very important in terms of the Bangladesh coast. In the most of the studies including the SMRC publication, landfall locations are assumed based on different sources such as newspapers and not judged from the actual storm track information.

In the recent times, Alam [10] have done work on the frequency of landfalling of the Bay of Bengal Cyclones with data from 1974 to 1999. Dube et al. [11] focused on the modeling work on storm surges for the Heady Bay region. Islam [12] recognized that there is a dearth of climatological studies on the tropical Cyclones of Bangladesh. In his book a reliable and comprehensive land falling tropical Cyclone database and subsequent climatology have been established for the Bangladesh coast. Cyclone wind hazard are assessed using Holland Wind Field Model and Monte Carlo Simulation procedure. Cyclone risk and vulnerability of the coastal areas are also analyzed. This study reveals that there is not much difference between the frequency and 5-year moving average for all the coastal segments. 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.

An extensive review of all the available and relevant literature such as different journals, research publications and study reports related with this research topic were made. At the same time this tool of literature survey has been used to collect secondary data and information also.

## 2.2 Theoretical Framework

### 2.2.1 Wind Field Model

To estimate maximum wind speed for the simulated parameters of Cyclones in all the cells a wind field model is needed. There are different types of wind field models such as the Rankine Vortex, Modified Rankine Vortex, Gradient Wind Model, Holland Wind Field Model and Modified Holland Wind Model. Two major models: Gradient Wind Model and Holland Wind Field Model are described as below.

***Gradient Wind Model***

In this study Gradient Wind Model has been used to determine the maximum wind speed for the simulated storm. The gradient wind model was used by Batts [13]. It is a commonly used hurricane wind model as Holton [14].

The mathematical representation of this model is:

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

where $V_{gr}$ is the gradient wind, $V_c$ is the cyclostrophic flow and $\gamma$ is a calculated parameter.

This is the actual representation of the gradient wind model, which can be solved by substituting the following two equations:

$$V_c = \{\Delta P.R\exp(-\frac{R}{r})/(\rho r)\}^{\frac{1}{2}} \qquad \dots \qquad \dots \qquad (2)$$

where $\Delta P$ is the pressure difference from the centre of the storm to its periphery, $R$ is the radius of maximum winds and $\rho$ is the air density.

$$\gamma = \frac{1}{2}(\frac{rf + V_f \sin\theta}{V_c}) \qquad \dots \qquad \dots \qquad \dots \qquad (3)$$

where $V_f$ is the forward speed of storm, $f$ is the Coriolis parameter, $\theta$ is the angle counterclockwise from the forward velocity vector to radius $r$ at the point of interest.

***Holland Wind Field Model (Holland, 1980)***

The mathematical representation of the Holland [15] wind field model is:

$$V = \{\frac{AB}{\rho r^B}(Pn - Pc).\exp(-\frac{A}{r^B}) + \frac{r^2 f^2}{4}\}^{\frac{1}{2}} - (\frac{rf}{2})\text{; R=A}^{1/B}\text{, } 1.0 \le B \le 2.5 \quad \ldots \quad \ldots \quad \ldots \quad (4)$$

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 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.

### 2.2.2 Simulation

Simulation is one of the best things to observing a real system. It allows us to collect pertinent information about the behavior of the system with the passage of time and also more information are obtained from Taha [16]. Simulation is not an optimization technique. Rather, it is used to estimate the measures of performance of a modeled system. The execution of present-day simulation is based on the idea of sampling used with the Monte Carlo method. It differs in that it is concerned with the study of the behavior of real systems as a function of time. Two distinct types of simulation models exist.

***Continuous Model***

These deal with systems whose behavior changes continuously with time. These models usually use difference-differential equations to describe the interactions among the different elements of the system. A typical example deals with the study of world population dynamics.

***Discrete Models***

These deal primarily with the study of waiting lines, with the objective of determining such measures as the average waiting time and the length of the queue. These measures change only when a customer enters or leaves the system. At all other instants, nothing from the standpoint of collecting statistics occurs in the system. The instants at which changes take place occur at discrete points in time, giving rise to the name discrete event simulation, described by Taha [16].

## 2.3 Identification of Variables and Data Sources

The study is based on secondary data. For the wind field model, data is needed of maximum wind speed, track speed, track angle and radius of maximum wind. Sources of these parameters and other related variables are given in **Table.1**.

## 2.4 Organization of Data

Tropical Cyclones in the GTCCA database are classified by the following criteria shown in **Table.2**. On the other hand WMO categorized Cyclone in seven groups on the basis of wind speed which is given in **Table.3** as WMO [17]. In this study, due to its simplicity GTCCA classification is used to develop the historical storm data set and climatology for Bangladesh. Occurred hurricanes are also categorized according to the Saffir-Sim/son Hurricane Scales which are shown in **Table.4**.

## 2.5 Data processing and analysis

For the systematic analysis of the collected data (collected from secondary sources), all the data are compiled. Then they are sought out and analyzed to attain the objectives through the help of different software such as MS Excel, SPSS and Arc GIS etc. The data analysis procedure is stated in a flow chart, shown in **Fig.2**.

**Table 1:** Sources of Cyclone data

| Variables | Year | Source |
|---|---|---|
| Maximum wind speed | 1960 to 2007 | Bangladesh Meteorological Department (BMD) |
| Track speed | 1960 to 1994 | Maniruzzaman (1997) |
| Variables | Year | Source |
| Radius of maximum wind | 1960 to 1994 | Maniruzzaman (1997) |
| | 1995 to 1998 | Statistical Year Book (2000) [18] |
| Cyclone track | 1877 to 2003 | Islam (2008) |
| Track angle at landfall point | 1877 to 2003 | Evaluated from the Cyclone tracks using the Arc GIS and Corel Draw software |
| Year of occurrence | 1877 to 2003 | Islam (2008) |

**Table 2:** GTCCA Classification

| Type | Category | Wind Speed (*knots*) |
|---|---|---|
| Tropical Depression | TD | <34 (<18*m/s*) |
| Tropical Storm | TS | 34-63 (18-33*m/s*) |
| Hurricane | H | >=64 (>=33*m/s*) |

**Table 3:** WMO classification

| **Category** | **Wind speed (knots)** |
|---|---|
| Low depression area | <17 *Knot* (<8.7 *m/s*) |
| Depression | 17-33 *Knot* (8.7 - 17 *m/s*) |
| Cyclonic storm | 34-47 *Knot* (17 - 24 *m/s*) |
| Severe cyclonic storm | 48-63 *Knot* (24 - 32.4 *m/s*) |
| Severe cyclonic storm with a core of hurricane winds | >=64 *Knot* (>=32.4 *m/s)* |
| Very severe cyclonic storm | 64-119 (32.4 - 61 *m/s*) |
| Super cyclonic storm | >120 *Knot* (>61.7 *m/s*) |

**Table 4:** Saffir-Sim/son Hurricane Scales

| Category | Wind speed |
|---|---|
| 1 | 64-83 *Knot* (32 -42.7 *m/s*) |
| 2 | 84-96 *Knot* (42.8 -49.4 *m/s)* |
| 3 | 97-113 *Knot* (49.5 -58.1 *m/s*) |
| 4 | 114-135 *Knot* (58.1 -69.45 *m/s*) |
| 5 | >135 *Knot* (more than 69.45 *m/s*) |

