CYCLONE HAZARD IN BANGLADESH

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1. SUSCEPTIBILITY TO STORM SURGE DISASTER DUE TO SOCIO ECONOMIC AND PHYSICAL ENVIRONMENTAL FACTORS

Bangladesh has the eighth largest population of the world This high population density (800/km^2) increases the susceptibility to storm surge disasters.
An other factor which increases the susceptibility is the migration of workers to the southern parts of the country in the months of April, May, October and November. These are favorable months for getting a job at aman paddy fields, but these months coincide with two cyclone seasons (see fig. 1).

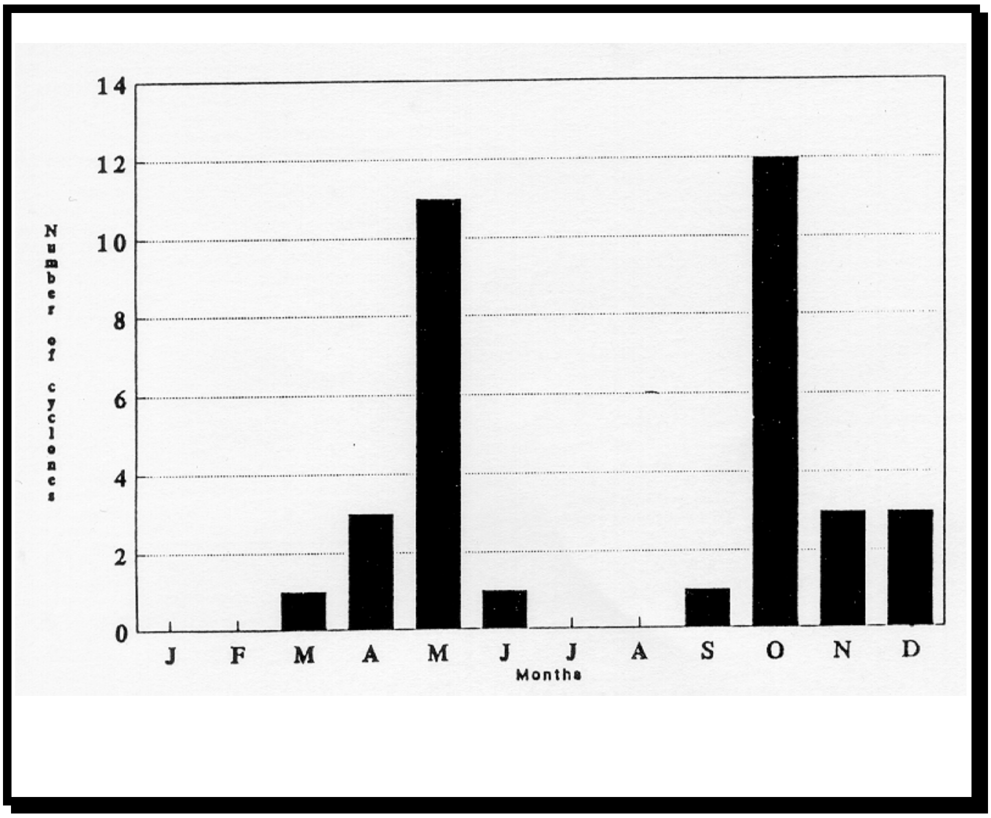

Figure 1. Monthly distribution of 35 Major Cyclones in Bangladesh (after M.M. Hoque, 1991).

The coastal areas and off-shore islands of Bangladesh are low lying and very flat. The height above mean sea level of the coastal zone is less than 3m.

The range of astronomical tide along the coast of Bangladesh is so large that the storm induced sea level is apt to become very high. The normal tidal range is about 3m near the Indian border in the west and becomes higher to the east (central coastal part) to about 5m near Sandwip Island at the mouth of the Meghna estuary (Figure 2).

The tidal range in the southeastern part is about 3.5 to 4m. If storm surges are superimposed on high tides, the situation becomes disastrous.

