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Storm Surge Modelling based on Analysis of Historical Cyclones for Patuakhali District of Bangladesh

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Abstract: *Bangladesh is one of the countries likely to be most susceptible to climate change. The future damaging impacts of natural hazards in the country will be exacerbated by geographic location, huge population and poverty. Cyclones and associated storm surges are considered as some of the most disastrous hazards of the country and have resulted in huge number of deaths and economic damages in the past. During the years from 1797 to 2017, there have been 75 events of cyclone in the coastal areas of Bangladesh most of which were accompanied by storm surges. This study focuses on storm surge modelling for Patuakhali district of Bangladesh located in the south central part of Bangladesh coast. Statistical analysis of historical cyclone data and Digital Elevation Model were used for producing hazard maps having surge inundation depth and spatial extent of inundation. For this study, maximum cyclonic winds of 5, 10, 20, 50 and 100 years return periods were calculated using Gumbel distribution of annual maximum wind speeds in Bangladesh between 1960 and 2017. The regression analysis of cyclone wind speeds and surge heights, excluding tidal heights, have been used for storm surge height prediction. A linear decay model namely the Surge Decay Coefficient was used to calculate the surge decrease with distance from the coast. Spatial analysis of the surge height, linear decay model and Digital Elevation Model (DEM) are used to produce the final hazard maps. The results show that inundation in some places exceeds 6m excluding the tidal heights and sea level rise issues. About 48.5% of the study area will be inundated in such scenarios. This will be further aggravated in case of high tide and sea level rise.*
Keywords - *Cyclone, Storm Surge, Surge Decay, Inundation Depth, Hazard Map.*

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I. Introduction

Bangladesh is a country whose geographic location sets the background of her association with disasters. Natural hazards affect almost 10 million people every year in the country with an area of 1,47,570 sq. km. [1]. Among the many hazards affecting this region, cyclones and storm surges have historically ravaged lives in the country. The country that is already affected by natural hazards now faces the direct climate change impacts like salinity intrusion, sea level rise and the indirect impact in intensification of tropical cyclone events [2].

Tropical Cyclone is a term used to define a non-frontal synoptic scale low pressure system over tropical or subtropical waters with organized convection and a surface wind circulation [3]. It is generally accompanied by high torrential rainfall and thunderstorms. The terms hurricane, cyclone, typhoon are all used to define the same weather phenomenon depending on different regions. Cyclone is used in the South Pacific and Indian Ocean, whereas in the Atlantic and Northeast Pacific it's coined as hurricane and in Northwest Pacific it is called Typhoon [4].

Usually tropical cyclones are accompanied by storm surges that flood the coastal regions. Due to the tangential wind stresses and atmospheric pressure gradient within the wind column of synoptic scale weather systems like tropical cyclones, water body swells up [5]. The water level rises in a nominal amount which is about 1cm per 1 Mb through this pressure drop process known as "inverted barometer effect" or the sucking effect [6]. This results in a massive wave of water moving at the same speed of the cyclone which is called Storm Surge [7]. In the Bay of Bengal the lifetime of cyclone ranges from a week to longer. In this time the height of storm surges are limited to 10 meters within the bay which further reduces in the shallower inland areas of the coast [8].

Historically Bangladesh is the most storm surge affected country not only among the countries in and around the Bay of Bengal but also globally. The table below shows the approximate percentage of storm surge impact around the globe.

Table 1.1: Percentage of storm surge impact around the world [9]

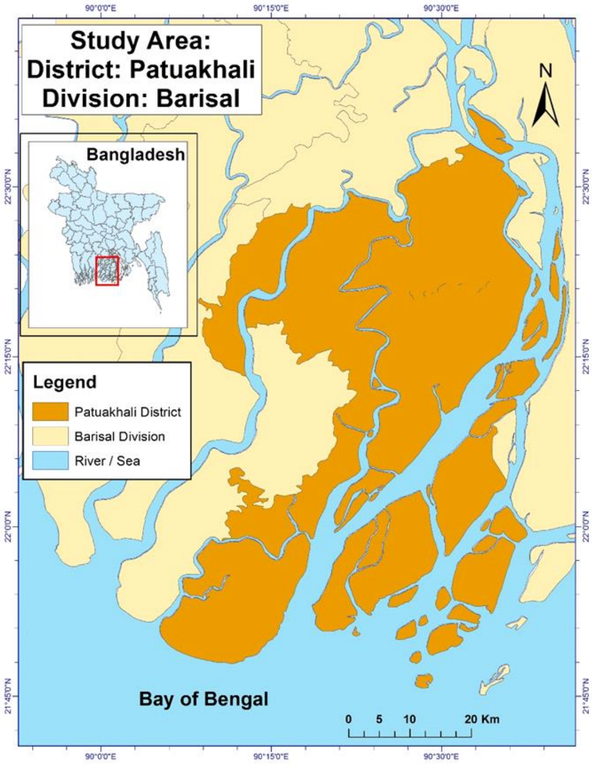
Region	Percentage
Bangladesh	40
Asia (excluding Bangladesh)	20
North America	20
Europe	10
Africa and South America	5
Australia and New Zealand	5

