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Tropical cyclone risk assessment with special reference to Bangladesh

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सार — उष्णकटिबंधीय चक्रवातों को सभी प्राकृतिक आपदाओं से अधिक विनाशकारी माना जाता है। ये जान और माल के साथ पर्यावरण में भी विनाशकारी तबाही लाते हैं। विश्व में उष्णकटिबंधीय चक्रवातों के विनाश से प्रभावित क्षेत्रों में बंगाल की खाड़ी के तट से लगे देश सबसे अधिक प्रभावित हैं और बंगलादेश विशेष रूप से इनसे भी अधिक विनाश से बुरी तरह से प्रभावित देश रहा है। भविष्य में जान माल की क्षति को कम करने के लिए समुचित चक्रवात आपदा प्रबंधन कार्य एक अपरिहार्य आवश्यकता है। इसके लिए चक्रवातों से संबद्ध आपदाओं के सही ढंग से मूल्याँकन की आवश्यकता है। प्रस्तुत शोध-पत्र में आपदाओं के मूल्यांकन के लिए मुख्य घटकों की चर्चा की गई है, जैसे: (*i*) आपदाओं के कारणों सहित चक्रवातों की तालिका, (*ii*) चक्रवातों से होने वाली हानि का विश्लेषण और आपदा से प्रभावित घटकों की तालिका तथा (*iii*) बंगलादेश के विशेष संदर्भ में सुभेद्य विश्लेषण। चक्रवातों की तालिका का संबंध बंगाल की खाड़ी के क्षेत्र में 1881 से 1990 तक की अवधि में चक्रवात जलवायु विज्ञान से संबंधित है। आपदाओं के कारणों के अंतर्गत तेज हवाएँ, तूफानी समुद्री तरंगों, वर्षा, सामाजिक-आर्थिक पहलुओं, ग्रीनहाउस प्रभाव आदि की यहाँ चर्चा की गई है।

ABSTRACT. Tropical cyclones are regarded as the most deadly among all natural disasters. They bring catastrophic ravages to life and property as well as to environment. Among all the areas in the world affected by tropical cyclones, the countries along the rim of the Bay of Bengal suffer most and Bangladesh is the worst sufferer. In order to minimise the future loss of life and property, proper cyclone disaster management action is an absolute necessity. This, in turn, requires a better assessment of risks associated with a cyclone. The present paper discusses the major components of risk asessment, *viz.*, (*i*) inventory of cyclones with associated causes of hazards, (*ii*) analysis of damages and inventory of elements at risks and (*iii*) vulnerability analysis with special reference to Bangladesh. Inventory of cyclones deals with the cyclone climatology in the Bay of Bengal region over the period 1881-1990. Discussions on causes of hazards cover strong winds, storm surges, rainfall, socio-economic factors, greenhouse effects, etc. An idea about the degree of cyclone damages and the elements at risks in Bangladesh is given. Some discussions on vulnerability analysis and risk reduction/mitigation with a few case studies in Bangladesh are made. Finally few recommendations are put forward.

Key words — Tropical cyclone, Surge, Meghna estuary, Risk assessment, Hazard.

1. Introduction

Tropical cyclones are regarded as the most deadly natural disaster. They bring catastrophic ravages to whatever comes in their way. Among the tropical cyclone forming areas in the world, the Bay of Bengal is one of the most favourable one. The Bay cyclones cause heavy loss of life and property to the littoral countries, particularly Bangladesh. In fact, Bangladesh is the worst sufferer of all cyclonic casualties in the world.

Increasing population growth, high population density and economic and infrastructural development activities in the coastal countries around the Bay of Bengal are likely to make the countries more vulnerable to cyclone threats. The countries may run higher risks of disasters in future unless proper adaptation and mitigatory measures are taken. If the global warming due to increase in the greenhouse gas concentration in the atmosphere has any effect in terms of increase in cyclone frequency/intensity and sea level rise, the littoral countries of the Bay of Bengal, particularly Bangladesh, may run even a more serious risk in the future.

Risk is a kind of threat to life and property that can result from the action of a hazard upon population, livestock, structures, etc. Thus risk involves a cause (a disaster, like cyclone) and an effect (damage to life and property). Risk assessment or risk analysis is, therefore, a methodology through which these two factors-cause and effect-are linked together and an estimate of the potential damages/losses in future is made. As mentioned by French (1991), the risk assessment has, therefore, three distinct components:

(a) analysing or inventorying the hazard,

(b) analysing the past damages and inventorying the population and property at risk, and

(c) applying vulnerability functions in estimating probable damages.

Keeping the above three components of risk assessment in view, the present paper makes a brief review of cyclones that formed in the Bay of Bengal, particularly during the past 110 years (1881-1990) and hit the littoral countries. The phenomenon of storm surges, which is mostly responsible for cyclonic casualties and damages, is discussed in the context of Bangladesh. Then an indication is given of the degree of damages that occurred in Bangladesh, specially during the 12 November 1970 and 29 April 1991 cyclones that hit Bangladesh and caused heavy death tolls and damages to properties. This is followed by a brief introduction on the risk assessment and risk reduction/mitigation. A few case studies on risk assessment in Bangladesh are presented and finally some recommendations are put forward.

2. Bay of Bengal and Bangladesh cyclone statistics

2.1. *With respect to world perspective*

We define here the terminology used in the paper for different categories of cyclones. A depression refers to a cyclone in which maximum sustained wind speed (MSWS) is less than 17.5 m/s. A cyclonic storm (CS) has MSWS between 17.5 m/s and 24 m/s, while a severe cyclonic storm (SCS) has speed exceeding 24 m/s. A tropical storm refers to both cyclonic storms and severe cyclonic storms. And a tropical cyclone or simply a cyclone stands for all categories of cyclones.

Gray (1968) has shown that about 10% of the world tropical storms (CS + SCS) form in the Bay of Bengal. Subsequently, however, Gray (1985) estimated that only 7% of tropical storms form in the north Indian Ocean (Bay of Bengal and Arabian Sea). Recently, Neumann (1993) has shown that only 6.5% form in the north Indian Ocean. Since the cyclone frequency in the Bay of Bengal is about 5-6 times the frequency in the Arabian Sea (IMD 1979), the Bay's share of the world total comes out to be about 5.5%, taking 6.5% as the north Indian Ocean contribution. Thus, a drastic reduction by about 50% (10% to 5.5%) is seen to occur. There may be a number of reasons for such a reduction. Two possible reasons are given below :

Firstly, the first number (10%) includes data of the pre-satellite era when all the cyclones were not detected/reported. As an example, an average of 8.6 cyclones was reported for the eastern and central north Pacific during the pre-satellite period. This average rose to 16.5 during the satellite era (McBride 1995). Such an increase might have affected the Bay of Bengal percentage. Secondly, the Bay of Bengal is presently passing through a decreasing trend in cyclone frequency. This trend started at around 1970 (*e.g.*, Ali 1995, 1996 and Joseph 1995). In an analysis Neumann (1993) considered cyclone data for the satellite period, *i.e.*, the period 1968-90, the decaying period for the Bay of Bengal. These two reasons should well explain the drastic reduction in the cyclone numbers in the Bay of Bengal in relation to the world statistics.

TABLE 1

Countrywise number of cyclones (1881-1990) for the Bay of Bengal. Numbers within brackets give percentages. The last row shows the percentage of CS+SCS with respect to world total
(Source : Ali 1995)

Type	Bangladesh	India	Myanmar	Sri Lanka	Dead	Total
All Categories	151 (13)	790 (68)	69 (6)	33 (3)	114 (10)	1157 (100)
Depressions	66 (10)	493 (74)	23 (3)	14 (2)	70 (11)	666 (100)
Cyclonic storms (CS)	44 (15)	192 (64)	22 (7)	11 (4)	31 (10)	300 (100)
Severe Cyclonic Storms (SCS)	41 (21)	105 (55)	24 (13)	8 (4)	13 (7)	191 (100)
CS+SCS	85 (17)	297 (61)	46 (9)	19 (4)	44 (9)	491 (100)
Percent of global total (CS+SCS)	(0.9)	(3.4)	(0.5)	(0.2)	(0.5)	(5.5)

Taking the Bay of Bengal share as 5.5%, the percentage shares of the littoral countries of the Bay of Bengal have been calculated by Ali (1995) and this is shown in the last row of Table 1. The tropical storms forming in the Bay of Bengal during the period 1881-1990 (110 years) have been considered in arriving at these percentages. It is seen that Bangladesh has 0.9% share of the global total, India 3.4%, Sri Lanka 0.2%, Myanmar 0.5% and 0.5% died in the Bay without hitting any country. Apparently, it seems that Bangladesh is not at high risk in the global perspective. The situation is, however, otherwise. In terms of human deaths, Bangladesh suffers the most.