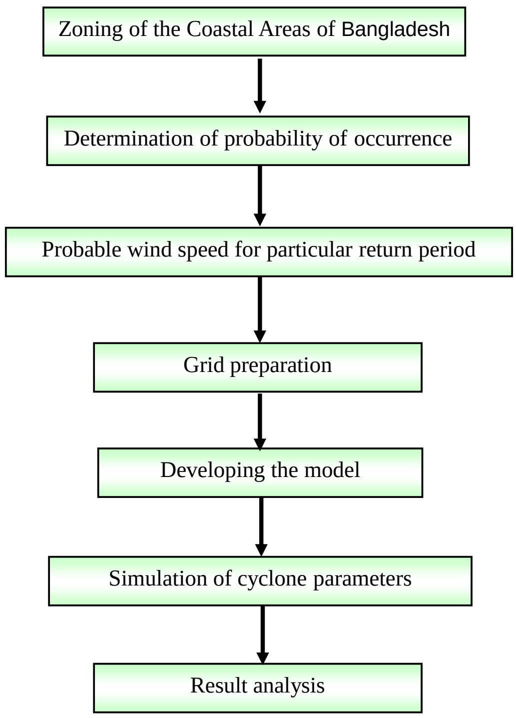



**Figure 2:** Flow chart of the data processing and analysis.

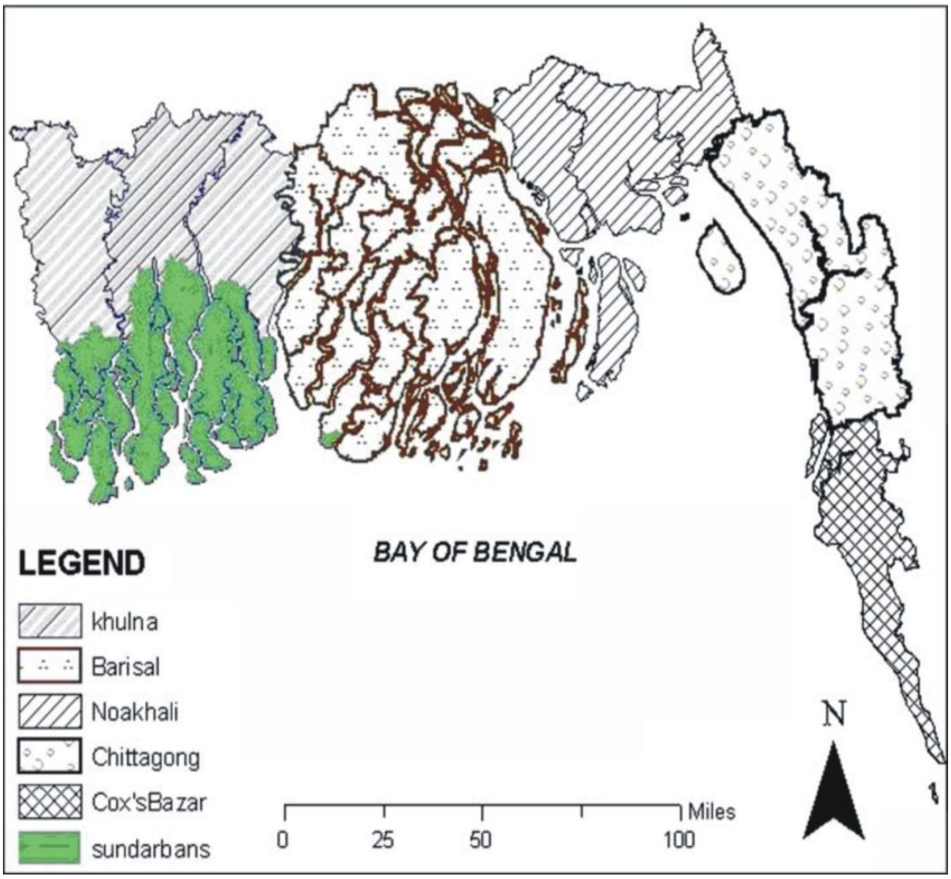



**Figure 3:** Coast of Bangladesh with subdivisions.

### *Zoning of the Coastal Areas of Bangladesh*

As Cyclone frequently battered Bangladesh coast the whole Bangladesh coast has been considered as study area. There are 14 districts namely Cox's Bazar, Chittagong, Feni, Noakhali, Laxmipur, Patuakhali, Barisal, Bhola, Pirojpur, Khulna, Satkhira, Bagerhat, Borguna and Jhalokathi. The total length of the study area is 708 *km*. For the purpose of the study the coastal areas of Bangladesh are divided into five zones namely greater Khulna, greater Barisal, Greater Noakhali, Chitttagong and Cox's Bazar on the basis of geographical and cultural characteristics and five zones in the coastal area are shown in Fig.3. As cyclonic storm and surge rarely battered area more than 242 *km* from sea for the study 298 *km* has been considered as depth. This means the study considered the impact of Cyclone formed in the Bay of Bengal up to 298 *km* from sea.

### *Determining Probability of Occurrence*

The first objective of the study is to determine the probability of Cyclone occurrence in different regions of Bangladesh coast. The number of Cyclone strikes in all five zones during the period 1877-2003 (127 *years*) is analyzed using the Cyclone tracks and frequency data were obtained by counting the numbers of tracks that carried Cyclone-force winds across the coast in each segment. Then for each area recurrence or return period, in years for tropical depression, tropical storm and hurricanes are calculated. At last the probability of a Cyclone striking in each zone in every year is calculated on the basis of it.

### *Probable Wind Speed for Particular Return Period*

The second objective of the study is to compute the maximum wind speed for Cyclone with of particular return period. To fulfill the objective, central pressure of the Cyclones that make landfall in the coast is needed. But Bangladesh Meteorological Department does not mention the pressure drop in its Cyclone warning bulletins. Instead, it mentions maximum wind speed. The following equation has been used to estimate central pressure from the maximum wind speed.

$$V_{\max} = 6.3(P_p - P_o)^{\frac{1}{2}} \quad \cdots \quad \cdots \quad \cdots \quad (5)$$

Where $V_{\max}$ is the maximum wind speed and $P_p$ and $P_o$ are the atmospheric pressures at the storm periphery and centre respectively [7]. In this study atmospheric pressure at the storm periphery is taken 1010 *mb* [8]. After that obtained central pressure of different Cyclone cases that affected the landfall area are ranked, the cumulative and discrete probabilities computed and from this, the frequency and recurrence intervals are determined. From the graph of recurrences, the minimum expected pressure is determined for the appropriate return periods and then converted to the maximum sustained- wind values.

### *Grid Preparation*

The third objective of the study is to simulate maximum wind speed in different regions of Bangladesh coast. For these a digital map of coastal areas is needed which was collected from the library of Urban and Regional Planning Department, Bangladesh University of Engineering and Technology and overlaid with a grid of approximately 5 *km* in size. The size of 5 *km* though arbitrary, allows significant decay of wind speed as the storm move towards from the sea. The grid cells offer regular areal units instead of the administrative units with their wide range of differing sizes and shapes. Also it allows better integration with the generally grid based data models. The grid has 58 rows and 80 columns which are shown in **Fig.4**. The grid is transformed into real world positioning system and coastal regions are divided into cells with the prepared grid.

As wind speed over the sea is not needed for the analysis and damage by the Cyclones occur due to the wind speed above the land. So only the cells that fall above the land area is selected to compute maximum wind speed. The final layout of the coastal regions overlaid with the grid is shown in **Fig.5**.

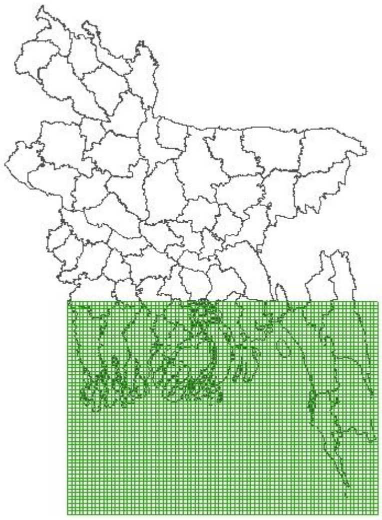


**Figure 4:** The wind speed grid system over the coastal region map.

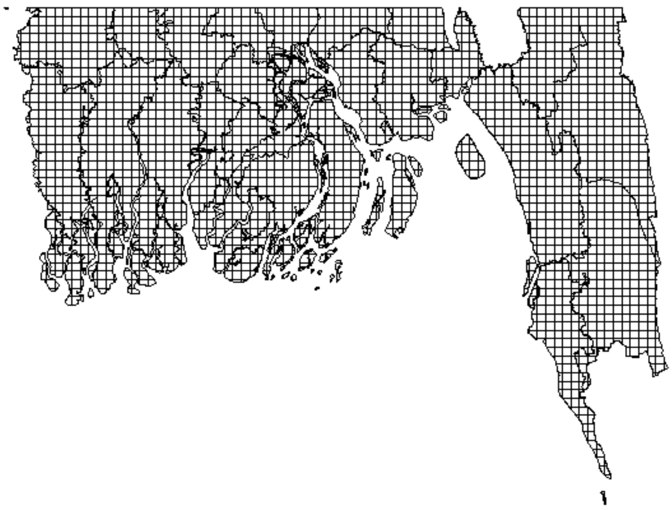


**Figure 5:** Coastal regions divided into cells.

***Developing the Model***

To determine maximum wind speed input required for the Gradient Wind Field Model are the pressure drop, radius of maximum winds, the track speed, the angle of track (measured clockwise in degrees from the north) and the maximum wind speed. A module to estimate the maximum wind speed in different locations during a Cyclone was developed by Maniruzzaman [8] for the UNIX operating system named "Rescue – Response Estimating System for Cyclones under Emergency". The Arc Macro Language (AML) was used to implement the wind model in each cell to calculate the maximum wind speed in workstation version of the ARC/INFO GIS software. In this study this model has been developed to make it executable in Windows XP platform through some editing and modification. The model was run with the generated Cyclone parameters for the each Cyclone. Values of the each parameter are generated by the probabilistic analysis of the past Cyclone parameters records that hit the costal areas of Bangladesh. Flow of the maximum wind speed estimation model is given in appendix.