According to Murty & El-Sabh (1992), the factors contributing to this huge impact on Bangladesh coast can be summed as below [9]-

- The phenomenon of recurvature of tropical cyclones in the Bay of Bengal
- Shallow continental shelf, especially in the eastern part of Bangladesh
- High tidal range
- Triangular shape at the head of the Bay of Bengal
- Almost sea-level orography of the Bangladesh coast
- High density of population

According to the IPCC (2007), the threat of storm surges and related flooding situations will be worsened by increases in more intense tropical cyclones [10]. In scenarios where storm surge threatens the coastal communities of Bangladesh in such a manner both historically and in terms of future prediction, a baseline hazard assessment is needed for further risk reduction planning. This study aims at generating inundation scenarios for the coastal areas of Bangladesh.

II. Study Area



The area of study for cyclone hazard assessment is the district of Patuakhali located in the south-central part of Bangladesh and is under the Barisal Division. The district is geographically located between the 21°48' and 22°36' North Latitudes and in between 90°08' and 90°41' East Longitudes [11]. Patuakhali has an area of 3221.31 sq. km. and consists of 8 Upazilas (Sub-district), 72 Union Parishads (Sub-sub-district), and 882 villages [12]. According to the Population and Housing Census 2011, the population of the district stands at 15,35,854 with 7,53,441 males and 7,82,413 females. The total number of households in this area is 3,46,462 with 45,231 located in the urban settings and 3,01,231 located in the rural parts [11]. The lands here are composed of alluvial soil deposits of the Meghna Basin and a number of char lands (Riverine Island) located in the southeast. Kuakata, the 18 km. long beach famous for watching both the sunrise and sunset, is located in the southernmost part of the district. The average height from sea surface ranges between 3 to 3.5 meters while average temperatures are highest 33.3°C and lowest 12.1°C [11]. Being a district open to the ocean in the south, it has been very frequently affected by cyclones and associated storm surges.

III. Methodology

Storm surge hazard assessment has been done using cyclone frequency analysis, wind speed and surge height of cyclones occurring between 1960 and 2017, linear decay model and Digital Elevation Model. The methodology of the study has been described below.