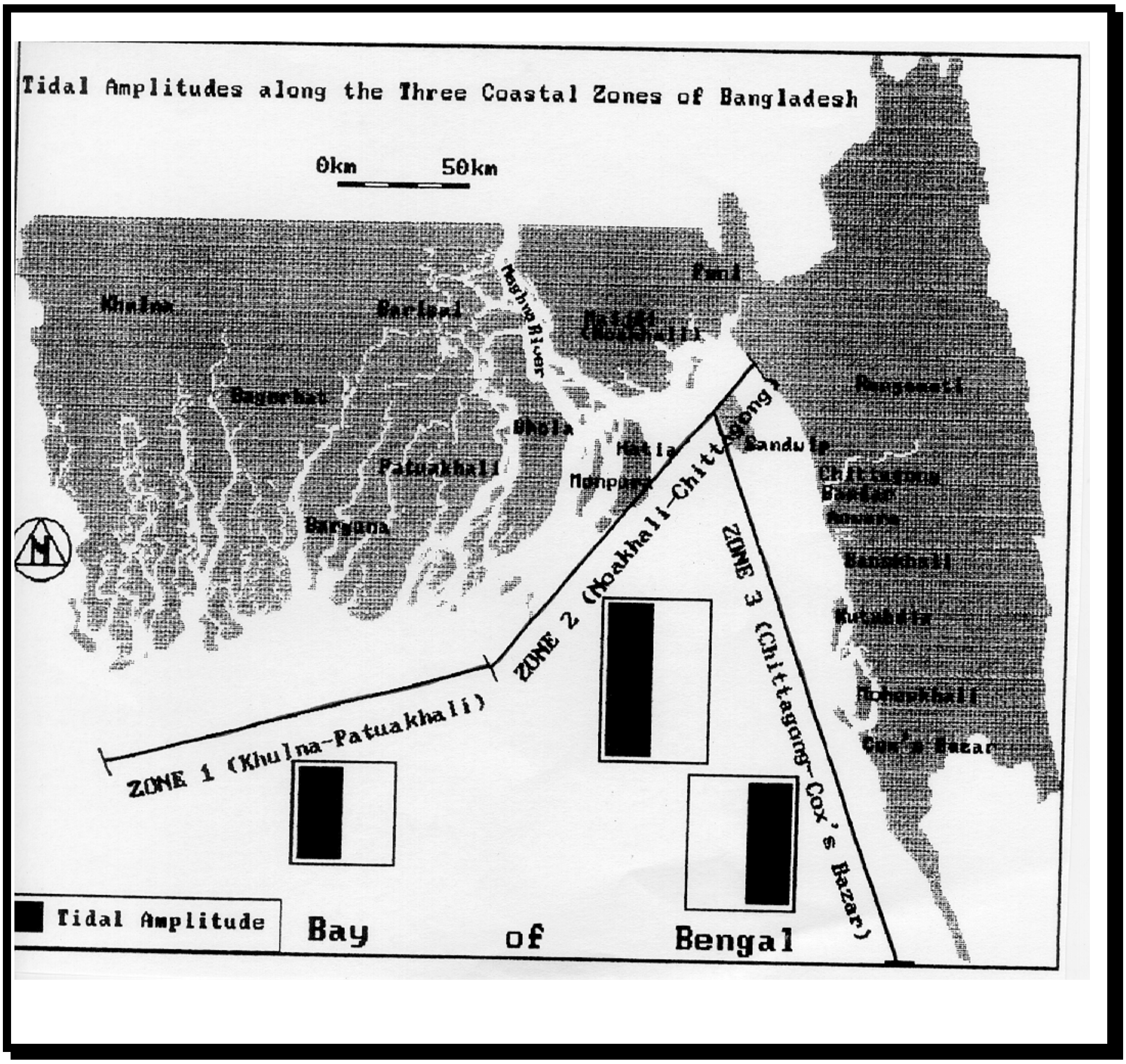

Figure 2. Average tidal amplitudes in the three coastal zones of Bangladesh.

A funneling coast line reduces the width of storm induced waves and increases the height. Also the fact that the coasts are situated at right angles in the northern corner of the Bay of Bengal (figure 2.) causes higher storm induced waves compared to a straight coast line (Flierl and Robinson, 1972).

2. DISASTER MANAGEMENT PROGRAMS IN BANGLADESH

The coastal areas of Bangladesh have been protected from storm surge inundation and salt water intrusion by high flood tide as well as from monsoon river flooding .

Protection of the coastal areas from the above mentioned problems was carried out under a project known as The Coastal Embankment Project (CEP). The concept of the CEP, however, dates back to the 17th century. Construction of small dikes or embankments around individual land parcels separated by numerous tidal creeks and inlets to limit saline water overflow has been practiced since the 17th century by Zamindars (Big Landlords). With the abolition of the Zamindari system in 1947, construction of embankments by local efforts practically ceased and the condition of existing embankments deteriorated due to lack of maintenance. Reconstruction and development of embankment started in 1961. The Dutch term "polder" has been adopted to designate the reclaimed bodies of land in the coastal areas. Sluices are built to remove accumulated rainfall from the polders by gravity flow during the periods of low tide level. This can be done because during that time the water level inside the polders is much higher than the channels outside. Empoldering of the coastal areas has increased the crop production at places up to 200 to 300 percent, because the crops are not affected by salinity and flooding.

3. CYCLONES

3.1. Definition, Classification and Causes

Typhoons are tropical revolving storms. They are called `Cyclones' in English, when they occur in the Indian Ocean area. The coastal regions of Bangladesh are subject to damaging cyclones almost every year. They generally occur in early summer (April-May) or late rainy season (October-November). Cyclones originate from low atmospheric pressures over the Bay of Bengal. Figure 3. shows a typical cyclone structure formed in the tropics of the northern hemisphere.