***Simulation of Cyclone Parameters***

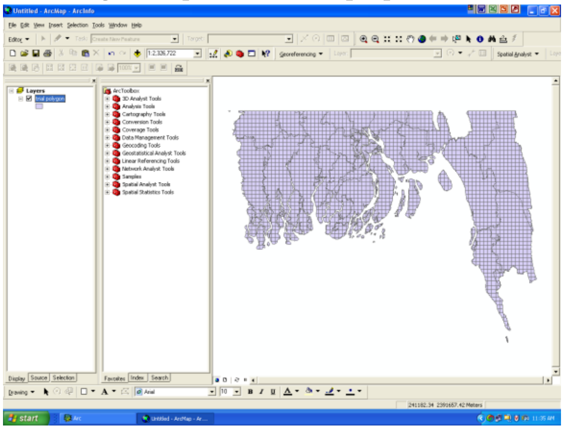
To compute the maximum wind speed in each cell, 100 Cyclones are simulated. Gradient wind field model required the data of pressure drop, radius of maximum winds, the track speed, the angle of track (measured clockwise in degrees from the north) and the maximum wind speed. At first land falling Cyclone tracks are analyzed to determine the number of Cyclones fall in different zones. Then all the parameters are classified into percentile ranges. After that the required number of values within the percentile range for each parameter is randomly generated and sorted. Thus 100 Cyclones are randomly selected in the simulation procedure.

## 2.6 Result Analysis

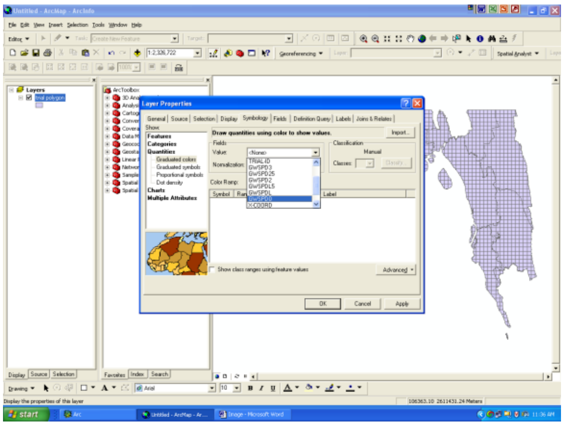
All the inputs required for the simulation procedure are given in the "arc" command of the Arc Info Workstation software and an output is obtained for each simulated Cyclone which is stored in the computer. Then the estimated maximum wind speeds are analyzed in the Arc Map tool of Arc GIS software. Steps of activity performed for the result analysis are given in the following photographs as shown in **Fig.6** (a), (b) and (c).

## 2.7 Findings and Conclusions

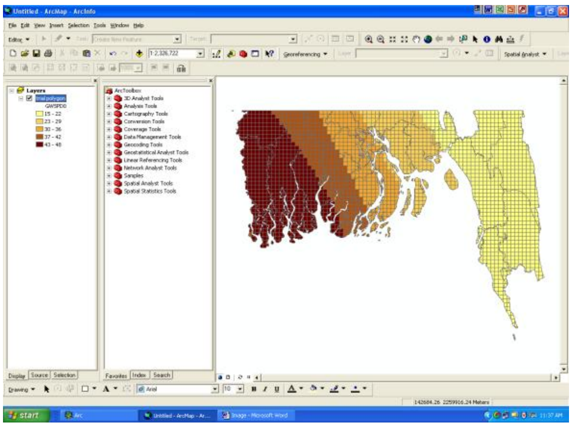
In this stage, major findings of the analysis are identified. On the basis of the analysis and major findings, a report has been prepared.



**(a).**



**(b).**



**(c).**

**Figure 6:** Coastal regions divided into cells.

## 3. PROBABILISTIC ANALYSIS

### 3.1 Number of Land Falling Cyclones

To identify the landfall area and to determine the probable Cyclone recurrence and severity is the first step for any Cyclone preparedness plan. 117 Cyclones hit the coastline of Bangladesh from 1877 to 2003. These Cyclones are classified as tropical depression, tropical storm and hurricane according to the GTCCA [19] classification. The number of Cyclone that make landfall in all five zones during the period 1877-2003 (127 *years*) is listed in Table.5. Frequency data were obtained by counting the numbers of tracks that carried Cyclone-force winds across the coast in each segment and by assuming that a landfall in one segment would cause the Cyclone-force winds in the right semicircle to intrude upon the adjacent segment [7].

Table.5 reveals that Khulna coast bears the greatest number of hits. This accounts for 31% of the total hit of tropical storms in Bangladesh in 1877-2003. However, every third of Cyclone that battered Chittagong and Cox's Bazar are of hurricane intensity compare to seventh for Khulna. The following Table.6 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.

Barisal and Chittagong subdivisions experienced a large number of deaths compared to the other coastal segments mainly due to the super Cyclones of 1970 and 1991. The former hit the Barisal coast and around 30000 people died; the latter made landfall at Chittagong and caused 138866 deaths [12].
Ironically, Khulna experienced fewer deaths compared to the number of storms hit. The key mitigation 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. Cox's Bazar also experienced the fewest deaths. Low population density may be one of the reasons for fewer casualties.

### 3.2 Attributes of Land Falling 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 Cyclones striking the coast is 10 *Cyclones/decade*, or one storm per year. Since 1950, the rate of land falling Cyclones in this area has increased, 1.18 per year for 1950 – 2000. The Fig.7 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.

**Table 5:** Number of land falling Cyclones in different coastal segments during the period from 1877 to 2003

| Coastal Subdivision | Tropical Depression (Wind Speed <18 *m/s*) | Tropical Storm (Wind Speed 18-33 *m/s*) | Hurricane (Wind Speed >=33 *m/s*) |
|---|---|---|---|
| Barisal | 15 | 9 | 7 |
| Noakhali | 4 | 4 | 1 |
| Chittagong | 2 | 12 | 7 |
| Coxs Bazar | 2 | 12 | 6 |
| Khulna | 16 | 15 | 5 |
| Bangladesh coast (Total) | 39 | 52 | 26 |

**Table 6:** Number of Cyclone deaths in Bangladesh 1904-2003

| Coastal Subdivision | Number of deaths | Frequency of Cyclones |
|---|---|---|
| Khulna | 5267 | 36 |
| Barisal | 354326 | 31 |
| Noakhali | 25616 | 9 |
| Chittagong | 157445 | 21 |
| Cox's Bazar | 413 | 20 |
| Total | 543067 | 117 |

*Source: Islam, 2008*

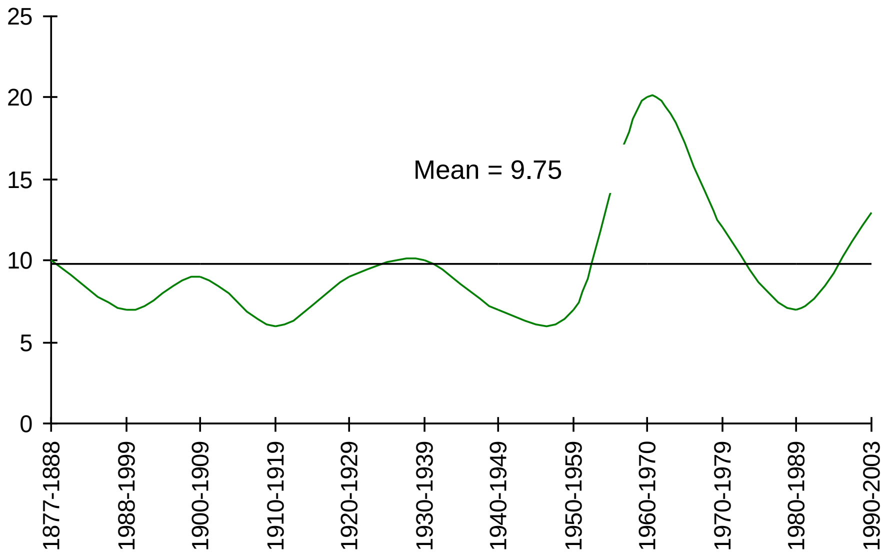



**Figure 7:** Frequency of Cyclones in 10-year period from 1877 to 2003.

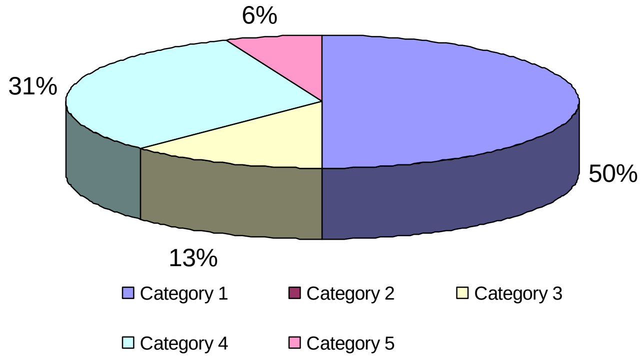



**Figure 8:** Frequency distribution of the major hurricanes according to Saffir-Sim/son hurricane Scale from 1877 to 2003.