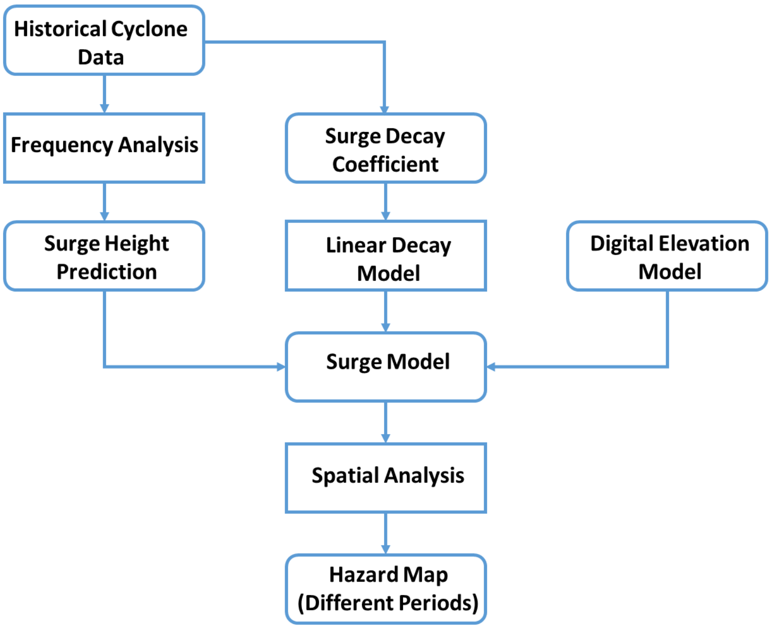


Figure 3.1: Methodological Framework of the study

3.1 Cyclone Frequency Analysis and Surge Height Calculation

Coast zonation and historical cyclone data like frequency of wind speed, surge height etc., have been used for the prediction of cyclone hazards of specific return periods. For this study, different aspects of the cyclones occurring from 30th October 1960 to the Cyclone Mora in 2017 have been considered. The analysis is carried out for 38 cyclones in this time interval after filtering out the cyclones not having satisfactorily available information about either wind speed or surge height or both. Data on maximum sustained wind speed and storm surge height in Bangladesh was obtained from different sources [6] [7] [13] [14]. Frequency analysis has been done to acquire the wind speeds for cyclones having return periods of 5, 10, 20, 50 and 100 years. Gumbel distribution, an Extreme Value Distribution, is known to fit quite well for this type of data and so it was chosen for intensity estimation [15]. Annual Maximum wind speed data was fitted in Gumbel distribution for estimating maximum cyclone wind speed. The annual maximum data has been acquired from two different sources [13] [14].

Gringorten estimation has been used for probability (Pv) calculation for 58 years annual maximum data from 1960 to 2017. Pv is acquired using the Gringorten estimation equation after ranking the wind speeds in ascending order. The regression analysis of -ln(-ln(Pv)) and the corresponding wind speeds give an equation relating probability with wind speed. Return periods are input in the form of probability to get the wind speeds of specific return periods (e.g. 100years).

The equation used for Gringorten estimation of probability is,

$$Pv = \frac{m - 0.44}{N + 0.12}$$

Where, Pv = Gringorten estimation of probability
m = rank of annual maximum wind speed
N = total count of cyclones

The relation between Probability and Return Period is,

$$R = \frac{1}{1 - Pv}$$

The calculated wind speed data of different return periods has been used as input for predicting different storm surge heights. Based on the different tidal amplitudes, bathymetry and bay configuration, the coast of Bangladesh has been divided into 3 zones [6]. The area of study, Patuakhali district, is situated in the Zone 1. Regression analysis of maximum wind speed and surge height, excluding the astronomical tide, has been performed for surge height calculation. Based on the regression analysis, storm surge heights of different return periods of 5, 10, 20, 50 and 100 years have been calculated.

3.2 Surge Model and Surge Decay Coefficient

A linear decay model, namely the Surge Decay Coefficient (SDC), has been utilized for storm surge modelling. SDC is a coefficient used for calculating how surge depth decreases after landfall with increasing distance from the coast. It is perceived as a function of friction caused by surface forms and land cover. The storm surge friction with terrain elements is still not clearly understood. However, in terrains with low or no dikes it is seen from previous records that storm surge height remains constant for a certain distance inland and then it decreases gradually [8]. The linear decay model hypothesis, along with a non-linear decay hypothesis, was used by the Flood Action Plan 19 (FAP 19) of the Irrigation Support Project for Asia and the Near East (ISPAN) for GIS zone analysis. The linear decay model was supported by the Multi-purpose Cyclone Shelter Project (MCSP) 1993 and has been used for this study [6].

The Surge Decay Coefficient (SDC) is calculated as-

$$SDC = \frac{Surge\ Height - Average\ Elevation\ at\ the\ end\ of\ Surge}{Total\ Inundation\ Width - Width\ of\ Constant\ Surge}$$

The figure below depicts an example for a storm surge of 665cm at the coastline and how it further decays from coast to inland.

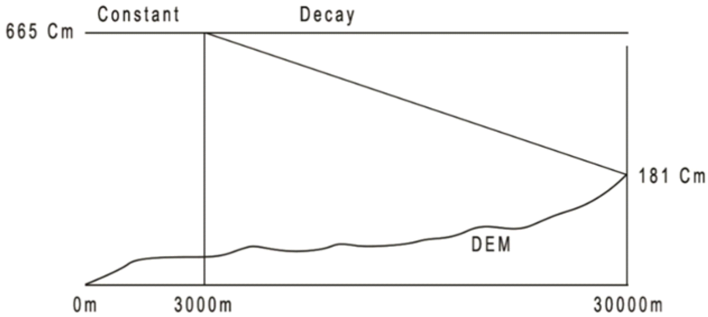


Figure 3.2: An example of 665cm surge decay from the coastline [13]

The parameters and values shown in the decay model (Figure 3.2) were used for this research, considering the assumption that terrain elevations of this study area are roughly the same as considered in a previous study as both the areas are situated side by side on the tidal zone 1 of Bangladesh coast [13]. It has to be mentioned that Patuakhali, the study area, has two major rivers' outlet in the Bay of Bengal. According to S. R. Khan (1995), if river outlet exists, the SDC has to be modified [6]. In this study, it has been assumed that the surge height will remain the same in this rivers. Based on this assumption, the whole study area has been divided into five parts (Figure 3.3) with different coastlines. Surge inundation depth for different return periods have been calculated for each of these five parts using their respective coastlines.