Table 2 gives the tropical cyclone disasters in the world in each of which death tolls were in excess of 5,000. It is seen that 15 out of 34 such disasters occurred in Bangladesh and 11 in India. About 53% of the world deaths took place in Bangladesh and about 23% in India; both these two countries having a combined share of 76%. It is also to be noted that major cyclone disasters are still continuing in Bangladesh unlike other places in the world. The last ones of 1985 and 1991 occurred in Bangladesh, when all the latest modern technologies were available. Thus,

TABLE 2

Deaths associated with noteworthy tropical cyclone disasters

Year	Location	Deaths
1970 C	Bangladesh	500,000
1737 F	India	300,000
1881 F	China	300,000
1923 F	Japan	250,000
1584 W	Bangladesh	200,000
1897 F	Bangladesh	175,000
1991 C	Bangladesh	138,000
1876 F	Bangladesh	100,000
1864 F	India	50,000
1833 F	India	50,000
1854 M	India	50,000
1822 F	Bangladesh	40,000
1942 M	India	40,000
1919 W	Bangladesh	40,000
1912 W	Bangladesh	40,000
1780 F	Antilles	22,000
1839 F	India	20,000
1779 M	India	20,000
1789 F	India	20,000
1965 (11 May)F	Bangladesh	19,279
1965 (31 May) W	Bangladesh	12,000
1963 C	Bangladesh	11,520
1961 C	Bangladesh	11,468
1985 C	Bangladesh	11,069
1937 Y	Hong Kong	11,000
1906 Y	Hong Kong	10,000
1977 D	India	10,000
1971 M	India	10,000
1941 W	Bangladesh	7,500
1963 F	Cuba-Haiti	7,196
1900 F	Texas	6,000
1960 F	Bangladesh	5,149
1960 F	Japan	5,000
1895 M	India	5,000

Source : C. Choudhury (1995), D. Dube and Singh (1981), F. Frank and Husain (1971), M. Murty *et al.* (1985), Y. Yim (1995), W. Warrick *et al.* (1994)

TABLE 3

Monthly distribution of the Bay of Bengal cyclones (1881-1990). First number gives depression and the second number the total of CS and SCS

Month	Bay of Bengal	Bangladesh	India	Sri Lanka	Myanmar	Dead
Jan	8+6 = 14	NIL	0+2 = 2	3+2 = 5	1+0 = 1	4+2 = 6
Feb	3+1 = 4	NIL	0+1 = 1	1+0 = 1	NIL	2+0 = 2
Mar	1+4 = 5	NIL	NIL	0+2 = 2	NIL	1+2 = 3
Apr	10+21 = 31	2+2 = 4	1+2 = 3	1+1 = 2	5+12 = 17	1+4 = 5
May	23+54 = 77	3+15 = 18	5+23 = 28	NIL	9+16 = 25	6+0 = 6
Jun	69+42 = 111	10+12 = 22	56+28 = 84	NIL	0+1 = 1	3+1 = 4
Jul	115+49 = 164	8+5 = 13	106+44 = 150	NIL	NIL	1+0 = 1
Aug	145+33 = 178	16+2 = 18	128+31 = 159	NIL	NIL	1+0 = 1
Sep	130+46 = 176	9+4 = 13	117+41 = 158	NIL	2+1 = 3	2+0 = 2
Oct	84+88 = 172	16+21 = 37	52+60 = 112	0+1 = 1	4+4 = 8	12+2 = 14
Nov	47+101 = 148	1+15 = 16	24+54 = 78	3+4 = 7	1+9 = 10	18+19 = 37
Dec	31+46 = 77	1+9 = 10	4+11 = 15	6+9 = 15	1+3 = 4	19+14 = 33
Total	666+491=1157	66+85 = 151	493+297 = 790	14+19 = 33	23+46 = 69	70+44 = 114

CS-Cyclonic storm, SCS-Severe cyclonic storm

it is vividly clear that although frequencywise, Bangladesh is not at that risk, but death or disasterwise, the country is highly vulnerable to cyclonic casualties and as such runs a high risk in the future. Similar is the case with India.

2.2. *Country statistics*

Table 1 also gives the countrywise distribution (Ali 1995) of all categories of cyclones that formed in the Bay of Bengal during the period 1881-1990 and hit (or did not hit) a littoral country. In analysing the cyclone climatology, Ali (1995) used the cyclone tracks published by the India Meteorological Department (IMD).

The maximum percentages for all types of cyclones are for India. The reason is understandable in consideration of its long coast along the Bay of Bengal. The second maximum is for Bangladesh and the least for Sri Lanka. About 13% of all cyclones hit Bangladesh. The percentage for Bangladesh shows an increase from depression to cyclonic storm to severe cyclonic storm (10 to 15 to 21% respectively) while it shows a decrease for India (74 to 64 to 55%). Bangladesh has a 10-21% probability of being hit by a Bay cyclone, highest for severe cyclonic storms and the lowest for depressions. India has 55-74% probability, Sri Lanka 2-4% and Myanmar 3-13%. Table 1 is thus useful in forming an idea about at what risk a littoral country is as far as the probability/possibility of being hit by a cyclone forming in the Bay of Bengal is concerned.

2.3. *Trend*

If all categories of cyclones that formed in the Bay of Bengal during 1881-1990 are considered, no trend can be observed in cyclone frequency (Ali 1995). However, there seems to be a period of oscillation of some 30-40 years for the storms (*e.g.*, Ali 1995, 1996 and Joseph 1995), the highest was during 1960-70. The reasons for such an oscillation is yet unknown. May be it has some relation with the solar activity, but this needs detailed investigation.

The Bay of Bengal is presently passing through a decreasing trend, which is likely to get reversed in the beginning of the next century (Ali 1995). A more active cyclonic period and hence a higher risk period may be expected in the coming decades.

There does not seem to be any trend for Bangladesh cyclones of any type, nor for any combination of them. This may mean that Bangladesh storms, unlike the Bay storms, are not related to any sequential/oscillatory physical mechanism. That is, Bangladesh is almost at equal risks for all time.

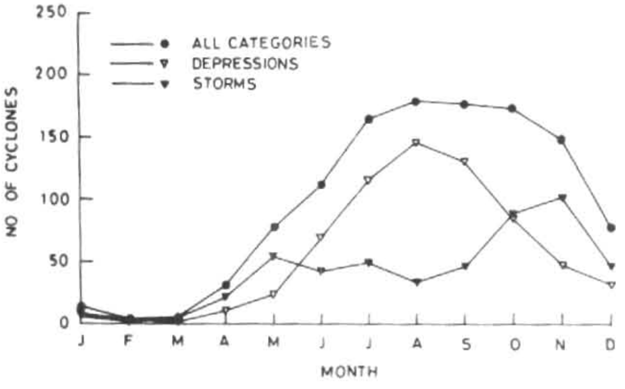

Fig. 1. Monthly variation of cyclones in the Bay of Bengal (1881-1990)

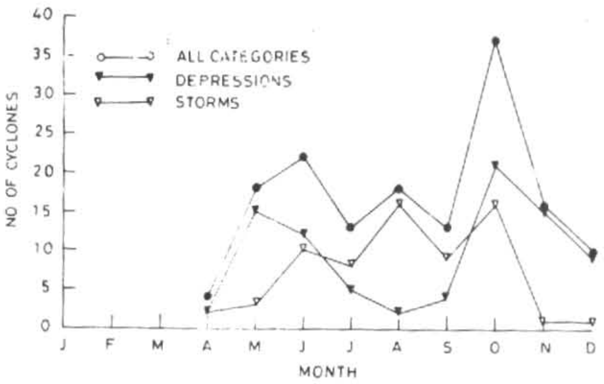

Fig. 2. Monthly variation of cyclones in Bangladesh (1881-1990)

2.4. *Monthly distribution*

Ali (1995) has given the categorywise and countrywise monthly distribution of all cyclones that formed in the Bay of Bengal during 1881-1990. The distribution is given in Table 3. Fig. 1 gives the monthly variation of cyclones for the Bay of Bengal. All the Bay cyclones combined show a peak in August with gradual falling offs on both sides to a minimum in February. The depression also show a maximum in August. The peaking of cyclones in and around August is dominated by depressions. On the other hand, as is usually the case, the cyclonic and severe cyclonic storms combined show two maxima- one in May and the other in November, with the numbers in November being higher than those in May.