The following **Fig.8** 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 *knot (kt)* according to the Saffir-Sim/son hurricane Scale. However the next largest group (31%) is Category 4 hurricanes (wind speed 114-135 *kt*). 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.

## 3.3 Return Period

One of the important factors of any cyclone modeling is return period. It was calculated as

$$r\,p_c = \frac{127}{f_c} \quad \ldots \quad \ldots \quad \ldots \qquad (6)$$

where $rp_c$ is the return period of particular type of storm and $f_c$ is the frequency [7]. The return periods of cyclones having wind speed more than 33 *m/s* and less than 33 *m/s* on the five zones is given in Table.7. Based on this it was found that Bangladesh will experience a cyclone with wind speed more than 33 *m/s* in every five years and will have a cyclone with wind speed less than 33 *m/s* in every two years. Khulna has the lowest return period (4.1 *years*) while Barisal and Chittagong is susceptible to severe cyclones in every 18.1 *years*. The Western part of the greater Khulna is considered here because many of the tropical cyclones had made landfall here. Those cyclones were originated in the Indian Ocean and travel towards the western part of the greater Khulna and hit the western part. It is observed from the recurrence map that Upazila of Kolaroa, Satkhira, Debhata and Shamnagar of Satkhira District, south-eastern part of Bhola and off-shore islands of Bhola (Char Fayezuddin and Manpura), Hatiya island of Noakhali district, Mirsarai upazilla of Chittagong district and Kutubdia islands of Cox's Bazar district has the highest return period (127 *years*) while "Char Kukri Mukri" and Char Manik of Bhola district and Patiya and Anwara Upazila of Chittagong has the lowest return period (14.1 *years*) which means these areas are more susceptible to Cyclone occurrence.

## 3.4 Probability of Cyclone Occurrence

It is very important to calculate the probability of Cyclone occurrence to minimize the damage caused by Cyclone. This probabilistic calculation will help in the disaster management plan for preparedness phase. Probabilities for a Cyclone strike in one-year in the coastal areas are given in Table.8.

Probabilities for a Cyclone strike in one-year = [frequency / length of recorded period (127 *years*)] * 100 [7].

The above analysis depict that Khulna is the most (24%) Cyclone prone area and Noakhali is the least (6%) Cyclone prone area and there is also 92% probability that Cyclone will make landfall in this country in every year.

**Table 7:** Return periods of Cyclones in different coastal segments

| Coastal Subdivision | Return period (in years) | |
|---|---|---|
| | Wind speed < 33 *m/s* | Wind speed >= 33 *m/s* |
| Barisal | 5.3 | 18.1 |

| | | |
|---|---|---|
| Noakhali | 15.9 | 127.0 |
| Chittagong | 9.1 | 18.1 |
| Coxs Bazar | 9.1 | 21.2 |
| Khulna | 4.1 | 25.4 |
| Bangladesh coast | 1.4 | 4.9 |

**Table 8:** Probabilities (in percentage) for a Cyclone landfall in any one year for each of the coastal segment

| Coastal Subdivision | Wind speed < 33 *m/s* | Wind speed >= 33 *m/s* | Total probability |
|---|---|---|---|
| Barisal | 19 | 6 | 25 |
| Noakhali | 6 | 1 | 7 |
| Chittagong | 11 | 6 | 17 |
| Coxs Bazar | 11 | 5 | 16 |
| Khulna | 24 | 4 | 28 |
| Bangladesh coast (Total) | 72 | 20 | 92 |

### 3.5 Probable Wind Speed for Particular Return Period

The probable extreme wind speed for Cyclone with of particular return period is the basis for developing and adopting Cyclone-resistant building standards and for deciding the allocation of public funds for structures to protect the beaches and shorelines against extreme erosion from Cyclones [7]. This type of analysis is always risky in a sense as there is no guarantee that the extreme for the 100-year interval will not occur the very next Cyclone season. But, a systematic assessment of the threat is the preliminary steps to reduce risks, and the study focused on the computation of expected extreme values of wind speed for various return periods.

There are some data of unknown reliability on the occurrence of Cyclones in Bangladesh that date from 1870, and definitely incomplete information that dates as far back as 1584. However, meteorologically useful descriptions of Cyclones have been available for the last 48 *years*. Moreover, the available data on the occurrences of Cyclones is very few and this places a heavy burden on the statistical analysis with so few cases available to determine probable wind speeds and thus the results may need to be qualified in terms of probable errors of estimate.

The following Table.9 chronologically lists the landfall strikes that brought Cyclone force winds to this zone during the period from 1960 to 2007 (48 *years*). Only the Cyclone that have maximum wind speed more than or equal to 33 *m/s* are considered for this analysis and there are 24 cases of Cyclone have been selected for these purpose. As mentioned by BMD [20], maximum wind speed instead of the central pressure in its bulletin and the Eq.5 has been used to estimate central pressure from the maximum wind speed. In this study atmospheric pressure at the storm periphery is taken as 1013 *mb*.

For these 24 cases, central pressure ($P_o$) values are then ranked from 908 *mb* to 985 *mb*, and then the cumulative probability ($P_a$) is computed using the following formula.

$$P_a = f\frac{r-0.5}{n} \qquad \ldots \quad \ldots \quad \ldots \qquad (7)$$

where $f$ is the coefficient, $P_a$ is the cumulative probability, $r$ is the rank number of the Cyclone case, and $n$ is the number of cases [7]. The coefficient, $f$ is 0.49 is the ratio of the number of Cyclones with hurricane – force winds (24) to the total number of Cyclone tracks (49) for the 48-year period (from 1960 to 2007). Total number of Cyclone tracks is the summation of the tropical storm and hurricanes. The determined cumulative probability is provided in Table.10. Cumulative probability is then plotted against the respective central pressure. It is

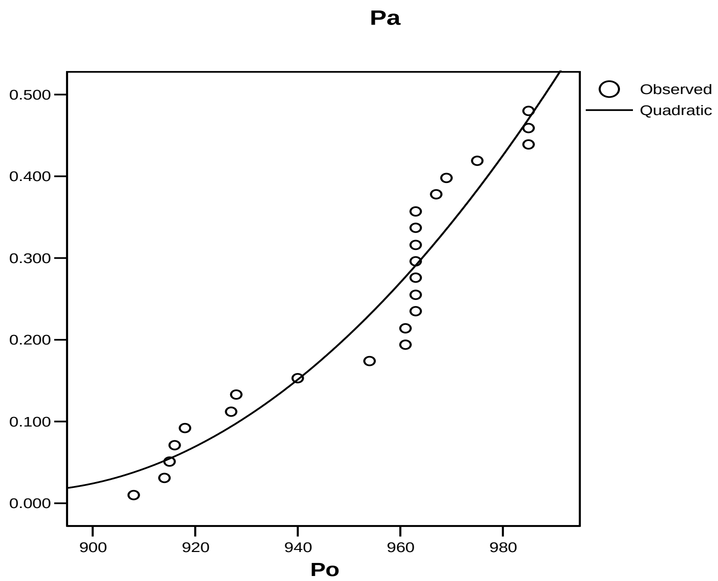



**Figure 9:** Cumulative probabilities for occurrence of minimum pressure for the Cyclones.

found out that quadratic curve best fit the probability, as shown in **Fig.9**, with an $r$ square value of 0.918.

For better analysis, of ten class of central pressure (10 *mb* intervals) are determined using Table.11 and cumulative probabilities **are shown in Fig.9**. Based on the cumulative probability expected frequency of return period is determined. For determining these two parameters following formula is used.

$$F_e = n\frac{P_a}{N} \qquad \ldots \qquad \ldots \qquad \ldots \qquad (8)$$

where $N$ is the length of the record (From 1960 to 2007, 48 *years*) and the recurrence ($r_e$) or the return period in years is listed as the reciprocal of expected frequency ($F_e$) [7].