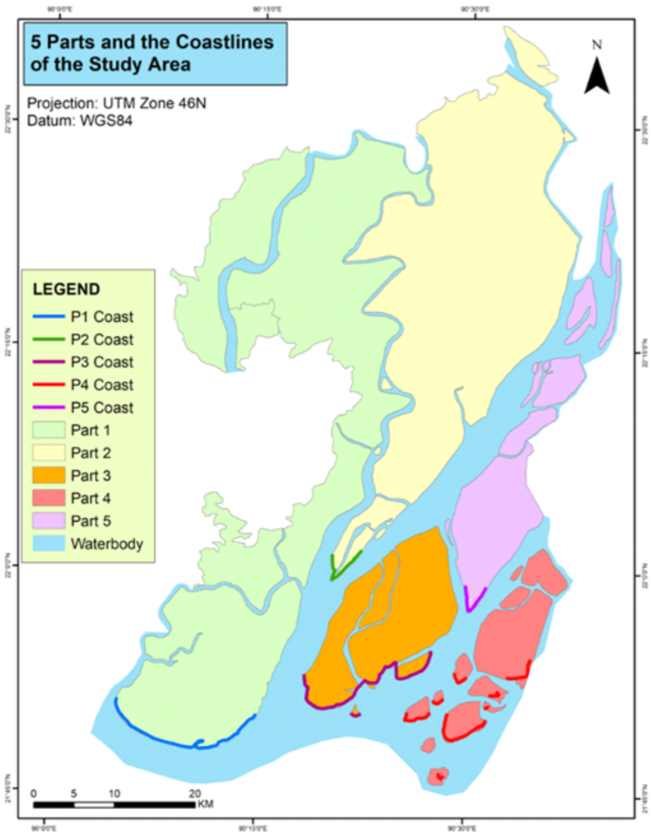


Figure 3.3: Coastlines of Study Area

3.3 Development of Hazard Map

Two models have been used in this research to develop hazard maps of different return periods. They are-

i. Surge model calculated using the historical cyclone and surge height data and Surge Decay Coefficient.

ii. Digital Elevation Model - a Digital Elevation Model (DEM) developed by Institute of Water Modelling (IWM), Bangladesh, commissioned by Comprehensive Disaster Management Programme (CDMP) of UNDP, Bangladesh and Ministry of Disaster Management and Relief, Government of Bangladesh has been used for this study. The DEM covers all the coastal districts of Bangladesh and was made for tsunami and storm surge risk mapping for the whole coastal region. It has the projection of BTM (Bangladesh Transverse Mercator) and datum of PWD (Public Works Datum) with a cell size of 50m x 50m.

Various Map Algebra calculations in ArcGIS 10.3 have been used to develop the final hazard maps using the storm surge heights, SDC and the DEM. All the spatial analysis for modelling surge inundation as well as the mapping have been done in this GIS software.

IV. Result and Discussion

4.1 Trend Analysis of Tropical Cyclones

A total count of 75 cyclones have hit the Bangladesh coast from 1797 to 2017. The month of May seems to be most likely for cyclogenesis as 28 of the 75 cyclones have been onset in the month alone. The next three months of June, July and August have all had just one cyclone occurrence while September has had 3 in this time period. Again, in October and November, the cyclone events have been increased with 21 and 12 events respectively. April and December have had 4 occurrences each. No cyclones have occurred in the first three months over this time period. This validates the well-established concept that Pre-monsoon and Post-monsoon periods are the probable seasons for cyclone forming. The monthly distribution of major cyclones occurring from 1797 to 2017 is shown in the figure 4.1 below.