A corresponding plot is made for the Bangladesh cyclones (Fig. 2). Cyclones (all categories) do not show any similarity with the Bay pattern. Rather the maximum occurs in October (compared to August for the Bay) with a second maximum in May/June. The tropical storm distribution in Bangladesh follows more or less the Bay of Bengal storm distribution. May/June (pre-monsoon) and October/November (post-monsoon) are the high risk months for Bangladesh.

There appears to be no cyclone in Bangladesh during the months January to March. These months, therefore, may be considered risk free. There were about 4 cyclones only in Bangladesh in April over the years 1881-1990. April also thus appears to be relatively risk free. But this is to be considered with great caution because one of the major cyclone disasters in history occurred in Bangladesh in April 1991.

The ratios of the numbers of tropical storms to that of depression are 0.74, 0.60 and 1.29 for the Bay of Bengal, India and Bangladesh respectively. This means that the cyclone numbers in the Bay and India are depression dominated and that for Bangladesh is storm dominated. Storm dominance would mean a higher risk.

3. Causes of hazards associated with cyclones

Cyclones cause damages in a number of ways. The important ones are discussed here in relation to Bangladesh.

3.1. *Strong winds*

Winds associated with cyclones cause most of the damages. Winds have both direct and indirect effects. Direct wind uproots trees, blows away roofs of buildings, causes damages to less strongly built buildings, sinks ships and boats at sea and makes the life miserable. Indirect effect is caused mostly by coastal inundation through the generation of storm surges.

An examination of annual maximum sustained wind speeds associated with cyclones that struck Bangladesh since 1960 shows that there is no trend in wind speed. But these winds are useful in estimating the design wind speed for different return periods. The design wind speed is useful in risk assessment. It is mostly used for developing building codes in cyclone prone areas as well as in predicting and calculating storm surge risks.

3.2. *Storm surges*

Most of the cyclonic damages in Bangladesh, as in other parts of the world, are caused by storm surges. Storm surges are generated mainly by wind and pressure drop associated with a cyclone. About 90% contribution

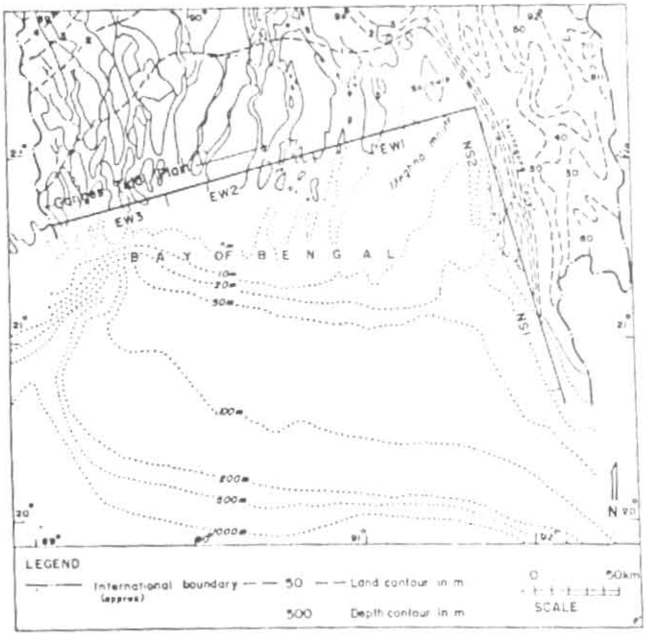

Fig. 3. Depth contours in the northern Bay of Bengal and contour heights in southern Bangladesh (After Barua 1991, BUET/BIDS 1993 and Chowdhury 1994)

to surge generation comes from wind. Storm surges, once generated, are modified/amplified by a number of local factors. The important ones in the context of Bangladesh have been discussed by a number of authors (*e.g.*, Ali 1980, 1992). Some of these are very briefly discussed below:

3.2.1. *Shallowness of the north Bay*

Surge height is inversely proportional to depth of water. In fact, storm surge is mostly a shallow water phenomenon.

Bangladesh has a large and shallow continental shelf. The approximate bathymetric contours for the north Bay near Bangladesh are given for reference in Fig.3. The depth varies from about 500 m along 20°N latitude to less than 5 m along the coast. Because of the vast shallow continental shelf, storm surge heights get amplified significantly in the Bangladesh coast, particularly near the Meghna estuary, where the shelf is very shallow and wide. In fact, most of the cyclonic casualties in Bangladesh occur when cyclones hit in and around the Meghna estuary.

3.2.2. *Convergence of the Bay*

Surge height is directly proportional to convergence. Convergence leads to amplification (Proudman 1955), in a somewhat similar way like shallow water effect. Because of the northward converging nature of the Bay of Bengal, at the head of which Bangladesh is situated, surge water is funneled towards Bangladesh leading to increase in the storm surge heights.

TABLE 4

M_2 and S_2 tidal amplitudes along the northern Bay of Bengal

Station	Lat	Long	M_2(m)	S_2 (m)
Paradip	20.16	86.41	0.620	0.280
Kidderpore	22.33	88.18	0.800	0.380
Hiron Point	21.43	89.28	0.798	0.352
Tiger Point	21.51	89.50	0.820	0.370
Rabnadab Ch.	22.04	90.22	0.720	0.300
Ilshaghat	22.84	90.39	0.735	0.287
Hatia	22.29	90.57	1.290	0.480
Sandwip	22.29	92.25	1.856	0.698
Norman Point	22.11	91.49	1.360	0.540
Sadarghat	22.20	91.50	1.355	0.479
Kutubdia I.	21.52	91.50	1.260	0.560
Cox's Bazar	21.26	91.59	1.060	0.460
St. Martin's I	20.37	92.19	0.900	0.420
Akyab	20.08	92.54	0.779	0.345

Source: Dr. David Pugh, Institute of Oceanographic Sciences (IOS), England-personal communication with author.

3.2.3. *Tides*

Tides in the Bay of Bengal are mostly generated in the Indian ocean and amplified at the Bay of Bengal, particularly in the shallow continental shelf at the north Bay.

Tidal amplitude in Bangladesh shows a gradual increase from west to east and reaches a maximum in the Meghna estuary. Then it decreases south-eastward along the eastern coast of Bangladesh. This is evident from Table 4 which gives amplitudes for M_2 and S_2 tides along the northern Bay of Bengal coast. A maximum spring tidal range of about 6 m (Barua 1991) is observed at Sandwip in the Meghna estuary. If storm surges and tides, particularly spring tides, get superimposed, the situation becomes disastrous.