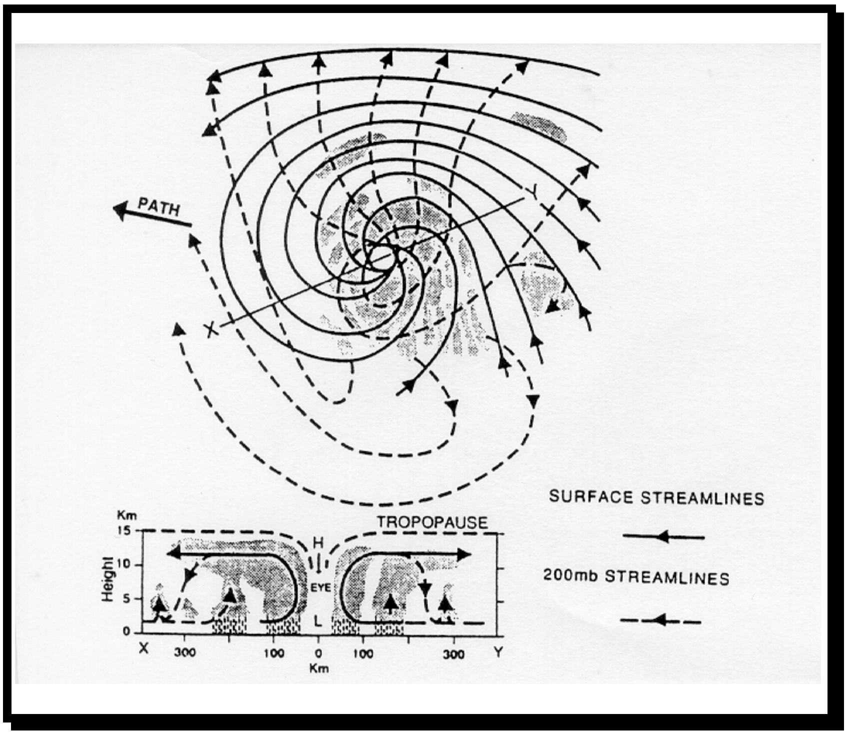

Figure 3. A model of the aerial and vertical structure of a tropical cyclone. The areas of rainfall are indicated in the vertical section X-Y across the system (after Barry and Chorley, 1992).

Cyclones in the South Asian Sub-Continent are presently classified according to their intensity and the following nomenclature is in use (Choudhury, 1992):

Depression	Winds up to 62 km/h
Cyclonic Storm	Winds from 63-87 km/h
Severe Cyclonic Storm	Winds from 88-118 km/h
Severe Cyclonic Storm of Hurricane Intensity	Winds above 118 km/h

Most of the coastal areas of the world are at risk from natural hazards created by geological or meteorological disturbances. The hazards are classified (Crater, 1988) as:

1) short term (minutes, hours, or days) events associated with storms or earthquakes (tsunamis), and
2) long-term events (decades, millennia) related to changes in rise of sea level caused by secular eustatic (atmospheric, cryospheric, geoidal) or isostatic (tectonic) processes.

Tropical cyclones or hurricanes are common within latitude 30^{o} north and south. These intense storms move across shallow shelf seas; the water is being piled-up along the coast as a surge. In most cases the mixture of these effects creates most dreadful effects in the coastal regions - a gradual rise in the regional sea level produces enhanced landward penetration of surges and storm waves.

3.2. Storm Surge Disasters in Bangladesh

Storm surges are oscillations of the water level in a coastal or inland water body in periods ranging from a few minutes to a few days, resulting from atmospheric forces in the weather system. A storm surge is partly caused by pressure differences within a cyclonic storm and partly by high winds acting directly on the water. This results in a mass of water, a huge wave, moving at the same speed as the cyclone. In the northern Bay of Bengal, a unique combination of high tides, a funnelling coastal configuration, the low flat coastal terrain, and a high population density have produced some of the highest mortality figures associated with storm surges (Flierl and Robinson, 1972).

3.3. Storm Surge and Flooding

Storm surges are generated by two principal factors: pressure drop and wind stress. Atmospheric pressure drop below normal raises the water through "inverted barometer effect" (which is also called "sucking effect") by a nominal amount, i.e. about 1 cm per 1 Mb drop of pressure. Wind is the main force for the generation of storm surges. Wind exerts tangential as well as normal (downward) stresses on the water underneath. Water being almost incompressible, the normal stress cannot generate any noticeable motion in water. The tangential stress generates long water waves or storm waves i.e. storm surges. The amplitude of the wave depends directly on the strength of the wind. The wind stress is approximately proportional to the square of the wind speed.

Flooding by storm surge in Bangladesh can be classified as follows:

a) Normal coastal flooding - no damage on crops,
b) Moderate coastal flooding - very limited damage on crops,
c) Moderately high coastal flooding - high damage on crops but relatively low damage on properties and lives,
d) High coastal flooding - large scale damage on crops, properties and lives,
e) Severe coastal flooding - severe damage on crops, properties and lives.

3.4. Historical Cyclones in Bangladesh

Appendix Background Information on the Storm Surge Modelling

During the years 1797 to 1991, Bangladesh has been hit by 59 severe cyclones, 32 of which were accompanied by storm surges. Table 1. gives a brief account of these disasters with particular reference to the wind speed, surge height, loss of life, damage to crop and properties, etc. A tropical cyclone forming in the Bay of Bengal has a lifetime of one week or longer. The height of the surges is limited to a maximum of 10 meters in the bay. When propagating into the shallower inland coastal areas, the heights of these waves are further reduced. The frequency of a wave (surge plus tide) with a height of about 10 m is approximately once per 20 years. A storm surge of approximately once in 5 years has a height of about 7 m (surge plus tide). Besides these exceptional surges, wind waves occur, the dimensions of which depend on wind speed and direction, fetch, water depth, and duration. Waves of 3 m height may occur under unfavorable conditions in the coastal regions (French Engineering Consortium and Bangladesh Water Development Board, 1989).

Table 1.
Chronology of major cyclones and storm surges in Bangladesh (compiled from T.S.Murty et al., 1986; Khalil, M.G., 1992; and Murty, T.S. and El-Sabh, M.I., 1992).