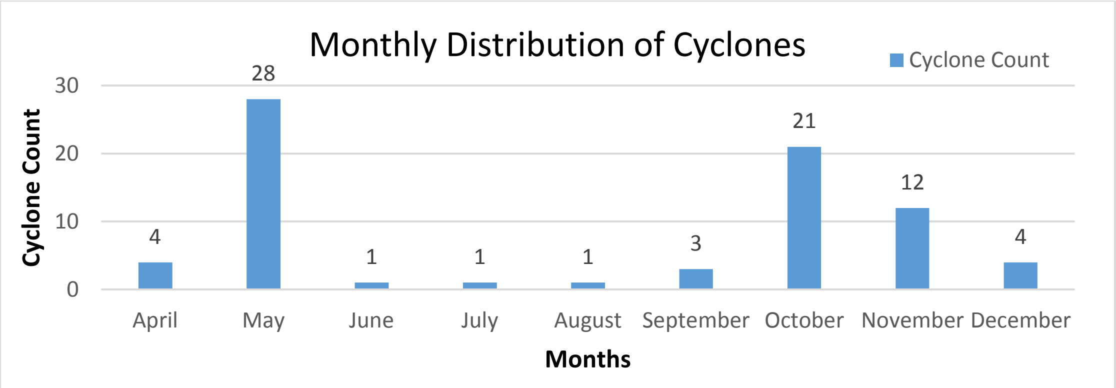


Figure 4.1: Monthly distribution of major cyclones along the Bangladesh coast since 1797

From the cyclone track data, it can be seen that Zone 3, which is the southeast coastal zone covering Chittagong to the end of Cox's Bazar is the most disastrous place for cyclone landfall. 32 of the 75 cyclones have made landfall there. Whereas the Zone 2 in the middle has faced 25 of these cyclones in this time period. In comparison, Zone 1 has had the least number of strikes during the time. Among the 75 cyclone events since 1797, 38 cyclones were selected for regression analysis based on availability of both wind speed and surge height data. The landfall counts of these 38 cyclones for Zone 1, 2 and 3 are 8, 11 and 19 respectively.

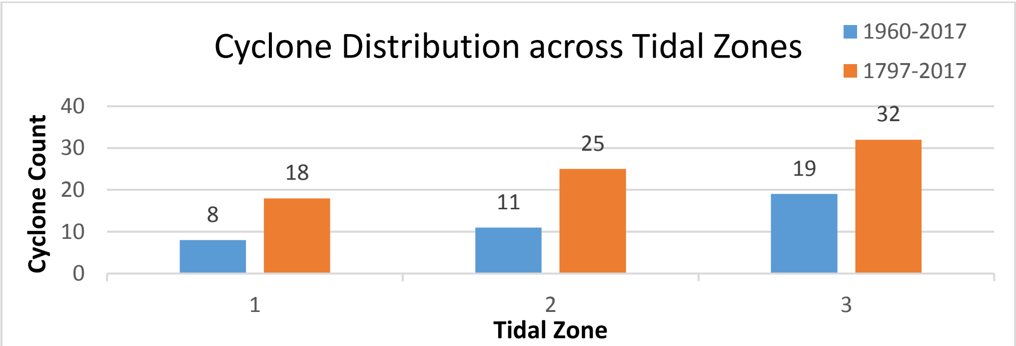


Figure 4.2: Distribution of Cyclones in different Tidal Zones of Bangladesh Coast

4.2 Cyclone Wind speed Analysis and Surge Height Calculation

The wind speed data acquired from various articles, reports and IMD database were mostly found identical with some little deviations. Also, as IMD database collects wind speed values in knots unit, rounding of the figure was made during conversion to km/h. The calculation of Maximum Wind Speed for different return periods using Gringorten estimation of probability can be shown as below.

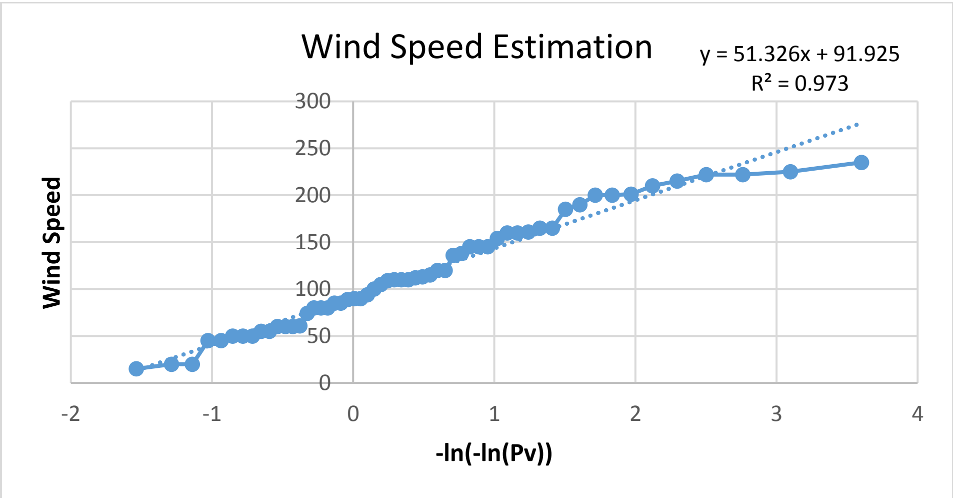


Figure 4.3: Wind speed estimation by plotting wind speed vs -ln(-ln(Pv));
Pv is Gringorten estimation of Probability

Cyclonic winds affecting the coast are independent variables and are assumed to have no other influences on bay configuration, tidal amplitude etc. Regression analysis, based on the wind speed of the historical cyclones and their corresponding surge height data, is done for both the entire coast and tidal zone 1 (Figure 4.4 & 4.5).