TABLE 5

Cyclones affecting Bangladesh since 1960 (during the satellite era)

Date	Max.wind speed (km/hr)	Storm surge ht. (m)	Deaths
9 Oct 1960	162	3.0	3,000
30 Oct 1960	210	4.5-6.0	5,149
9 May 1961	146	2.5-3.0	11,466
30 May 1961	146	6.0-9.0	-
28 May 1963	203	4.0-5.0	11,520
11 Apr 1964	-	-	196
11 May 1965	162	3.5	19,279
31 May 1965	-	6.0-7.5	12,000*
14 Dec 1965	210	4.5-6.0	873
1 Oct 1966	146	4.5-9.0	850
11 Oct 1967	-	2.0-8.5	-
24 Oct 1967	-	1.5-7.5	-
10 May 1968	-	2.5-4.5	-
17 Apr 1969	-	-	75
10 Oct 1969	-	2.5-7.0	-
7 May 1970	-	3.0-5.0	-
23 Oct 1970	-	-	300
12 Nov 1970	223	6.0-9.0	500,000
8 May 1971	-	2.5-4.0	-
30 Sep 1971	-	2.5-4.0	-
6 Nov 1971	-	2.5-5.5	-
18 Nov 1973	-	2.5-4.0	-
9 Dec 1973	122	1.5-4.5	183
15 Aug 1974	197	1.5-6.7	-
28 Nov 1974	162	2.0-5.0	a few
21 Oct 1976	105	2.0-5.0	-
13 May 1977	122	-	-
10 Dec 1981	97	1.8	2
15 Oct 1983	97	-	-
9 Nov 1983	122	-	-
3 Jun 1984	89	-	-
25 May 1985	154	3.0-4.5	11,069
29 Nov 1988	162	1.5-3.0	2,000
29 Apr 1991	225	6.0-7.6	138,000
2 Jun 1991	100	1.8	-
2 May 1994	200	-	170
25 Nov 1995	100	-	6

Source Choudhury 1995, *Warrick *et al.* (1994)

3.2.4. *Coriolis effect*

The Coriolis force has some contribution to surge modification/amplification, particularly near the Meghna estuary. If storm surge water is moving northward in the northern Bay of Bengal, it will be deflected towards the east, thereby increasing surge heights along the east coast of Bangladesh. In 1988, when a cyclone had hit the western coast of Bangladesh, significant surge heights were observed in the Meghna estuary area, which was apparently and partly due to the Coriolis deflection towards the right. Not only that, sometimes it has been observed that significant surge heights develop in the Meghna region, even if a cyclone hit India well away from the Meghna coast and these surges cause substantial damages to crops.

3.2.5. *Chittagong coastal effect*

The coast of Chittagong (*i.e.* eastern coast of Bangladesh) and the western coast of Myanmar play a significant role in surge amplification/modification. If, theoretically, the north-south Chittagong coast is replaced by an east-west coast something like the Atlantic coast, the surge height is likely to be much less than that at present at the Meghna estuary (supposing that the cyclone is hitting the estuary or west of it). This is because the surge water will then have more space to be deflected eastward (by the Coriolis force, for example) and hence will get less amplified at the Meghna estuary. Storm surge models show that if the eastern coast of the Bay of Bengal is moved further east, surge height near the Meghna estuary decreases.

TABLE 6

Areas under different elevations in Bangladesh coastal area

Elevation above MSL (m)	Area (km^2)	Percentage of the whole country
1.0	14,000	9.7
1.5	22,320	15.5
3.0	33,920	23.6
4.5	47,600	33.1

Source : Ali and Ahmad (1992)

The position and orientation (south-east to north-west) of the Chittagong coast is largely responsible for the natural convergence of the Bay. A kind of artificial convergence is also created by this coast in relation to cyclone track (Ali 1992).

3.2.6. *Island effect*

There are a good number of small islands and a few large islands in the Bangladesh coastal area. These islands are not much above the mean sea level. They can be easily over-run by surge heights of the magnitude given in Table 5. The islands are thickly populated and they easily fall prey to cyclonic winds and storm surges. An island named Urir Char in the Meghna estuarial region went under water during the May 1985 cyclone, killing about 20,000 people alone in this island. The surge heights above ground level in another island named Char Jabbar went upto 6 m and 3 m respectively during the cyclones of November 1970 and May 1985.

The effects of islands on surge modification are not well understood. But apparently, the islands play some important role in surge modification. Some of these roles have been speculatively discussed by Ali (1992).

3.2.7. *Low and flat coastal topography*

Most of the coastal area of Bangladesh is flat and low. The land height is less than about 4.5 m above the mean sea level (see Fig. 3). Areas and percentages of land under different elevations are given in Table 6. It is vividly clear that the low-lying areas of Bangladesh can be easily flooded by storm surges of magnitude given in Table 5.

3.2.8. *River effect*

A large number of rivers, including the Ganges - Brahmaputra - Meghna (GBM) rivers which constitute one of the largest river systems in the world, discharge through Bangladesh, into the Bay of Bengal. A river system can have a number of effects on surges and tides. Firstly, the presence of rivers has a negative effect on surge amplification. Numerical models have shown that surges at the coast are higher without rivers than with rivers (*e.g.* Sinha *et al.* 1985). Secondly, fresh water discharge through rivers modifies sea surface elevations resulting from surges and tides (*e.g.* Ali *et al.* 1996). Thirdly, surges, tides and SW monsoonal wind produce back water effect on river discharges. This is particularly important during flood period (June-September). The back water effect in the Meghna estuary has been numerically investigated,for example, by Ali and Hoque (1994), Ali (1995), and Ali *et al.* (1996). Fourthly, but most importantly the presence of a large number of wide estuaries and rivers in Bangladesh allows a potentially deep inland penetration of surge waters leading to flooding in the areas adjacent to the rivers. A significant part of the southwest region of Bangladesh becomes flooded due to storm surges penetrating through several estuaries in the region, where the penetration distance of more than 60 km has been reported by BUET/BIDS (1993).

3.2.9. *Track effect (Dependence)*

Surge height, particularly in Bangladesh, is strongly dependent on cyclone track. If there were two identical cyclones with parallel tracks one hitting western coastal area and the other striking the Meghna estuary, the surge height due to the latter track would be much higher.This has been explained, as an example, by Ali (1980, 1992). It is the Meghna estuarial region where most of the severe cyclone casualties in Bangladesh occurred. Favourable cyclone track, convergence, vast shallow continental shelf, high tide and Coriolis force all act favourably in amplifying surge in this area. This is the region which runs most of the cyclone risks.

3.2.10. *Short water waves*

The storm surge is a long wave, *i.e.*, its wavelength is much larger compared to the depth of water. However, cyclonic winds also generate transient waves, which are generally called short water waves or local water having periods in the range 1-20 secs (Harris 1982). These waves ride on longer storm surge waves and move at faster speeds. They can be compared with 'wind gusts'.

The height of short waves may be large during a severe cyclone. As a thumb rule, the height of these waves in shallow coastal waters may be 0.50 to 0.75 times the surge heights (Jelesnianski 1989). They often cause most of the harm to the people desperately trying to escape the onslaught of the main surges.

3.3. *Rainfall*

Cyclone disasters are mainly caused by strong winds, storm surges and torrential rains. Although rains are not as disastrous as storm surges, sometime they attain unbearable dimensions. As for example, the rains associated with the June 1996 cyclone that struck southeast coast of India produced severe floods inland. Rain water on the top of surge water may add to the fury of storm surges; because it is the last few fractions of a metre or so that is often responsible for inundation and damages. And in that sense, at least, rain is an important contributor to the damaging effects of cyclones.

Rain is an annoying factor for people who become shelterless due to a cyclone. It creates problems in disseminating cyclone warning by local volunteers, in evacuation work, immediate relief operation, movement of transports, etc.

3.4. *Socio-economic factor*

The socio-economic condition of the people in the coastal area is an important factor that contributes significantly to the cyclone disaster, specially in the countries along the rim of the Bay of Bengal. In Bangladesh, the large population, the high population density and poor economic condition of the people in the coastal area are big contributing factors to cyclone disasters.

A good number of people in Bangladesh migrate from the north to the coastal area in the south to work as labourers. They work in agricultural fields, fish farms (*e.g.*, shrimp farms), fishing boats and salt beds. The migration period coincides with the harvesting seasons which unluckily coincide with the two peak cyclone seasons (the pre- and post-monsoon). These migratory people become easy victims of cyclones. They live in temporarily built houses which easily fall to the ground by the first spell or whip of a cyclone. Although the transient population is insignificant compared to the total vulnerable population, they are significant when the number of deaths during a storm surge disaster is considered. The houses of the local people are also not well-built to withstand cyclones' onslaught. Moreover, settlers in newly formed chars and islands also become vulnerable to cyclone threat. Example is the population of the Urir Char (Section 3.2.6).