Sl No.	Year, Month & date	Affected Area	Nature of the Phenomena	approximate loss/damage
1	1797, May-June	Chittagong	Most severe cyclone	Every hut levelled to ground and 2 vessels sunk in the Chittagong port
2	1822, May	Barisal	Most severe cyclone	40,000 people killed and 100,00 cattle lost
3	1831, October	Barisal	Storm surge	Damage report not available
4	1872, October	Cox's Bazar	Cyclonic storm	270 people killed
5	1876, 27 Oct. to Nov. 1	Patuakhali, Noakhali and Chittagong coast	More severe storm surge of 12m height	400,000 lives were lost and enormous properties were destroyed
6	1895, October	Sunderban	Cyclonic surge	Damage report not available
7	1897, October	Chittagong and Kutubdia island	Hurricane with surge	175,000 lives were lost
8	1898, May	Teknaf	Cyclonic storm surge	Damage report not available
9	1901, November	Western Sunderban	Cyclonic storm	Damage data not available
10	1909, October	Chittagong	Cyclonic storm surge	Damage data not available
11	1909, December	Cox's Bazar	Cyclonic storm	Damage data not available
12	1911, April	Teknaf	Cyclonic storm	120,000 people killed
13	1917, May	Sunderban	Cyclonic storm	70,000 people killed
14	1919, September	Barisal	Cyclonic storm	40,000 people killed
15	1922, April	Teknaf	Cyclonic storm	Damage data not available
16	1923, May	Teknaf	Cyclonic storm	Damage data not available
17	1926, May	Cox's Bazar	Cyclonic storm	606 people killed
18	1941, May 26	Eastern Meghna estuary	Cyclonic storm	7,000 people killed
19	1948, May 17-19	Between Noakhali & Chittagong	Cyclonic storm	Damage data not available
20	1950, Nov. 15-20	Patuakhali	Cyclonic storm	Damage data not available
21	1958, May 16-19	Eastern Meghna estuary	Cyclonic storm	Damage data not available

22	1958, October 21-24	Noakhali and West Meghna estuary	Cyclonic storm	12,000 people killed
23	1960, May 25-29	Sunderban Coast (landfall at Sunderban)	Cyclonic storm, s= 3.2m and t=0.0m	106 people killed
24	1960, October 10-11	Meghna estuary (landfall at Noakhali)	Severe cyclonic storm, w=129 km/h, s=6.6m and t=1.5m.	6,000 to 11,446 people killed
25	1960, October 30-31	Chittagong coast (landfall at Chittagong)	Severe cyclonic storm, w=161 to 210 km/h, s=4.2m and t=1.8m.	70% buildings in Hatia blown-off and 8,149 lives lost
26	1961, May 6-9	Meghna estuary (landfall near Feni river)	Severe cyclonic storm, w=145 km/h, s=4.5m and t=1.2m at Galachipa.	11,468 people killed in Char Alexander and rail road damaged near Noakhali
27	1961, May 27-30	Chittagong-Noakhali coast	Cyclonic storm, w=95 to 145 km/h and total water level was 7m at Chittagong.	10,466 people killed
28	1962, October 26-30	Feni-Chittagong coast	Cyclonic storm, w=200 km/h, s=5.8m and t=0.0m.	50,000 people killed
29	1963, May 28-29	Noakhali-Cox's Bazar Coast (landfall near Chittagong)	Severe cyclonic storm, w=201 km/h, s=5m and t=0.3m at Chittagong.	11,520 people killed
30	1963, June 5-8	Sunderban	Cyclonic storm, s=3.1m and t=0.0m.	Damage data not available
31	1963, October 25-29	Teknaf	Cyclonic storm, w=105 km/h, s=2.2m and t=0.0m.	Damage data not available
32	1965, May 10-12	Barisal-Chittagong coast (landfall between Barisal and Noakhali)	Severe cyclonic storm, w=161 km/h, s=4.0m and t=1.2m.	19,270 people killed
33	1965, May 31 to June 1	Chittagong Coast (landfall near Chittagong)	Tide plus surge was 7.1m at Companyganj. At Chittagong 1.6m surge on tide.	12,000 people killed
34	1965, December 14-15	Cox's Bazar-Teknaf coast (landfall near Cox's Bazar)	Severe cyclonic storm, w=200 km/h, s=4.0m and t=0.2m.	40,000 salt beds in Cox's Bazar were inundated and 870 people were killed
35	1966, October 1	Chittagong and Sandwip (landfall near Chittagong)	Severe cyclonic storm, w=145 km/h, tide plus surge was 6-7m.	850 people killed
36	1966, December 12	Cox's Bazar	Cyclonic storm	Damage data not available
37	1967, October 11	Sunderban-Noakhali coast (landfall at Noakhali)	Cyclonic storm, w=160 km/h, s=3.0m and t=0.0m.	Damage data not available
38	1967, October 23-24	Chittagong-Cox's Bazar coast (landfall in between)	Cyclonic storm, w=130 km/h, s=2m and t=0.0m.	128 people killed
39	1969, October 11	Khulna coast	Cyclonic storm	175 people killed
40	1970, May 5-7	Chittagong-Teknaf coast (landfall at Cox's Bazar)	Cyclonic storm, w=148 km/h, s=2.3m and t=0.2m.	18 people killed
41	1970, November	Khulna-Chittagong coast	Most severe cyclonic storm,	300,000 lives lost and innumerable