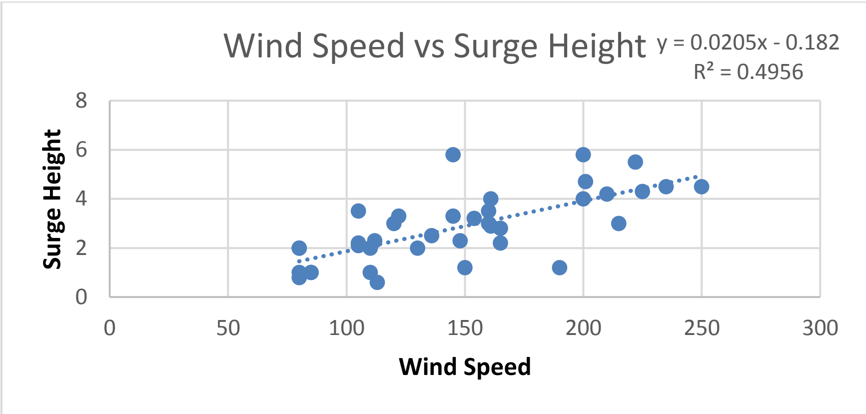


Figure 4.4: Regression analysis result of Wind speed and Return Period for entire coast

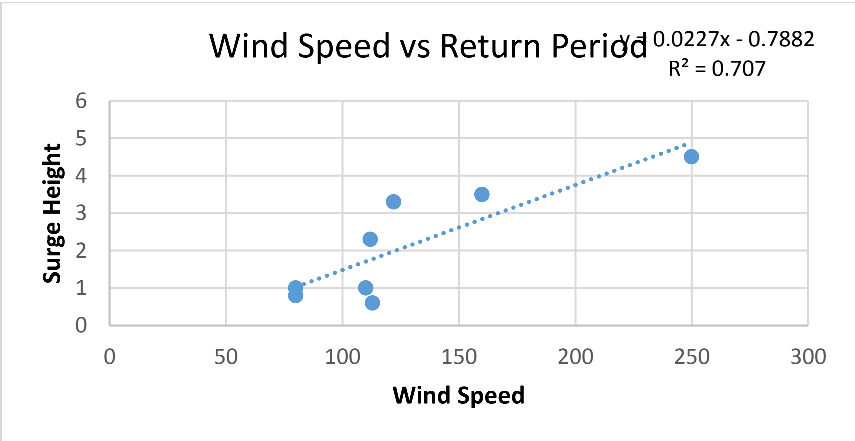


Figure 4.5: Regression analysis result of Wind speed and Return Period for tidal zone 1

The results (Table 4.1) show an 11cm higher storm surge for 100 years return period for Zone 1 compared to the entire coast. In contrast, surge heights for other return periods in Zone 1 remain close the surge heights for the entire coast or actually drop below it.

Table 4.1: Calculated wind speeds and storm surge heights for different return periods.

Return Period (Year)	Wind Speed (km/h)	Storm Surge Height (m)	
		Entire Coast	Zone 1
100	**328**	**6.54**	**6.65**
50	**292**	**5.81**	**5.85**
20	**244**	**4.83**	**4.75**
10	**207**	**4.07**	**3.92**
5	**169**	**3.28**	**3.04**

4.3 Surge Decay Coefficient Calculation

The SDC values for the study area and estimated surge heights have been calculated as below.

Table 4.2: SDC calculation for surge model

Return Period (Y)	Surge Height at Zone 1 (cm)	Width of Constant Surge (m)	Width of total Inundation (m)	Average Elevation at End of Surge (cm)	SDC (cm/m)
5	300	2000	15000	184	0.009
10	390	2200	20000	183	0.012
20	475	2500	25000	202	0.012
50	585	2800	28000	181	0.016
100	665	3000	30000	181	0.018

The width of total inundation, width of constant surge and average elevation at the end of surge have been assumed based on the field data collected during 2007 Cyclone SIDR and obtained, as calculated, from Rana & Gunasekara (2010) [13]. Here, an assumption considered is, the friction is negligible due to trees and other elements that may obstruct the surge. Inundation depths have been calculated separately for five different parts of the area using the corresponding SDC values for specific surge heights.