Lack of awareness and motivation among the people and illiteracy also contribute to the cyclone misery. It has been found that even if the people knew that a cyclone was coming, they did not like to leave their places. There are many reasons for doing so and these have been discussed in literatures; one such good survey can be found in Ahmed *et al*. (1992).

Industrial and economic activities are increasing at a greater rate in the coastal area of Bangladesh. The Export Processing Zone (EPZ), shrimp farm development, etc. are a few examples. The increasing economic activities are likely to increase the risk of cyclone disasters.

3.5. *Greenhouse effect*

The global warming due to increase in the greenhouse gas concentration in the earth's atmosphere and the consequent sea level rise (SLR) are likely to have adverse effects on cyclone activity and hence on cyclone risk. We very briefly discuss here some major effects on cyclone frequency, cyclone intensity and storm surges with respect to the Bay of Bengal and particularly to Bangladesh.

As is well known, one of the necessary but not sufficient conditions for tropical cyclone formation is that the sea surface temperature (SST) should have a threshold value of 26-27°C. This temperature dependence has led to the anticipation that a SST rise due to global warming will be accompanied by a consequent rise in cyclone frequency. But this could not be confirmed as yet. Analyses (For example, by Ali 1995 and Joseph 1995) of cyclones that formed in the Bay of Bengal during the last 110 years or so show that there is no trend in cyclone frequency which could be related to SST variation in the Bay of Bengal. However, Ali (1995) tried to look at the cyclone frequency and SST relation from a different angle and this is discussed below:

Table 1 shows that about 114 cyclones (more than the total for Myanmar and Sri Lanka) died in the Bay without hitting any country. There were another 250 cyclones or so whose mention is there in records but not included in the IMD (1979) tracks used in arriving at the numbers in Table 1. As mentioned in the introduction of IMD (1979), these cyclones were either stationary or short-lived (less than 1 day) or had no well-defined tracks and as such they were not included. If there were higher SSTs, these 364 cyclones (250+114) could have further developed and hit the littoral countries thereby increasing the cyclone casualty/damages. In this sense at least, it may be said that an increase in SST could have energised the dead or not-taken-into- account cyclones, and hence could have increased the cyclone risk.

It is almost certain that an increase in SST will be accompanied by a corresponding increase in cyclone intensity. The relationship between cyclone intensity and SST is quite well discussed in literature. Recently, Emanuel (1987) has developed some numerical relationship of maximum sustained wind speed with SST. If the IPCC (Intergovernmental Panel on Climate Change) standard of a lower bound of 2°C and an upper bound of 4°C rise in temperature is used, the corresponding increases in maximum wind speed (by Emanuel's table) comes out to be 10% and 22% respectively with respect to that of 27°C. Using a two-dimensional numerical model. Ali (1996) developed some surge scenarios for Bangladesh under three different SSTs (present 2°C and 4°C) and three sea levels (present 30 cm and 100 m, the latter two being the IPCC standard again). The April 1991 cyclone was used as the reference cyclone (*i.e.*, the present situation). The model shows that if the 1991 cyclone had occurred under 4°C rise in SST and the present sea level, the maximum surge height would have increased by about 49% with respect to present and the inland penetration distance would have increased by about 31%.

It is to be noted here that, apparently the surge height would be expected to decrease with a rise in sea level, if the coastal boundary remains unchanged. But the reality is that more lands would be converted into sea by SLR and this land area will be a shallow water region where surge heights will get amplified (Ali 1995). The calculated areas likely to go under water in Bangladesh due to different SLRs are given in Table 6.

It is thus apparent that global climate change is likely to increase the cyclone risk in Bangladesh.

TABLE 7

A comparative statement of damages due to 1970 and 1991 cyclones that hit Bangladesh

Items	1970*	1991**
Population affected	4.7 m	10.8 m
People died	500,000	138,000
Loss of cattle & poultry	780,000	1061,029
Educational institutes damaged	3,500	9,666
Houses damaged	400,000	1702,358
Districts affected	-	19
Thanas affected	-	102
Roads (earthen) destroyed (km)	-	1,230
Bridges and culverts destroyed	-	496 (number)
Embankments destroyed (km)	-	1,130
Fishing boats destroyed (marine & inland)	-	-

Source: *Frank and Husain (1971), **Ministry of Relief and Rehabilitation, Govt. of the People's Republic of Bangladesh 1991

4. Damages and elements at risk

One of the components of risk assessment is the damage analysis which helps identify the elements at risk as well as indicate the degree of risk. Cyclones cause heavy loss of lives and livestocks and damages to crops and properties. An idea about human deaths in Bangladesh and India in relation to major world cyclone disasters has been given earlier (Section 2.1). Death figures for Bangladesh due to cyclones during the satellite era (Since 1960) are given in Table 5.

Damages to properties are equally colossal and similar to human deaths in Bangladesh. A full picture of damages due to cyclones hitting Bangladesh is not available. Neither is it appropriate here to describe all the damages. We make here a non-monetary comparison (Table 7) of damages due to the last two most devastating cyclones that hit Bangladesh, *i.e.*, the cyclones of November 1970 and April 1991. Both the cyclones had almost the same maximum sustained wind speed (about 225 km/hr) but the 1991 cyclone was the most damaging among all cyclones. The casualty figure for 1991 was less than that in 1970, but

TABLE 8

Extent of damages to the economy of Bangladesh due to 1991 cyclone

S. No.	Sector		Estimated value of damage (Million US$)
1.	Agriculture		
	(a) Crop Production		78.86
	(b) Forestry		28.20
	(c) Fisheries		206.14
	(d) Livestock		50.37
		Sub-total	363.57
2.	Industry		
	(a) Export Processing Zone		16.77
	(b) Public Sector Industries (Other than EPZ)		57.22
	(c) Private Sector Industries		314.28
		Sub-total	388.27
3.	Physical infrastructure		
	(a) Rural Infrastructure		107.00
	(b) Railways		28.20
	(c) Chittagong Port Authority		41.91
	(d) Inland Water Transport Authority		52.05
	(e) Post and Telecommunication		128.42
	(f) Others		2.43
		Sub-total	360.01
4.	Socio-economic Infrastructure		
	(a) Education		132.02
	(b) Health and Family Planning		78.74
	(c) Science & Technology		49.28
	(d) Mass Media		7.31
		Sub-total	267.35
5.	Others		5.72
		Total	1,384.92

Source : UNCRD (1991)

damagewise, the 1991 cyclone surpassed all recorded history. The high damage figures may be attributed to the rapid economic growth infrastructural development and improved service-facilities which are vulnerable to cyclone threat.

Table 8 gives some damage figures due to 1991 cyclone in various sectors of economy in Bangladesh and indicates that the list of elements at risk is exhaustive. But, basically, major properties that are considered in risk assessment are buildings and civil engineering structures, economic activities, public utilities, services and infrastructures. For Bangladesh and the countries in the region, the other important elements are agriculture/crops, livestock and homesteads.

One important item that is generally not taken into account in risk assessment is the environmental degradation and/or loss of ecological balance. The major environmental components of concern are: drinking water supply, decomposition of deadbodies and carcasses, increase in soil and water salinity, intrusion of brackish water, destruction of both homestead and coastal forests, deterioration of sanitation, increase of diseases, depletion of fresh water, washing of toxic industrial wastes into waterbodies and loss of wildlife.

An inventory of elements at risk should have a space-time variation. That is the property location and population distribution should be made spatially and updated at some intervals of time. Such an inventory can be thought of as a data base for risk assessment and may form a kind of a Geographic Information System (GIS).

In Bangladesh, there does not seem to be any good inventory of elements at risk. But recently BUET/BIDS (1993) has made some inventories of population and properties in the coastal areas. The major items of such an inventory are Unionwise (Union is the smallest administrative unit) distribution of population, public and private buildings and services. As mentioned above, these need to be updated from time to time with more expansion of the listed items.