	12-13	(landfall at Hatia)	w=222 km/h, s=5.5m and t=2.1m.	animals were killed, widespread damage to crops and properties
42	1971, May 7-8	Meghna estuary	Cyclonic storm, w=80 km/h.	Damage data not available
43	1971, November 5-6	Chittagong coast (landfall near Chittagong)	Cyclonic storm, w=105 km/h, s=2.1m and t=0.0m.	Damage data not available
44	1971, November 28-30	Sunderban coast	Cyclonic storm, w=110 km/h, s=1.0m and t=0.0m.	11,000 people killed
45	1973, November 16-18	Chittagong coast	Cyclonic storm, w=165 km/h, s=3.5m and t=1.0m.	Damage data not available
46	1973, December 6-9	Sunderban-Patuakhali coast (landfall at Sunderban)	Severe cyclonic storm, w=122 km/h and s=4.5m.	183 people killed
47	1974, August 13-15	Khulna coast	Cyclonic storm, w=80 km/h, s=2.5m and t=1.7m.	Damage data not available
48	1974, November 24-28	Cox's Bazar-Chittagong-off-shore Islands (landfall at Chittagong)	Severe cyclonic storm, w=161 km/h, s=3.1m and t=0.2m.	20 people killed
49	1975, May 9-12	Sunderban-Bhola-Chittagong coast	Severe cyclonic storm, w=110 km/h.	5 people killed
50	1976, October 19-20	Meghna estuary	Cyclonic storm, w=105 km/h, tide plus surge at Companygonj was 3.5m.	Damage data not available
51	1977, May 9-12	Sunderban-chittagong coast (landfall at Sunderban)	Cyclonic storm, w=113 km/h, s=0.6m and t=0.7m.	Damage data not available
52	1978, September 30 to Oct. 3	Sunderban khulna coast	Cyclonic storm, w=74 km/h.	Damage data not available
53	1983, October 15	Chittagong-Feni coast (landfall near Chittagong)	Cyclonic storm, w=122 km/h.	43 persons were killed, 1000 fishermen missing and 20% aman crops destroyed
54	1983, November 9	Chittagong-Teknaf coast (landfall between Chittagong and Cox's Bazar)	Severe cyclonic storm, w=136 km/h, s=2.5m.	300 fishermen with 50 boats missing; 2000 houses,22 institutions destroyed
55	1985 May 24-25	Noakhali-Cox's Bazar coast (landfall at Sandwip)	severe cyclonic storm, w=154 km/h, s=3.2m and t=1.8m.	11,069 people killed, 94,379 houses damaged,64 km road and 390 km embankment damaged
56	1986, November 9	Barguna-Chittagong coast	Cyclonic storm, w=110 km/h.	14 lives lost and huge damage to crops and properties
57	1988, November 29	Sunderban	Severe cyclonic storm, w=160 km/h , s=3.5m and t=1.5m.	5,708 people killed and 6,000 missing; 65,000 cattle were lost
58	1990, October 7-8	Barguna-Noakhali coast	Cyclonic storm, w=2m.	150 fishermen with 16 mechanised boats missing
59	1991, April 29	Patuakhali-Cox's Bazar coast (landfall north of Chittagong)	Most severe cyclonic storm, w=235 km/h, s=5.8m and t=1.7m.	145,000 people killed, 70,000 cattle killed, crops were damaged

w= Wind Speed s= Surge height t= Tidal height

3. 5. Causes of Storm Surge Severity in Bangladesh

Table 2. shows the approximate percentage of storm-surge impact in various regions on the globe. Storm surges generated by tropical cyclones are most common in the Bay of Bengal and the Gulf of Mexico.

Table 2. Approximate percentage of storm surge impact.

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

(Source: Murty and El-Sabh, 1992)

The reasons for this disproportional large impact of storm surges on the coast of Bangladesh are the following.

(1) The phenomenon of recurvature of tropical cyclones in the Bay of Bengal,
(2) Shallow continental shelf, especially in the eastern part of Bangladesh,
(3) High tidal range,
(4) Triangular shape at the head of the Bay of Bengal,
(5) Almost sea-level orography of the Bangladesh coastal land,
(6) High density of population and coastal defence system.

The phenomenon of recurvature of tropical cyclones in the Bay of Bengal is the single most cause of the disproportional large impact of storm surges on the Bangladesh coast. Extra-tropical cyclones, such as those that occur in Canada and Europe, generally travel from west to east. On the other hand, tropical cyclones such as those that occur in the Bay of Bengal, are expected to travel from east to west, as would be expected from considerations of the general circulation of the atmosphere. However, in the Bay of Bengal, tropical cyclones most often do not travel towards the west or Northwest, but they turn towards the north or even Northeast. This turning back, referred to as recurvature (Figure 4), is still not fully understood. If the phenomenon of recurvature does not happen, then Bangladesh would rarely be affected by tropical cyclones and the storm surges that result from them.

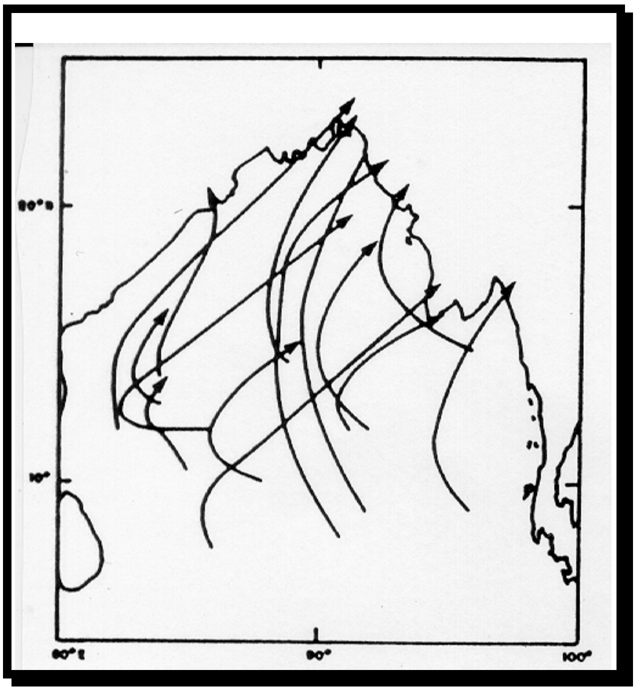

Figure 4. Tracks of some of the recurving storms in the Bay of Bengal during the period 1945-1954 (after Chakravorthy and Basu, 1956).