Maximum sustained wind speed is determined by using the following formula:

$$V_{\max} = 6.3(1013 - P_o)^{\frac{1}{2}} \qquad \ldots \qquad \ldots \qquad \ldots \qquad (9)$$

Return period and maximum sustained wind are then plotted against central pressures which are shown in Fig.10 and Fig.11 respectively. From these figures it can be concluded that the lower the pressure, the higher the maximum wind speed and return period. Based on this maximum sustained wind speed of Cyclones for different return period of Cyclones is determined from **Table.12**. The data in **Table.12** reveals that Cyclone with the probable maximum wind speed 40 *m/s* will occur in every five years. And the highest probable wind speed which is 66 *m/s* has a return period of 40 *years*.

**Table 9:** List of Cyclones with maximum wind speed equal or more than 33 *m/s*

| **Year** | **Month of occurrence** | **Maximum wind speed (*m/s*)** | **Pressure (*mb*)** |
|---|---|---|---|
| 1960 | 7-11 October | 45 | 963 |
| 1960 | 27-31 October | 54 | 940 |
| 1961 | 4-9 May | 45 | 963 |
| 1961 | 27-30 May | 45 | 963 |
| 1963 | May | 58 | 928 |
| 1965 | 9-12 May | 45 | 963 |
| 1965 | October | 45 | 963 |
| 1965 | December | 58 | 927 |
| 1966 | September | 33 | 985 |
| 1967 | 19-23 October | 33 | 985 |

| | | | |
|---|---|---|---|
| 1970 | October | 45 | 961 |
| 1970 | November | 62 | 915 |
| 1974 | November | 45 | 961 |
| 1977 | May | 45 | 963 |
| 1981 | November | 33 | 985 |
| 1985 | May | 43 | 967 |
| 1988 | November | 45 | 963 |
| 1991 | April | 63 | 914 |
| 1994 | April | 61 | 918 |
| 1995 | November | 39 | 975 |
| 1997 | September | 42 | 969 |
| 1997 | May | 65 | 908 |
| 1998 | May | 48 | 954 |
| 2007 | 15 November | 62 | 916 |

*Source: BMD, 2008*

**Table 10:** Determination of cumulative probability for the listed central pressure

| Pressure | Rank | Cumulative Probability (*Pa*) |
|---|---|---|
| 908 | 1 | 0.010 |
| 914 | 2 | 0.031 |
| 915 | 3 | 0.051 |
| 916 | 4 | 0.071 |
| 918 | 5 | 0.092 |
| 927 | 6 | 0.112 |
| 928 | 7 | 0.133 |
| 940 | 8 | 0.153 |
| 954 | 9 | 0.174 |
| 961 | 10 | 0.194 |
| 961 | 11 | 0.214 |
| 963 | 12 | 0.235 |
| 963 | 13 | 0.255 |
| 963 | 14 | 0.276 |
| 963 | 15 | 0.296 |
| 963 | 16 | 0.316 |
| 963 | 17 | 0.337 |
| 963 | 18 | 0.357 |
| 967 | 19 | 0.378 |
| 969 | 20 | 0.398 |
| 975 | 21 | 0.419 |

| | | |
|---|---|---|
| 985 | 22 | 0.439 |
| 985 | 23 | 0.459 |
| 985 | 24 | 0.480 |

**Table 11:** Expected frequency and recurrence intervals

| Central pressure ( $P_o$) | Cumulative probability ($P_a$) | Expected Frequency ($F_e$) | Return period ($r_e$) |
|---|---|---|---|
| 900 | 0.0416 | 0.0208 | 48 |
| 910 | 0.0602 | 0.0301 | 33 |
| 920 | 0.088 | 0.044 | 23 |
| 930 | 0.125 | 0.0625 | 16 |
| 940 | 0.1712 | 0.0856 | 12 |
| 950 | 0.2266 | 0.1133 | 9 |
| 960 | 0.2912 | 0.1456 | 7 |
| 970 | 0.365 | 0.1825 | 5 |
| 980 | 0.448 | 0.224 | 4 |
| 990 | 0.5402 | 0.2701 | 4 |

**Table 12:** Maximum sustained wind speed for various recurrence intervals

| Recurrence year or return period | Pressure | Max wind speed (*m/s*) |
|---|---|---|
| 5 | 973 | 40 |
| 10 | 949 | 50 |
| 20 | 926 | 59 |
| 30 | 912 | 63 |
| 40 | 903 | 66 |

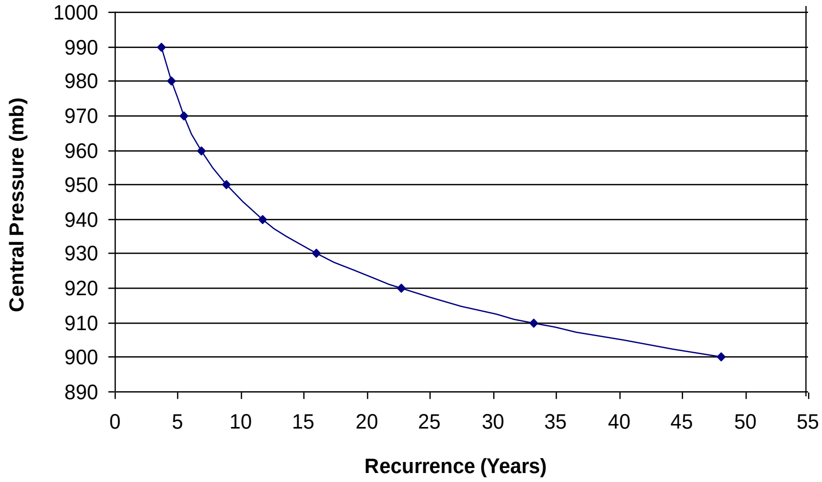



**Figure 10:** Recurrence interval (years) for Cyclones when strength is measured by central pressure.

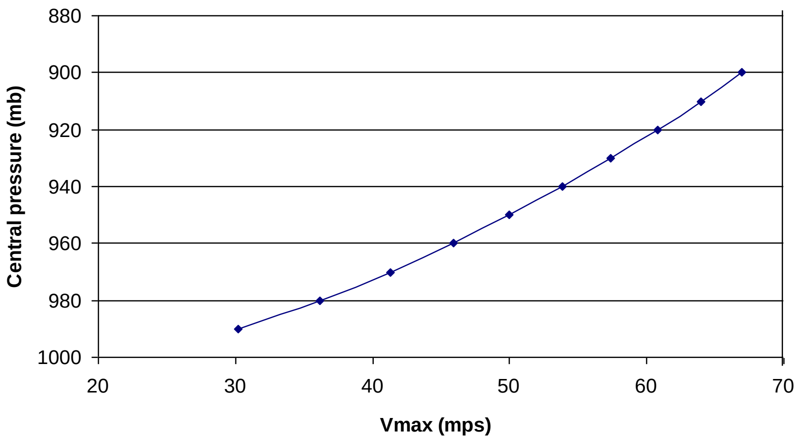



**Figure 11:** Approximate values of maximum sustained wind speed of the Cyclones as a function of central pressure.

## 4. CYCLONE WIND ANALYSIS

### 4.1 Simulation of Wind Field Parameters

The third objective of the study is to simulate maximum wind speed in different regions of Bangladesh coast. Gradient Wind Field Model has been used to determine the maximum wind speed for the simulated storm. For this purpose the pressure differences, radius of maximum winds, the track speed, the angle of track (measured clockwise in degrees from the north) and the maximum wind speed (more discussion included in Appendix) has been used as variables. In order to achieve the objective, values of all the parameters have to be simulated from the historical data resources of the occurred Cyclones. The primary data collected for maximum wind speed, radius of maximum wind and track speed are available from 1960 to 2007 as the corresponding data for the earlier storms are not available. But Cyclone tracks are available from 1877 to 2003. As a result data of Cyclone track have been analyzed according to the coastal subdivisions and from this, number of simulated Cyclones in each of the five zones have been determined which are shown in Table.13. All other parameters of Cyclones are analyzed grossly and it is assumed that the distribution would be applicable to all the five zones of coastal area. All data for all the variables are not available. In case of missing data on particular variable it was assumed that the missing value followed the pattern of available data.

### *Angle of Landfall*

The data of storm heading or the angle of landfall data are collected for each of the five zones from 1877 to 2003. Data for each zone are divided into percentile ranges which are shown in Table.14. The table reveals that the lowest angle of landfall ($3^o$) is found in Chittagong and Cox's Bazaar. The table also shows the percentage of data fall within a particular range of value. From Table.15, total of 100 data are simulated for the five zones. For example in Barisal zone 10 – 25 percentile range means that 15% of angle of landfall will be within the range of $17.4^o$ to $33^o$, so in the simulation process 4 data will fall within this range. Then the required number of data from a specified percentile range is randomly generated and sorted using the "Random Generator" command of Ms Excel software to eliminate predisposition.