5. Risk assessment for storm surge prone area

5.1. *Estimation of risk*

A manual on mitigating natural disasters prepared under the auspices of UNDRO (1991) discusses various aspects of risk assessment. Excellent reviews and illustrations of risk analysis for hydraulic structures have been made by Mays (1987) and Plate (1995).

Risk, as defined in UNDRO (1991), is the sum of all losses that can be expected from the occurrence of a particular natural phenomenon. Risk is, therefore, the mathematical expectation of consequence as expressed below :

$$r = \int_{-\infty}^{\infty} K(u)\, f(u) \mathrm{d}u \qquad (1)$$

where r is the risk, $K(u)$ is the consequence function (Plate 1995), u is the magnitude of hazard and $f(u)$ is the probability density function for u. Use of u as argument is to indicate that the function is dependent on u.

The consequence function $K(u)$ changes when risk reduction measures are taken. $K(u)$ can be expressed in monetary units, material units, number of persons, etc. In flood risk analysis, $K(u)$ is usually expressed by a depth-damage function. Arnell (1989) investigated various forms of depth-damage function and their effect upon the estimated/expected damages.

For a natural phenomenon, such as a flood, the damage generally occurs when the flood magnitude u exceeds a critical value u_c. Then the risk is given by

$$r = \int_{u}^{\infty} K(u) f(u) \mathrm{d}u \qquad (2)$$

The integral in Eqn. (2) is evaluated by dividing the range of $u > u_c$ into intervals and r can be calculated as given below (Chow *et al.* 1988) :

$$r = \sum_{i=1}^{m} \frac{[K(u_{i-1}) + K(u_i)]}{2} [P(u_{i-1}) - P(u_i)] \qquad (3)$$

where P is the probability of exceedance for u, m is the number of intervals and $u_{i-1} \leq u_i$. Eqns. (2) and (3) are for a particular category of elements. Total risk can be obtained by combining the values of r for different categories of elements.

If the consequence is independent of the hazard magnitude u when $u > u_c$, Eqn. (2) simplifies to (after Plate 1995),

$$r = K \int_{u_c}^{\infty} f(u)\, \mathrm{d}u \qquad (4)$$

$$= KP(u_c)$$

It is to be noted that K is now free from argument. Eqn. (4) is applicable in many situations, such as, submerged roads and bridges, failure of dikes due to overtopping, loss of lives due to storm surge flood, etc.

5.2. *Hazard assessment*

Hazard is a probabilistic function of magnitude or intensity over time of the phenomenon that causes damage. In order to assess the magnitude or intensity of a hazard, a number of different parameters are to be estimated. For example, in the assessment of flood hazard, the important parameters are depth of water, rate of rise of water level, velocity of water, duration of flood, frequency of occurrence, seasonality, etc. All parameters are not necessarily independent of each other.

In the coastal region of Bangladesh, the most catastrophic hazard associated with a tropical cyclone is the flooding of land by storm surge. Bangladesh National Building Code (1993) designates a coastal area as being surge prone area (SPA) where the expected occurrence of a surge or wave set-up is 1m or higher.

The data on storm surge height in the coastal region of Bangladesh are very limited. Mathematical models are used to predict the surge height. Based on an approximate solution for the slope of water surface due to wind stress during cyclonic storm over a uniformly rising continental shelf, a formula for the maximum surge height at the coast of Bangladesh has been derived by Chowdhury (1994) as given below:

$$h_p = \frac{13 \times 10^{-6} LW_{2p}^2}{(5 \times 10^6 + LW_{2p}^2)^{0.2}} \qquad (5)$$

where h is the maximum surge height at the coast in m, W is the maximum wind speed in km/hr and L is the distance in km between the 200 m depth contour of the continental shelf and the coast. The subscripts p and $2p$ indicate the probability of exceedance for h and W respectively. They show that the exceedance probability of W is twice that of h which implies that the return period interval of the surge height is approximately twice that of the annual maximum wind speed of the cyclones which approached the coast of Bangladesh as shown by Chowdhury (1994).

Wind speed data required in Eqn. (5) are obtained by fitting a Gumbel distribution to a censored sample of annual maximum wind speed data for the period

1960 to 1991. The fitted distribution, alongwith the approximate 90% confidence limits is given below (Chowdhury 1994):

$$W_p = 104.53 - 40.10\ln[-\ln(1 - P)] \pm 16.8\ C_p \quad (6)$$

where, C_p = 1.4055, 1.7195, 2.1383 and 2.4574 for P = 0.10, 0.05, 0.02 and 0.01 respectively.

Magnitudes of W from Eqn. (6) are comparable with those obtained by Venkateswarlu (1987) for the east coast of India.

To establish design surge heights, Chowdhury (1994) divided the coast of Bangladesh into 5 segments as shown in Fig. 3 (EW3, EW2, EW1, NS2, NS1) NS stands for north-south coast and EW for east- west coast. Then surge heights for each segment were predicted using Eqns. (5) and (6) for different values of P. For example, the predicted surge heights at the coast fot P = 0.02 are 4.3, 5.1, 6.5, 5.8 and 3.7 m for coastal segments EW3, EW2, EW1, NS2 and NS1 respectively. Using predicted surge heights, the flooded area was determined by Chowdhury and Karim (1995) with the help of a numerical hydrodynamic model of unsteady flow. The flooded area was determined for the extreme condition where the peak surge reached the coast at the time of spring tide high water. Such extreme condition occurred during the cyclone of April 1991.

5.3. *Vulnerability analysis*

To develop a consequence function $K(u)$ for Eqns. (1) to (4), it is required to establish the degree of vulnerability of an element to a hazard. The total consequence on all elements can then be obtained from,

$$K(u) = nv(u) \quad (7)$$

where, $v(u)$ is the vulnerability of a given element or a set of such elements and n is the number of elements.

The vulnerability is usually expressed by,

$$v(u) = V(u)\ D(u) \quad (8)$$

where, $V(u)$ is the vulnerability factor on a scale from 0 (no damage) to 1 (maximum damage) and $D(u)$ is the maximum damage which occurs per element when the full consequence of the hazard takes place.

Vulnerability analysis starts with the identification of elements at risk. Then a relationship between hazard and damage, that is relationships of V and D with u are to be established for every category of elements at risk. Two important parameters that determine the vulnerability of an element to flooding are resistance to the force of water and its material characteristics when immersed in water (UNDRO 1991). Based on these parameters, damage to an element can be related to depth of water, velocity of water and duration of flood.

In delineating the area where cyclone shelters are needed to provide refuge to exposed population during storm surge floods in the coastal region at Bangladesh, the deciding parameter was the minimum depth of flood that can cause risk of losing life of a person. As shown in a study by BUET/BIDS (1993), there is a possibility of loss of life when the depth of flood exceeds the waist of a person. The height of waist of an average adult is near to 1 m. So the area that requires shelter as proposed by BUET/BIDS (1993) extends from the coastline upto an inland limit where the depth of flood may reach 1 m.

The vulnerability of people to hazard due to storm surge floods in the coastal region of Bangladesh is affected by many factors. Some of them are population density, seasonal migrant population, type of housing, road communication, water supply, disaster preparedness, employment, income level, savings etc. In assessing the risk due to storm surge flood, the population density has been selected as the vulnerability indicator by Mott MacDonald and others (1993), Chowdhury and Karim (1995) and Sener *et al.* (1996). This is because the population density indicates numbers of people in any area and it also gives some indication of socio-economic status. The lower the socio-economic status of people the more likely they are to fall victims to cyclones.

5.4. *Hazard and risk mapping*

Risk mapping is an overlay process that identifies potential losses in areas identified as being hazardous (UNDRO 1991). Hazard maps are used to show the areas at risk due to various hazards. Separate maps may be used to indicate the magnitude of a particular hazard. Risk map shows plots of elements at risk on hazard maps. There can be various levels in hazard and risk mapping such as national, regional, local, project level, etc.