The coast line of Bangladesh is characterised by a wide continental shelf, especially off the eastern part of Bangladesh. This wide shelf amplifies the storm surges as the tangential sea-level wind-stress field associated with the tropical cyclone pushes the sea water from the deep water side onto the shelf. Being pushed from the south by wind stress, the water has no place to go but upwards; which is the storm surge.

The triangular shape at the head of the Bay of Bengal helps to funnel the sea water pushed by the wind towards the coast and causes further amplification of the surge. This is basically what happens in the amplification of surges on the Bangladesh coast.

The storm-surge waves belong to the class of long gravity waves. Their speed of propagation is given by the square root of the product of the acceleration due to the earth's gravity and the local water depth. In deep water, the long gravity wave propagates much faster than the speed with which the weather system travels. Thus, the weather system cannot keep up with the water wave and, hence, cannot impart any momentum. But on the continental shelf, where the water depth is smaller, the gravity wave travels much slower than in deep water and a significant transfer of energy from the weather system to the water wave occurs by resonance. Hence, the storm surge which has zero amplitude in the deep water, quickly builds up to several meters amplitude on the shallow continental shelf. As this amplified water level approaches the coast, the coastal areas become flooded with surge water.

3.6. Surge Modification/Amplification Along the Coast of Bangladesh

Once storm surges are generated, a number of local factors contribute to their modification/amplification. Contributions from some of such factors are discussed below in the context of Bangladesh.

Shallow Water Effect: Storm surges are mostly shallow water phenomena. The amplitude/height of surges depends inversely on the depth of water. The effect of shallow water on the modification/amplification has been discussed in the previous section.

Coriolis Effect: The Coriolis force due to the rotation of the earth has a minor contribution to surge modification/amplification. This force acts to the right of the direction of water motion in the Northern Hemisphere and to the left in the Southern Hemisphere. Thus, for example, if surge water is moving northward in the northern Bay of Bengal, it will be deflected towards the east, thereby increasing surge height along the east coast.

Convergence Effect: Surge height is directly proportional to convergence. Convergence leads to amplification (Proudman, 1955). Because of the northward converging nature of the Bay, surge water is funnelled towards Bangladesh in the north (depending on the track of a cyclone) leading to amplification of surge height. Amplification by convergence takes place somewhat like amplification due to shallow water.

Tidal Effect: Tidal range in Bangladesh shows a gradual increase from west to east to reach a maximum at the Meghna estuary and then it decreases south eastward. Tidal amplitude varies in different seasons along the coast of Bangladesh. During the monsoon time a large volume of water discharges through the Meghna estuary and other distributary channels. This non-saline water when mixed with the saline water of the bay, cause an increase of the volume of the water; and consequently the tidal amplitudes are increased. Pattalo et al. (1989) estimated an increase of tidal height above the normal height between 60 cm to 100 cm during the monsoon period. When this high tide level (during the months of October and November) coincide with the storm surge, the impact becomes severe, especially around the estuary. Tide and surges are not linearly additive but interactive. This means that if, for example, a 5m surge is superimposed on a 5m tide, the total height will not be 10m. Tides modify the surge amplification.

River Effect: A river system can have a number of effects on surges and tides. Firstly, the presence of rivers has a negative effect on surge amplification. If there were no rivers, then the surges in the coast would be higher (Sinha et al., 1985). Secondly, fresh water discharge through rivers will modify the sea surface elevation. Thirdly, the presence of a number of waterways allows a deep inland penetration of surges originating in the Bay. A consequence of this is an inland flood hazard and saline water intrusion, which may extend over several hundred of kilometres. Lastly, the surge and tidal water has a back water effect on river discharges. This is particularly important during flood periods. The back water effect slows down the discharge rates, thus making the flood situation more disastrous.

Island Effect: The presence of offshore islands plays an important role in surge modification. Some of these may be identified as follows: i) The channels in between the islands confine the water within them and compel it to pass through them (until the island becomes inundated), thereby causing surge amplification; ii) islands act as barriers to impending surge water which may lead to surge amplification; and iii) islands may also retard the outflow of surge water back to the Bay after the cyclone dissipation.

Track Effect: Surge height, particularly in Bangladesh, is strongly dependent on the cyclone track. Storm surges are usually highest to the right (looking down the direction of the cyclone motion) of the track. This is principally because of the occurrence of the maximum wind speed to the right of the cyclone where the forward motion of the cyclone is superimposed on the wind speed. As a cyclone approaches the land to the north, this wind tends to pile up water against the coast. This tendency is reinforced by the shallow water and convergence effects. The consequence of all these factors is to produce even a higher positive surge to the right of the cyclone path or point of landfall. Wind on the left (being predominantly in the off-shore direction) drives water away from the coast and produces a negative surge.