### *Track Speed*

Track speed or the forward speed data are available only from 1960 to 1994. Available data of track speed are divided into percentile range. Table.16 shows that 25 percentile indicates that 25% of data are less than 10 *km/hr* and 90 percentile indicates that 90% data are less than 20 *km/hr*. From Table.17, total

**Table 13:** Number of simulated Cyclones in each of the five zones

| Coastal subdivision | Frequency in the study period | Simulated Cyclone |
|---|---|---|
| Barisal | 31 | 26 |
| Chittagong | 21 | 18 |
| Coxs Bazar | 20 | 17 |
| Khulna | 36 | 31 |
| Noakhali | 9 | 8 |
| Total | 117 | 100 |

**Table 14:** Percentile values of angle of landfall

| Coastal subdivision | Min Value | Percentile (Units are in degrees) | | | | | Max Value |
|---|---|---|---|---|---|---|---|
| | | 10 | 25 | 50 | 75 | 90 | |
| Barisal | 8 | 17.4 | 33 | 47 | 69 | 86 | 88 |
| Chittagong | 3 | 7.2 | 32 | 45 | 72.5 | 81.4 | 83 |
| Cox's Bazaar | 3 | 29.1 | 34.75 | 45 | 75 | 80.6 | 85 |
| Khulna | 5 | 11.2 | 27.5 | 45 | 59.75 | 77.6 | 345 |
| Noakhali | 15 | 15 | 19 | 45 | 49.5 | 57 | 57 |

**Table 15:** Number of simulated data in different percentile range

| Percentile range | No of data within the Percentile range | No of simulated data | | | | |
|---|---|---|---|---|---|---|
| | | Barisal | Chittagong | Cox's Bazar | Khulna | Noakhali |
| 0 – 10 | 10 | 3 | 2 | 1 | 3 | 1 |
| 10 – 25 | 15 | 4 | 3 | 3 | 4 | 1 |
| 25 – 50 | 25 | 6 | 4 | 5 | 8 | 2 |
| 50 – 75 | 25 | 6 | 4 | 5 | 8 | 2 |
| 75 – 90 | 15 | 4 | 3 | 2 | 5 | 1 |
| 90 – 100 | 10 | 3 | 2 | 1 | 3 | 1 |
| Total | 100 | 26 | 18 | 17 | 31 | 8 |

**Table 16:** Percentile value of track speed (Units are in *km/hr*)

| | | |
|---|---|---|
| **Min Value** | | 10 |
| **Percentiles** | 25 | 10 |
| | 75 | 15 |
| | 90 | 20 |
| **Max Value** | | 20 |

of 100 data are simulated for the five zones. Track speed data is a discrete data and its value are only limited to 10, 15 and 20 *km/hr*. So the table reveals that 25 percentile indicates that 25 % data will be 10 *km/hr*, 25 – 75 Percentile range indicates that 50 % data will be 15 *km/hr* and rest of the value will be 20 *km/hr*. The table shows maximum number of landfall Cyclones in all the zones has track speed 15 *km/hr* (25 – 75 Percentile range).

### *Maximum Wind Speed*

Maximum wind speed data are available only from 1960 to 2007. Available data of maximum wind speed are divided into percentile ranges which are shown in Table.18. Table.18 shows the percentage of data fall within a particular range of value. It reveals that 90% data are less than 223 *km/hr*. From Table.19, total of 100 data are simulated for the five zones. The required number of data from a specified percentile range is then randomly generated and sorted in the above mentioned procedure.

### *Radius of Maximum Wind*

Radius of maximum wind is available only from 1960 to 1998. Available data of radius of maximum wind are divided into percentile ranges which are shown in Table.20. Table.20 shows the percentage of data fall within a particular range of value. It reveals that 85% data are less than 70 *km*. From Table.21 total of 100 data are simulated for the five zones. The required number of data from a specified percentile range is then randomly generated and sorted in the above mentioned procedure.

### *Data Compilation*

All the parameters of Cyclones have been prepared through the above mentioned procedure. After that data of maximum wind speed, radius of maximum wind, track speed and angle of landfall are compiled to use as input in the Wind Field Model. But the model also required central pressure data which are obtained from the data of maximum wind speed. In these way 100 Cyclones has been simulated to run the model.

## 4.2 Results and Analysis

Using the distributions of historical data of storm parameters provided in the discussed tables (Table.13– Table.21) all the variables for 100 Cyclones have been simulated. The randomly generated values of storm parameter are then used in the model as input. Maximum wind speed for each of the cell for the each 100

**Table 17:** Number of simulated data in different percentile range

| Percentile range | No of data within the Percentile range | No of simulated data | | | | |
|---|---|---|---|---|---|---|
| | | Barisal | Chittagong | Cox's Bazar | Khulna | Noakhali |
| 0 – 25 | 25 | 6 | 4 | 4 | 8 | 2 |
| 25 – 75 | 50 | 13 | 9 | 8 | 15 | 4 |
| 75 – 90 | 15 | 4 | 3 | 3 | 5 | 1 |
| 90 – 100 | 10 | 3 | 2 | 2 | 3 | 1 |

| Total | 100 | 26 | 18 | 17 | 31 | 8 |
|---|---|---|---|---|---|---|

**Table 18:** Percentile value of maximum wind speed (Units are in *km/hr*)

| Minimum value | | 56 |
|---|---|---|
| Percentiles | 5 | 70 |
| | 25 | 85 |
| | 35 | 100 |
| | 50 | 150 |
| | 75 | 163 |
| | 80 | 193 |
| | 90 | 223 |
| Maximum value | | 232 |

**Table 19:** Number of simulated data in different percentile range

| Percentile range | No of data within the Percentile range | No of simulated data | | | | |
|---|---|---|---|---|---|---|
| | | Barisal | Chittagong | Cox's Bazar | Khulna | Noakhali |
| 0 – 5 | 5 | 1 | 1 | 1 | 2 | 0 |
| 5 – 25 | 20 | 5 | 4 | 3 | 6 | 2 |
| 25 – 35 | 10 | 3 | 2 | 2 | 3 | 1 |
| 35 – 50 | 15 | 4 | 3 | 2 | 4 | 1 |
| 50 – 75 | 25 | 6 | 4 | 4 | 8 | 2 |
| 75 – 80 | 5 | 1 | 1 | 1 | 2 | 0 |
| 80 – 90 | 10 | 3 | 2 | 2 | 3 | 1 |
| 90 – 100 | 10 | 3 | 1 | 2 | 3 | 1 |
| Total | 100 | 26 | 18 | 17 | 31 | 8 |

**Table 20:** Percentile value of maximum wind speed (Units are in *km/hr*)

| Minimum value | | 30 |
|---|---|---|
| Percentiles | 10 | 42 |
| | 30 | 55.2 |
| | 40 | 62.4 |
| | 70 | 65 |
| | 85 | 70 |
| Maximum value | | 74 |

**Table 21:** Number of simulated data in different percentile range

| Percentile range | No of data within the Percentile range | No of simulated data | | | | |
|---|---|---|---|---|---|---|
| | | Barisal | Chittagong | Cox's Bazar | Khulna | Noakhali |
| 0 – 10 | 10 | 3 | 2 | 2 | 3 | 1 |
| 10 – 30 | 20 | 5 | 3 | 4 | 6 | 2 |
| 30 – 40 | 10 | 3 | 2 | 2 | 3 | 1 |
| 40 – 70 | 30 | 7 | 5 | 5 | 9 | 2 |
| 70 – 85 | 15 | 4 | 3 | 2 | 5 | 1 |
| 85 – 100 | 15 | 4 | 3 | 2 | 5 | 1 |
| Total | 100 | 26 | 18 | 17 | 31 | 8 |

simulated Cyclones is then estimated with the model. The resulting maximum wind speed of the 100 simulated Cyclones are then analyzed to determine the highest, lowest and average of the maximum wind speed in each of the cell of the coastal areas.

### *Highest Maximum Wind Speed*

It has been found that some pocket regions comprises of part of Sundarban, off-shore islands of Bhola and Patuakhali, Hatiya (Noakhali), southern part of Noakhali and another three pocket region of Cox's Bazar are highly vulnerable to Cyclones with probable highest maximum wind speed of 55 to 57 *m/s* and outside the coastal region has the lowest (43 to 47 *m/s*) maximum wind speed which shown in **Fig.12**.