Hazard maps for Bangladesh were prepared at a scale of 1: 1000000 by Mott MacDonald and others

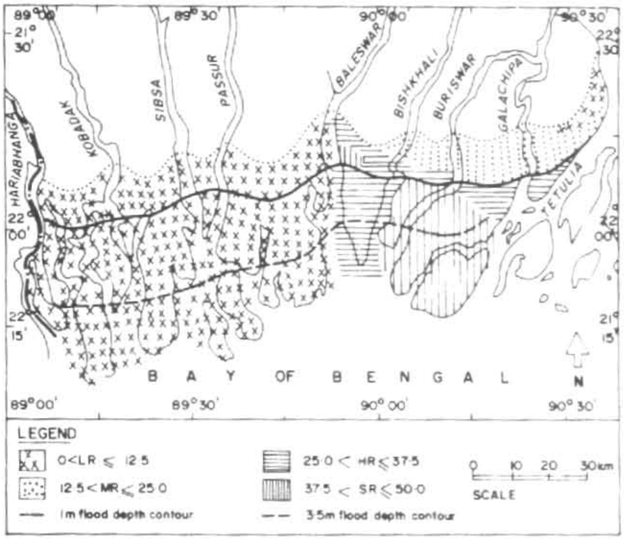

Fig. 4. Risk index map for a storm surge flood prone area in the Ganges Flood Plain (Chowdhury and Karim 1995)

(1993) under a disaster management programme. Hazard included tornadoes and tropical cyclones, storm surges, fluvial floods, river bank erosion and drought. A hazard index was devised to indicate the intensity of a hazard. It is a numerical grading on the basis of an area's history of disasters. The hazard index scale varied from 1 to 5 for a particular hazard. Then, a risk index was defined as expressed below :

$$R = H.V \tag{9}$$

where R is the risk index for a unit of land within the area at risk and H is the hazard factor and they can be estimated as given below :

$$H = \frac{q \text{ of the land unit} \times 10}{\text{highest } q \text{ among all land units}} \tag{10a}$$

$$V = \frac{s \text{ of the land unit} \times 10}{\text{highest } s \text{ among all land units}} \tag{10b}$$

where, q is the hazard index and s is the density of population. In the formulation in Eqn. (9) and (10), the magnitude of R lies in the range 0 to 100. A scale is to be devised showing the relationship between q and the magnitude of the phenomenon that causes damage.

The risk index R in Eqn. (9) is in fact equivalent to the vulnerability v in Eqn. (8). Chowdhury and Karim (1995) performed a storm surge risk analysis where integer numbers for q were used as a function of flood depth to represent the relative magnitude of flood hazard. The flood depth is divided into intervals. Value of q is 1 for the lowest interval and then q increases for successive intervals as per adopted scale. They studied alternative scaling systems and selected one that produced a map of R which was consistent with the available data on spatial distribution of damage. The indicator for selecting depth intervals to develop a scale for q can be physical features such as plinth level of a house, height of a tubewell for drinking water supply, road level, height of one storey building, etc. An example of risk index map produced by Chowdhury and Karim (1995) for a storm surge flood prone region in the Ganges Tidal Plain is shown in Fig. 4.

6. Risk reduction/mitigation

Risk reduction/mitigation involves undertaking of measures for minimising the impacts of disasters. There are a number of ways to reduce/mitigate the cyclone risk. We discuss here a few major ones in respect of Bangladesh.

6.1. *Cyclone shelters*

Construction of cyclone shelters is an effective means to provide refuge to the exposed population during storm surge floods in the coastal area of Bangladesh. The shelters stand on stilts so that storm surge flood water can pass below. The shelters are used as schools and community centres during normal time. There are some important issues that require to be addressed so that an effective programme for construction of shelters can be undertaken. Which are the areas that require shelters? How many shelters are needed? What should be the design criteria? Recently two studies have been made to address these issues. These studies attempted to follow risk-based approach to some extent. The studies are briefly discussed below:

6.1.1. *Study by BUET/BIDS*

BUET/BIDS (1993) has prepared a master plan of cyclone shelters. It delineated a high risk area of approximately 9,100 km^2 where there is a possibility of loss of lives. It extends from the coastline upto an inland limit where depth of storm surge flood may reach 1 m. The width of high risk area varies from 1 to 7 km on the north-south coast and 20 to 45 km on the east-west coast of Bangladesh. The shelters were designed for surge heights of 2.0% exceedance probability superimposed with local wind generated short waves. The design surge heights at the coastline were estimated using Eqns. (5) and (6).

The height of stilt of shelters varies with the distance from the coastline. Catchment areas of shelters are such that the travel distance does not exceed 1.5 km. After considering existing shelters and two or more storied public and private buildings together with projected demographic and socio-economic conditions in the year 2002, it is estimated that 653,863 and 984 number of shelters with stilt heights of 7.0, 5.25 and 3.5 m respectively are required with a total capacity of 4.4 million persons. The unit of land for shelter allocation is the Union which is the lowest tier in the Local Government system in Bangladesh.

6.1.2. *Study by Sener and other's*

Another study has been done by Sener *et al.* (1996). This study is an improvement over the study by BUET/BIDS (1993). The depth and area of storm surge flooding was estimated by using a two-dimensional model. A risk index was used to assist in ranking the areas for priority investment. The risk index R was calculated as below :

$$R = q.s \tag{11}$$

where s is now the population per hectare. Eqns. (9) and (11) are equivalent. Eqn. (9) gives a relative measure, while Eqn. (11) gives an absolute measure. The inundation depth was divided into 5 intervals with an increment of 0.5 m where the first interval was below 0.5 m while the fifth one was unbounded and above 2.0 m. Values of q for 5 intervals are 0.5, 1.0, 4.0, 9.0 and 16.0. Then the areas were grouped into the following 5 classes on the basis of the values of R.

Range of R	*Risk class*
Below 10	Low
10-30	Medium
30-75	High
75-175	Very High
Above 175	Severe

Areas in Severe and Very High risk classes were identified as priority areas for shelter allocation except that some areas in the Very High risk class were excluded since they are protected by embankment. The number of vulnerable population in the priority areas which require shelters is 8 million. Unions have been prioritized on the basis of the magnitude of R with rank 1 for the Union having the highest R which is 577. There are 57 Unions in the Severe risk area. Population in the Severe risk area is 2.2 million and shelters are required for 1.6 million.

6.2. *Coastal embankments*

Construction of embankments along the coast as well as along the rivers is an effective means of reducing the cyclone risk. A large number of embankments and polders have been constructed along the coast. But, they are not meant for protection against storm surges but against tides. Storm surges overtopped the embankments (sometime broke them) during severe cyclones. Nevertheless, the embankments helped reduce energy of surge waves during crossing. Construction of embankments all along the coast to bar storm surges entering the country may not be cost-effective and also may not be desirable. Such embankments, if constructed, may also slow down the discharge of flood water coming from upstream of rivers and thus may aggravate the flood situation. Construction may be made at selected places like the Export Processing Zone, Chittagong Port, etc. Embankments of marginal heights in the interior of the country and along the rivers can provide protection against the overtopping of the river banks by storm surges.

6.3. *Coastal afforestation*

Forests, particularly the mangrove forests along the coast of Bangladesh, substantially reduce the wind speed of cyclones and the associated storm surge heights. It has been found that the Sunderban mangrove areas in the west of Bangladesh coast and in the West Bengal State of India suffer less from cyclonic wind and storm surges than those areas where there are less mangroves or no mangroves. A compromise apportionment may be made between embankments and afforestation. Some areas may be heavily afforested and some areas may be embanked. This is likely to be more cost-effective. Nevertheless, it is better to build a greenbelt all along the coast as far as possible.

6.4. *Cyclone forecasting and warning*

Risk assessment may be made for shorter/longer time period and for real or near-real time. While the shorter/longer scale risk assessment is useful for development planning for the coastal zone, the real or near-real one relates to an impending cyclone which is already in the sea and is likely to hit a country. In the latter case, the risk assessment may help develop evacuation programme, take relief and rehabilitation measures, etc. For assessing risk in such a case, the risk of being struck by the impending cyclone should first be determined. And then assessment should be made of the magnitude of wind speed, storm surge heights, etc. These require reliable cyclone forecasting and warning system. It is, therefore, essential that to minimise the cyclone-risk better forecasting techniques should be developed with improved mechanisms of dissemination of information to coastal people.