3.7. The Chittagong Cyclone of 1991 and its impact

The Chittagong cyclone of 29 April 1991 was first detected as a depression (wind speed not exceeding 62 km/h) on 23 April 1991 from satellite imagery (NOAA-11).

The depression was located at 10.0°N latitude and 89.0°E longitude at 0900 BST (Bangladesh Standard Time) in the morning of 25 April. It intensified into a deep depression in the evening and very quickly turned into a cyclonic storm at midnight on 25 April. The maximum sustained wind was 65-87 km/h, having a central pressure of 996 Mb. It retained this intensity till 1500 BST of 27 April when it was found to have developed into a severe cyclonic storm. The maximum wind velocity was 90-115 km/h, having 990 Mb as the central pressure. On the same day (27 April) at midnight, it turned into a storm with a hurricane core that had wind speeds of more than 130 km/h. From 28 April, it started moving in a north-easterly direction and finally, crossed the coast north of Chittagong port in the early morning (0400 BST) of 30 April. The estimated maximum pressure drop was about 60 Mb (Talukdar et al., 1992).

The maximum wind speed observed at Sandwip was 235 km/h. But the actual wind speed there was much higher, since the wind measuring device was blown away after this speed was recorded. The central pressure of the 1991 cyclone was as low as 938 Mb (Figure 6), as measured by the Chittagong Port Authority of Bangladesh (1991).

This lowering of pressure, in conjunction with the full moon, was sufficient to raise tidal levels to the highest of the normal range. The storm surge (surge plus tide) was 4 to 8 meter high in different areas. Vast areas in the districts of Cox's Bazar, Chittagong, Noakhali, and Bhola were submerged. The depth of water at Chittagong Airport exceeded 2m. The flood levels due to the surge at various locations (Figure 2) are given in Table 3.

Fatality figures caused by the April cyclone varies between 130,000 (Bangladesh Bureau of Statistics, 1991) to 200,000 (Rashid,1991). Human casualties were almost exclusively caused by the storm surge (Khalil, 1993). Casualties in the unprotected islands were on the average 40-50% of the total population of the areas affected by the storm surge. Islands protected by embankments, the figure may have been 30-40%; while on the mainland coast, which faced the fury of the surge, deaths were probably 20-30% of the population. Casualties in the cities and in the industrial areas were relatively few (Govt. of Bangladesh, 1991b).

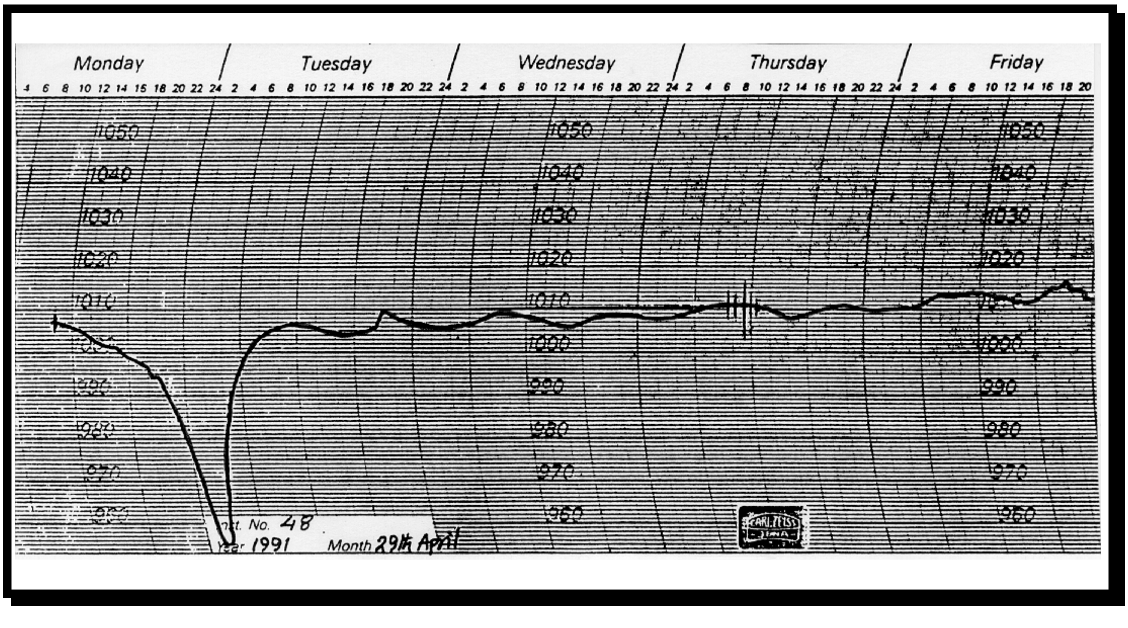

Figure 6. Showing the recorded atmospheric pressure drop condition in the mid-night, 29th April, 1991.

Table.3: Estimated water heights of April 1991 Cyclone.

Thana (Police Station)	Water Height in metre
Anowara	6.06
Banskhali	6.20
Bandar	6.06
Sandwip	6.00
Cox's Bazar	7.58
Moheshkhali	6.06
Kutubdia	6.06
Manpura	4.85
Hatia	6.00

The greatest damage done by the cyclone was in paddy fields which were submerged by saline water. The standing crops were totally destroyed and the harvested grains washed away by the storm surge. According to an estimate of FAO/WFP, 210,000 tonnes of boro rice, 36,000 tonnes of aus rice, and 35,00 tonnes of other food crops (particularly potatoes and vegetables) were destroyed. The storm surge killed some 224,000 cows and buffaloes, 218,000 goats and sheep, as well as 240,000 poultry (FAO/WFP, 1991). All ponds in the affected areas were flooded by saline water, resulting in the loss of 100% of freshwater fish.