### *Lowest Maximum Wind Speed*

The lowest value among all the maximum wind speed in each cell is also analyzed and found that lowest speed of 4 *m/s* is observed in most of the part of Satkhira, northern part of Khulna and southern part of Cox's Bazar. Lowest maximum wind speed of 7 to 9 *m/s* is observed in rest of the Barguna, Patuakhali, Bhola, Laxmipur and Noakhali. From these observation it can be said that Satkhira and northen part of Khulna are the less vulnerable due to Cyclone wind because the lowest value of the maximum wind speed is observed there which are shown in **Fig.13**.

### *Average Maximum Wind Speed*

The average maximum wind speed of a Cyclone is also classified into five ranges. The highest average maximum wind speed is found in the southern part of Bagerhat, large portion of greater Barisal, greater Noakhali, Chittagong and a small portion of Cox's Bazar district and lowest average only in the small part of the Satkhira district.

The average maximum wind speeds of the 100 simulated Cyclones at each zone are shown in **Fig.14**. These average maximum wind speeds are steady for Chittagong and Noakhali and Khulna has the lowest maximum wind speed. The average maximum wind speeds are highest at Barisal zone. 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 average maximum wind speed.

**Fig.15 to Fig.19** shows the frequency of Cyclones in different average maximum wind speed categories for a total of 100 simulated storms at each of the five regions. For this all the cells fall within a zone is considered and for each Cyclone average of the maximum wind speed in all the cells is estimated. At Barisal, the highest value of the average maximum wind speed is 51m/s and for other zones average maximum wind speed is 53 *m/s*. Cox's Bazaar experiences highest frequency (three) with the average maximum wind speed of above 51 *m/s*.

Bangladesh, being one of the most densely populated and hazard prone countries of the world encounter heavy economic loss almost every year due to severe Cyclone. The trend of economic growth is disrupted since a huge amount from the national budget and international aid has to be diversified for post disaster relief and rehabitation. Cyclone forecasting is thus the first step towards an improved and effective approach for disaster management. This study is oriented toward wind hazard assessment of the Cyclones that make landfall in the coastal regions of Bangladesh. For this, the study aims to understand the land falling tropical Cyclones of Bangladesh and the associated risk and vulnerability in coastal areas. The present study was aimed at exploring the probability of Cyclone occurrence in Bangladesh coast along with the probable wind speed

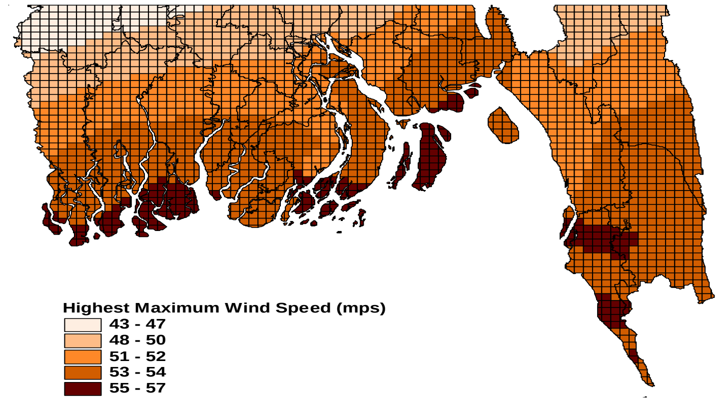



**Figure 12:** Highest value among all the maximum wind speed in each cell estimated by the model for the 100 simulated Cyclones.

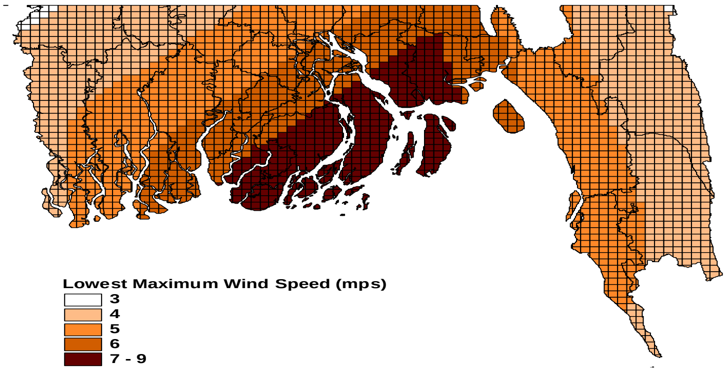



**Figure 13:** Lowest value of all the maximum wind speed in each cell estimated by the model for the 100 simulated Cyclones.

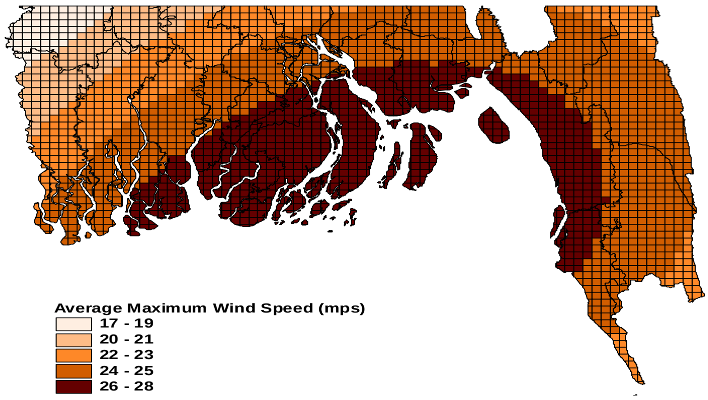



**Figure 14:** Average value of all the maximum wind speed in each cell estimated by the model for the 100 simulated Cyclones.

through the possible utilization of GIS by disaster management personnel. It is hoped that a system that offers into probable distribution of damaging winds would make the job of the Cyclone response planner more effective and the lives of the survivors more bearable.

Cyclonic disturbances are absent in January, February and March in Bangladesh. Most of the tropical Cyclones with hurricane winds strike the coast of Bangladesh during the pre and post monsoon periods, thus establishing two annual Cyclone seasons for the country. In the past century (1901 - 2000), the rate of Cyclones striking the coast is one storm per year but since 1950 there is an increasing trend of Cyclone occurrences in Bangladesh. Khulna experienced fewer deaths compared to the number of storms hit (31% of the total hit) and Barisal and Chittagong experienced a large number of deaths compared to the other coastal segments. In terms of probability of Cyclone occurrence Khulna is the most (24%) Cyclone prone area with the lowest return period (4.1 *years*) and Noakhali is the least (6%) Cyclone prone area. Barisal is highly susceptible to severe Cyclones in every 18.1 *years*. There is also 92% probability that Cyclone will make landfall in this country in every year. Cyclone with the probable maximum wind speed 40 *m/s* will occur in every five years. And the highest probable wind speed which is 66 *m/s* has a return period of 40 *years*.

The average maximum wind speeds of the 100 simulated Cyclones are steady for Chittagong and Noakhali. The highest average maximum wind speed is found in the southern part of Bagerhat, large portion of greater Barisal, greater Noakhali, Chittagong and a small portion of Cox's Bazar district and lowest average only in the small part of the Satkhira district. At Barisal, the maximum wind speed is 51 *m/s* and for other zones maximum wind speed is 53 *m/s*. Cox's Bazar experiences highest frequency (three) with the maximum wind speed of above 51 *m/s*. Some pocket regions comprises of part of Sundarban, off-shore islands of Bhola and Patuakhali, Hatiya (Noakhali), southern part of Noakhali and another three pocket region of Cox's Bazar are highly vulnerable to Cyclones with probable highest maximum wind speed of 55 to 57 *m/s* and outside the coastal region has the lowest (43 to 47 *m/s*) maximum wind speed.