4.4 Hazard Maps

The calculated surge height, surge decay coefficient and the obtained DEM is used to perform Map Algebra calculations in ArcGIS 10.3 to produce the final hazard maps for different return periods. The maps are depicted below.

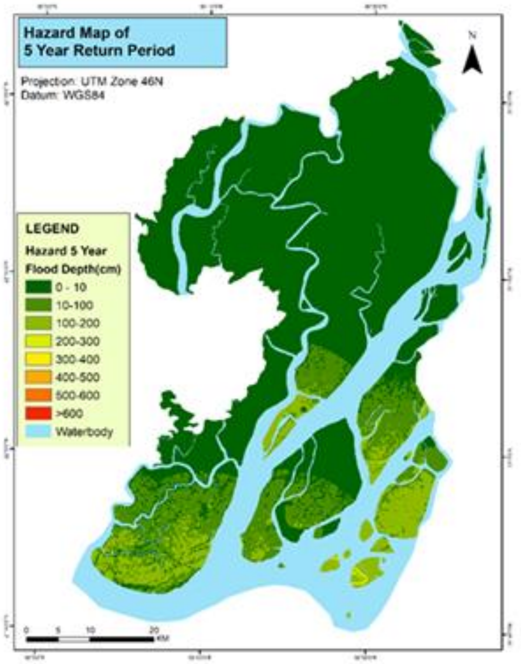


Figure 4.6: 5 year return period hazard map

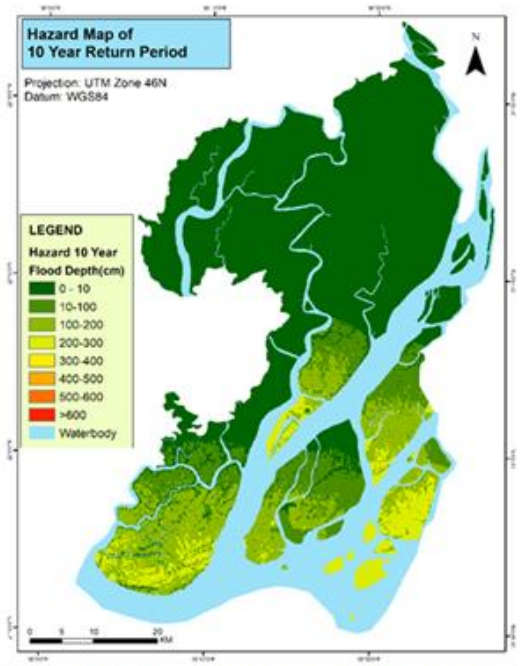


Figure 4.7: 10 year return period hazard map

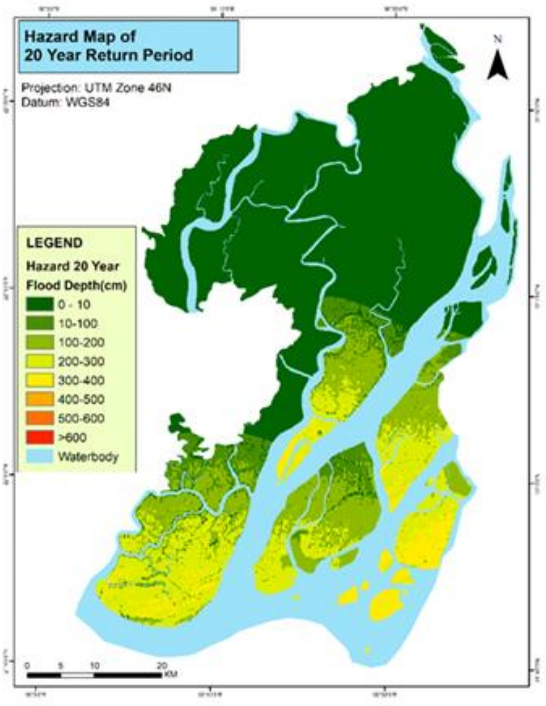


Figure 4.8: 20 year return period hazard map

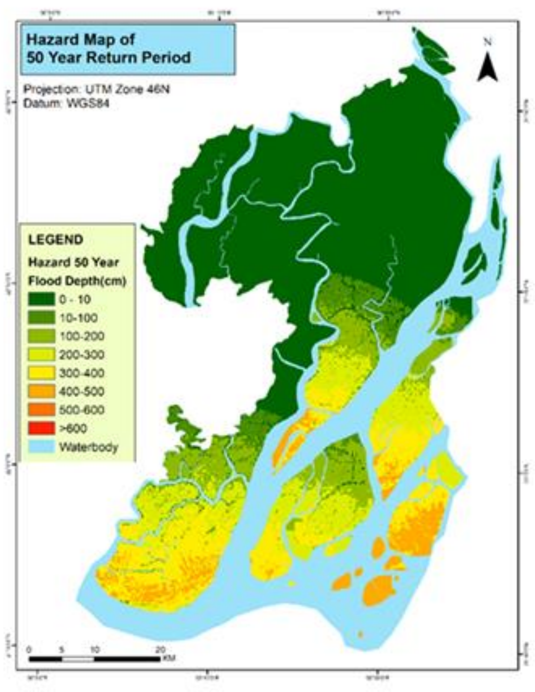


Figure 4.9: 50 year return period hazard map

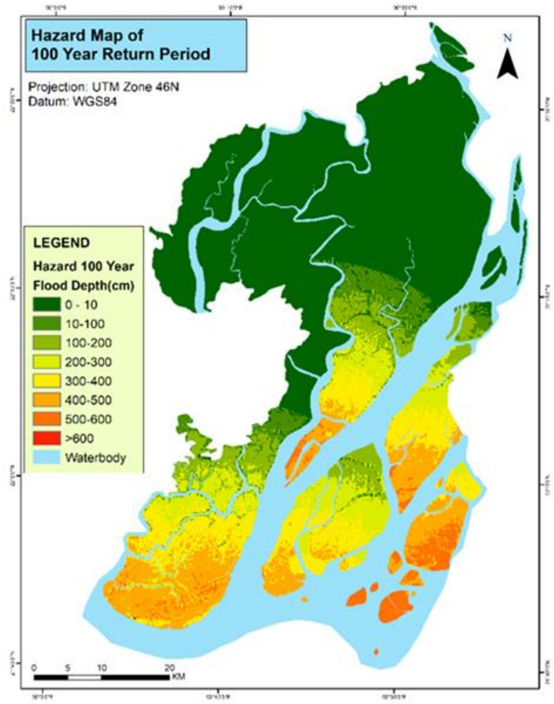


Figure 4.10: 100 year return period hazard map

For a storm surge of 100 years return period, it is calculated from the hazard map that almost 48.5% of the district will be inundated by the surges. It is seen from the maps that the highest inundation depth is more than 600 cm for the 100 year storm surge of 665 cm surge height. The inundation depth of this class is present in minor quantities. These values occur close to river channels and immediate coastline. The 4th part of the study area has the highest inundation depths occurring for any return periods. This is because this part is composed mostly of newly formed chars where elevation is very low. According to these maps the 3rd part will be the least affected of the study area. This is probably due to this area having the highest elevation calculated from the DEM.

V. Conclusion

While the cyclones in 1970 and 1991 have caused massive death counts, the cyclones SIDR and AILA in 2007 and 2009 respectively, have caused huge damages to the country's environment and economic sector. So it is imperative to study cyclone and storm surges for risk reduction of coastal communities. This study looks into the trend of past cyclones to do a baseline forecast on how the Bangladesh coast may be affected in the future by cyclone associated storm surges.