4. EXISTING METHODS IN STORM SURGE MODELLING RESEARCH

4.1. Mathematical Studies and Hydrodynamic Models

A number of hydrodynamic numerical models have been developed for storm surge generation and propagation. Numerical models, constructed by Reid and Bodine (1968), Sielecki and Wurtele (1970) and Flather and Heaps (1975), were able to simulate the extent of inundation, but not the actual processes of wave propagation, breaking, and interaction with the coastal structures.

This approach was quite successful in predicting flooding due to a major tsunami in Chile (Hebenstreit et al., 1985). A very extensive and thorough study by Lewis and Adams (1983) resulted in a complicated numerical solution for the one-dimensional problem only. Kowalik and Bang (1987) derived a solution using a different numerical algorithm, but again, only to the one-dimensional case. Hibberd and Peregrine (1979) studied the runup and back-wash by considering the long wave equations together with the wave front condition represented by a bore.

Numerical models have also been developed for simulating storm surges in the Bay of Bengal especially along the Bangladesh coast by many scientists. Numerical models developed by Das (1972), Jones and Ali (1980), Ghosh et al., (1983), Qayyum (1983), Dube et al., (1985), Flather and Khandaker (1987), Abrol (1987), and Katsura et al., (1992) are noteworthy.

All of the above mentioned models considered the following parameters for their calculations:

-time,

-elevation of the sea surface,

-components of depth-mean current,

-components of the wind-stress on the sea surface,

-components of the bottom stress,

-atmospheric pressure on the sea surface,

-the total water depth,

-the density of the sea water,

-the acceleration due to gravity, and

-the Coriolis parameter.

4..2. GIS Studies

The Multi-purpose Cyclone Shelter project (MCSP) in Bangladesh (1993) modelled storm surge along the Bangladesh coast with the help of GIS and also delineated Risk Zones.. The MCSP risk zone map extends from the coast to the inland limit of surge water where property may be damaged by flow velocity. The most important parameters of this flooding are its depth and duration. Within the risk zone is a "high risk area" where lives may be lost as a result of flooding greater than one meter deep.

MCSP also prepared a table which shows surge inundation characteristics for cyclones of varying strength in Bangladesh (Table 4).

Table 4. Typical Storm Surge Inundation Characteristics for cyclones of Varying Strength in Bangladesh.

Wind Velocity (km/h)	Storm Surge Height (m)	Limit to Inundation (km) from the Coastline
85	1.5	1.0
115	2.5	1.0
135	3.0	1.5
165	3.5	2.0
195	4.8	4.0
225	6.0	4.5
235	6.5	5.0
260	7.8	5.5

The Flood Action Plan 19 (FAP 19) of the Irrigation Support Project for Asia and the Near East (ISPAN) working in Bangladesh took the MCSP map and Table 4 as a basis for the GIS risk zone analysis. Wind velocity was factored into the analysis based on the reported 235 km/h winds of April 29, 1991. The surge reportedly travelled at about 2.5 meters per second, advancing 2.25 km in 15 minutes. The inundation estimates in table 2.4 are only applicable as a guideline where the coastal plain is very flat and there is minimal friction from trees or other obstructions. For areas with large river outlets in the Bay of Bengal, these limits must be modified since those rivers allow deep inland penetration by the surge. Tidal phases, too, are not considered in the estimates.

Two hypotheses of tidal surge development were used in GIS by FAP 19. The first hypothesis assumed that the surge height remained unchanged for the first kilometre inland. Thereafter it decreased in height by about 0.5 meter/km inland (Figure 9). The second hypothesis assumed that after travelling a few kilometres inland it suddenly tapered off in a breaking wave (Figure 10).

Linear Method: The hypothesis that storm surge depth reduces linearly inland was supported by the MCSP work. For the GIS modelling, surge height at the coastline was kept constant for the first kilometer; thereafter a linear reduction in height was assumed to the limit of inundation, which was set at 5 km from the coastline. The 5 km limit was based on Table 2.4 estimates or reports of actual inundation limits of the 1991 cyclone of Bangladesh.

Once the linear surge model was created, two models, both using the MCSP definitions of
risk zone and high risk area, were used to delineate risk zones in the area. The first model assumed that the depth of inundation was equal to the surge height and that land relief was smooth. In this manner, a GIS map of risk was created directly from surge inundation depth.
The second model for mapping risk zones took account of topographical variations by using a digital elevation model (DEM). It was created from Spot elevations and other topographic information on 1:7920 scale Bangladesh Water Development Board (BWDB) maps. In this model the land surface was subtracted from the surge surface and grouped into one meter increments to produce a digital map of inundation levels with a water level for every 100 X 100 m area. These levels were then converted into a map of risk zone and high risk area as described above.

Non-linear Method: The second hypothesis of storm surge characteristics was modelled by simulating a minimal reduction in surge height inland up to the approximate limit of inundation, where the surge height reduced rapidly (Figure 10). Information gathered during the field visit by the FAP 19 workers indicated that a wall of water crossed the coastline of Banskhali and maintained its height until 4 to 5 km inland where inundation tailed off rapidly.

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