The study is based upon information collected from secondary sources. The serious paucity of data was felt throughout the study. Many important data are either not collected or are poorly archived and confusion abounds. Even the Meteorological Department supplies conflicting data at different times. Since Bangladesh experiences frequent Cyclones over a relatively short length of coastline, the country can act as a laboratory for Cyclone researchers from home and abroad if data collection and storage systems are improved. Guidelines on estimating and collecting damage data should be issued to ensure better

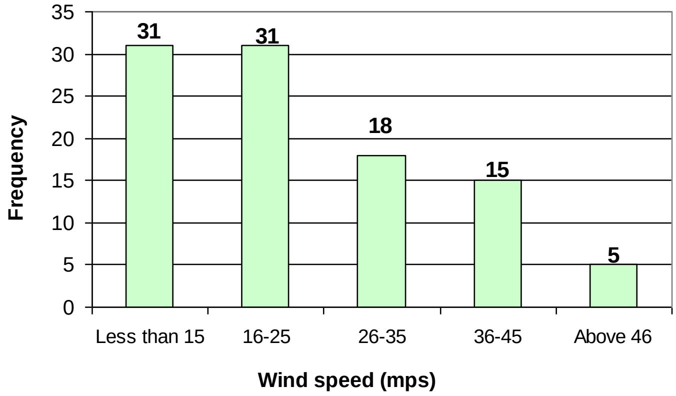



**Figure 15:** Frequency of simulated Cyclones in different average maximum wind speed categories at Khulna.

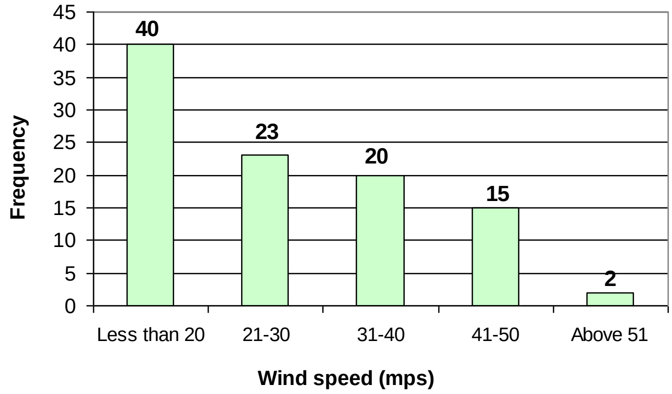



**Figure 16:** Frequency of simulated Cyclones in different average maximum wind speed categories at Barisal.

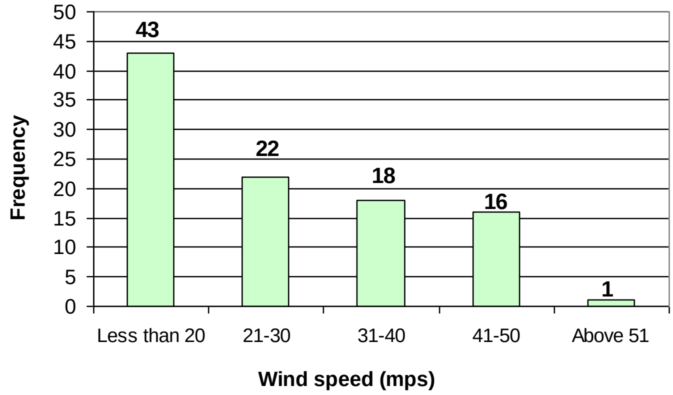



**Figure 17:** Frequency of simulated Cyclones in different average maximum wind speed categories at Chittagong.

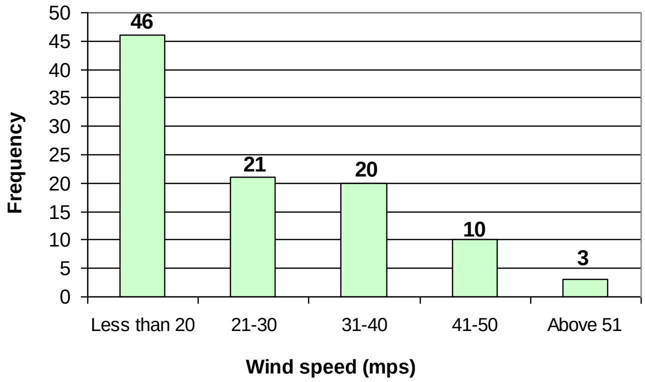



**Figure 18:** Frequency of simulated Cyclones in different average maximum wind speed categories at Cox's Bazar.

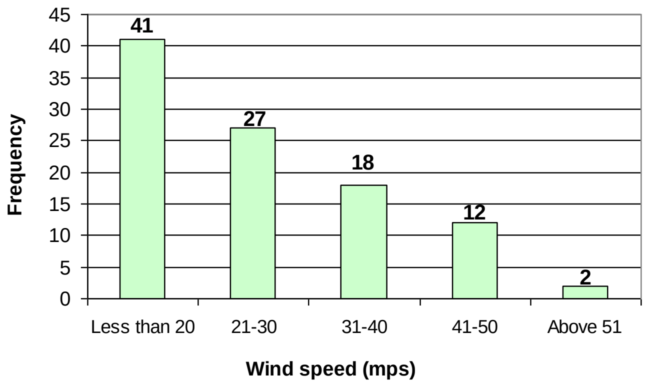



**Figure 19:** Frequency of simulated Cyclones in different average maximum wind speed categories at Noakhali.

correspondence and comparability of data collected from different areas.

Computation of maximum wind speed is the important factors behind damage amount and distribution. It is expected that a visual display of these factors, estimated or reported, would give a disaster response planners a better perspective to their jobs. The government and concerned agencies should ensure proper recording and storing of data related to damage, wind speed and other Cyclone features.

The result can be used for devising 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 in the analysis of 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 identify in this study should be given the highest priority to take mitigation measures. For instant, it may not be possible for a country like Bangladesh to build levies along for its whole coast, but it can be possible to do so at least along the coast of the high shelter distribution is less and located in the higher vulnerable areas. Efforts should be taken 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.

Thus it can be concluded from the discussion that owing to the very geographic location and physical characteristics, Bangladesh will have to face frequent attacks of devastating calamities. The economic loss that incur to the country can be minimized if proper precautions are taken.

## REFERENCES


[1] Hoque MM and Abdullah. (1997) Zonation of Chittagong Metropolitan and Industrial Area Against storm surges inundation. *United Nations Centre for Regional Development (UNCRD), Nagoya, Japan.*

[2] BUET-BIDS. (1993) Multipurpose Cyclone Shelter Programme (MCPS). *Final Reports Vol. i-v, World Bank/UNDP/GoB/Project (BDG/91/025), Dhaka*.

[3] Rai Sircar NC. (1956) A climatological study of storms and depressions in the Bay of Bengal. *Indian Journal of Meteorology and Geophysics*, Vol. 7: pp. 157–60.

[4] Raghavendra VK. (1973) A statistical analysis of the number of tropical storms and depressions in the Bay of Bengal during 1890–1969. *Indian Journal of Meteorology and Geophysics*, Vol. 24: pp. 125–130.

[5] Mooley DA (1980) Severe cyclonic storms in the Bay of Bengal, 1877–1977. *Mon Weather Re,* Vol. 08: pp. 1647–1655.

[6] Mooley DA, Mohile CM. (1983) A study of the cyclonic storms incident on the different sections of the coast around the Bay of Bengal. *Mausam* Vol. 34: pp. 139–152.

[7] Sim/son, RH and Riehl H. (1981) The Hurricane and its Impact. *Louisiana State University Press, Baton Rouge and London*.

[8] Maniruzzaman KM. (1997) GIS-Based Disaster Management System for Cyclone Disaster Response in Bangladesh. *Department of Urban Engineering, University of Tokyo*.

[9] Shrestha ML (ed) (1998) SMRC-no.1—the impact of tropical Cyclones on the coastal regions of SAARC countries and their influence in the region. *SAARC Meteorological Research Center (SMRC), Dhaka*.

[10] Alam M. (2003) Frequency of Bay of Bengal cyclonic storms and depressions crossing different coastal zones. *International Journal of Climatology*, Vol. 23: pp. 1119–1125.

[11] Dube SK, Chittibabau P, Sinha PC and Rao AD. (2004) Numerical modeling of storm surge in the Head Bay of Bengal using location specific model. *Nat Hazards*, Vol. 31: pp. 437–453.

[12] Islam T. (2008) Cyclone Wind Analysis and Disaster Planning. *VDM Verlag Muller Aktiengesellsschaft & Co, Department of Meteorology, University of Texas*.

[13] Batts ME. (1980) Hurricane wind speeds in the United States. *National Bureau of Standards Building Science Series 124, U.S. Department of Commerce, Washington, D.C.*

[14] Holton JR. (1992) An introduction of Dynamic Methodology. *3rd edition, Academic press*, pp. 511.

[15] Holland GJ. (1980) An analytical model of the wind and pressure profiles in hurricanes. *Monthly Weather Review*, Vol. 108: pp. 1212 – 1218.

[16] Taha HA. (2002) Operation Research. *Thomsom Press Ltd.*, *India*.

[17] WMO (1986) TCP-21: tropical Cyclone operational plan for the Bay of Bengal and the Arabian Sea. *WMO/ TD-No.84, Geneva.*

[18] Bangladesh Bureau of Statistics. (2000) *Statistical year book of Bangladesh. Dhaka*.

[19] Global Tropical Cyclone Climatic Atlas (GTCCA), Version 1.0. Fleet Numerical Meteorology and Oceanography Detachment, Asheville, North Carolina. Internet version was available at *http://navy.ncdc.noaa.gov/products/gtcca/gtccamain.html* (now closed). Cited 15 Sept 2003.

[20] Bangladesh Meteorological Department. (2008) *Cyclone2.doc. Unpublished report, Dhaka.*