The major findings of this research are-

i. The occurrence of a 100 year return period cyclone will cause 48.5% of the study area to be submerged under water.
ii. The southernmost part of the district is most susceptible to storm surge.
iii. Surge Decay Coefficient acquired from field data has to be modified according to study area in the presence of river outlets. In this study the modification was done by dividing the study area into 5 exclusive parts.
iv. Trend analysis of historical cyclones indicates that predicted storm surge height for Zone 1 of the Bangladesh coast is higher than that predicted for the whole coast.

Limitations of the study are-

i. The research is dependent on high resolution DEM, so better resolution data like that of LiDAR could improve the accuracy of the results.
ii. Features like embankment, polder, etc. need to be incorporated into surge model.
iii. This study doesn't include the influence of Sea Level Rise and Global Warming on surge prediction.
iv. Tidal height is not considered in the calculation of storm surge height.

This study comprises of hazard assessment of cyclone induced storm surges in the coastal areas of Bangladesh. It is part of a complete risk assessment of the cyclone hazard, which will allow various policy decisions to form as well as be implemented from different levels of Government or other stakeholders. Further studies are also needed for the results to become more applicable in implementation of strategies. The research is easily reproducible across different study areas and can lead the pathway towards risk assessment of the coastal areas which will let advanced planning for cyclone disaster management.

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