6.5. *Disaster management/preparedness*

Disaster management covers all activities relating to disasters-collection and analysis of data on past disasters, risk assessment, prevention/mitigation, preparedness, relief, reconstruction, rehabilitation, policy planning and action plans. Disaster management is thus a big subject by itself. A better disaster management programme and activity would substantially reduce the disaster risk and minimise the loss of life and property.

7. Conclusions and recommendations

The present paper deals with risk assessment with respect to tropical cyclones forming in the Bay of Bengal with special reference to Bangladesh which is most vulnerable to cyclone disasters. Discussions are made on various aspects of risk assessments: analysis/inventorying of past cyclones as well as causes of cyclone hazards, damages caused by a few of them and elements that are at risk and finally the risk assessment methodology itself with some case studies for Bangladesh. An analysis of the past cyclones that formed in the Bay of Bengal during the period 1881-1990 shows that there is a 30-40 oscillation in the tropical storms in the Bay and the Bay of Bengal is presently passing through a decreasing trend which is likely to get reversed in the very near future with the possibility of a higher risk period in coming decades. Bangladesh has a 10-21% probability of being struck by a cyclone and India has 55-74% probability.

It is found that work on risk assessment in Bangladesh is still at initial stages and more work should be done in future. But one of the major problems in risk assessment is the non-availability of sufficient and reliable data on cyclones, damages as well as on elements at risk. Systematic data collection on all parameters relating to risk assessment should be made and a data base should be created. The data base may form the basis of a GIS which should be updated from time to time. Safety regulations for transient population and stricter settlement regulation for chars and islands may be introduced. Storm surge proof/ resistent buildings and infrastructures should be made. In this connection, it may be mentioned here that the recently constructed Chittagong Urea Fertilizer Factory sustained less damage during the 1991 cyclone; the main reasons being the selection of an appropriate design wind speed and construction of a flood level above the highest storm surge height (Choudhury 1993).

In order to minimise the impacts of cyclones, better forecasting techniques should be developed with improved mechanism of dissemination of information to the coastal people. Along with this, extensive disaster preparedness, disaster management and disaster mitigation programmes and action plans should be undertaken.

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References

Ahmed, N., Haque, M.M., Haque, M.S., Karim, S.M.Z.E., Haque, M.A., Rahman, M.A. and Baby, S.Y., 1992, "Living with disasters: a study on 1991 cyclone in Bangladesh-Research and Consultancy Division", Bangladesh Public Administration Training Centre, Savar, Dhaka.

Ali, A., 1980, "Storm surges in the Bay of Bengal and their numerical modelling", SARC Report No. 120/80, Bangladesh Atomic Energy Commission, Dhaka, Bangladesh.

Ali, A., 1992, "Storm surges in Bangladesh," Presented in the workshop on Coastal Zone Management in Bangladesh, 27-31 December 1992, Dhaka, Bangladesh.

Ali, A., 1995, "Impacts of global climate change on tropical cyclones in the Bay of Bengal and Bangladesh, Presented in the Workshop on Global Climate Change and Tropical Cyclones, Dhaka, Bangladesh, 18-21 December 1995 and submitted for publication as the Workshop Proceedings by the SASCOM Regional Research Centre, New Delhi, India.

Ali, A., 1996, "Vulnerability of Bangladesh to climate change and sea level rise through tropical cyclones and storm surges," *J. Water, Air & Soil Pollution*, Kluwer Academic Publishers (in press).

Ali, A. and Ahmad, A.A.Z., 1992," Impact of sea level rise on other disasters in Bangladesh", Presented in the IOC/UNEP Workshop on Impact of Sea Level Rise due to Global Warming for South Asian Region, Dhaka, Bangladesh, 16-19 December 1992.

Ali, A. and Haque, M.A., 1994, "Mathematical modelling of back water effect in the Meghna river mouth in Bangladesh", *J. NOAMI*, Dhaka, Bangladesh, **Vol. II**, No. 1,27-33.

Ali,A., Rahman,H., Chowdhury,S.S.H. and Begum,Q.N., 1996, "Back water effect of tides and storm surges on fresh water discharge through the Meghna estuary in Bangladesh", *J. Remote Sensing & Environ.*, Dhaka, Bangladesh (submitted).

Arnell, N.W., 1989, "Expected annual damages and uncertainties in flood frequency estimation", *J. Water Res. Plan & Manage. ASCE*, **115**, 1, 94-107.

Bangladesh National Building Code, 1993, Housing and Building Research Institute, Dhaka, Bangladesh.

Barua, D.K., 1991, "The coastline of Bangladesh: an overview of processes and forms", Proc. 7th Symp. Coastal Ocean Management, Am. Soc. Civ. Eng., 2284-2301.

BUET/BIDS, 1993, "Multipurpose cyclone shelter programme", Bangladesh University of Engineering and Technology (BUET) and Bangladesh Institute of Development Studies (BIDS), UNDP/BGD/91/025, Final Report, Planning Commission, Government of Bangladesh.

Choudhury, A.M., 1995, "Monitoring and warning of tropical cyclones using space technology", Presented in the Workshop on Global Change and Tropical Cyclones, Dhaka, Bangladesh, 18-21 December 1995.

Choudhury, J.R., 1993, "The impact of natural disasters on urban infrastructure", Presented in the Technical Conference on Tropical Climates, held in Dhaka, Bangladesh, 28 March-2 April, 1993.

Chow, V.T., Maidment, D.R. and Mays, L.W., 1988, "Applied Hydrology", McGraw-Hill Book Co., 425.

Chowdhury, J.U., 1994, "Determination of shelter height in a storm flood risk area of the Bangladesh coast", *Water Res. J.*, ESCAP Ser. **C/182**, 93-99.

Chowdhury, J.U. and Karim, M.F., 1995, "Assessment of storm surge flood risk in a coastal region of Bangladesh", Proc. 4th Int. Conf: Coastal & Port Engg. in developing countries, COPEDEC IV, Rio de Janeiro, Brazil, 1772-1785.

Dube, S.K. and Singh, M.P., 1981,"Can storm surges be predicted"? *Science Today*, Bombay, India, **15**, 11, 39-43.

Emanuel, K.A., 1987, "The dependence of hurricane intensity", *Nature*, **326**, 483-485.

Frank, N.L. and Husain, S.A., 1971 "The deadliest tropical cyclone in history?" *Bull. Amer. Meteor. Soc.*, **52**, 6, 438-444.

French, S.R., 1991, "Utilization of geographic information system (GIS) for landuse planning and disaster preparedness" - In disaster Management and Regional Development Planning with People's Participation, UNCRD Meeting Report Series; No. 40/**Vol. II**, United Nations Centre for Regional Development, Nagoya, Japan and Centre on Integrated Rural Development for Asia and the Pacific (CIRDAP), Dhaka, Bangladesh, 3-28.

Gray, W.M., 1968, "Global view of the origin of tropical disturbances", *Mon. Wea. Rev.*, **96**, 669-700.

Gray, W.M., 1985, "Tropical cyclone global climatology", WMO Technical Document WMO/TD No. 72, **Vol. I**, WMO, Geneva, Switzerland, 3-19.

Harris, D.L., 1982, "The prediction of hurricane storm surges," A state-of-the-art survey-Report No. 49, Florida Sea Grant College, Florida, USA, 42 p.

India Meteorological Department, 1979, "Tracks of storms and depressions in the Bay of Bengal and the Arabian sea 1877-1970", IMD, New Delhi, India.

Jelesnianski, C.P., 1989, "Storm surge and sea state", 2nd International Workshop on Tropical Cyclones, Manila, Philippines, 27 November-8 December 1989, WMO/TD-No. 319, **Vol. II**, WMO, Geneva.

Joseph, P.V., 1995, "Changes in the frequency and tracks of tropical cyclones in the Indian ocean seas", Presented in the Workshop on Global Change and Tropical Cyclones, Dhaka, Bangladesh, 18-21 December 1995.

Mays, L.W., 1987, "Review of advances in risk and reliability analysis for hydraulic structures", In application of Frequency and Risk in Water Resources, ed. V.P. Singh, D. Reidel Publishing Co., 227-262.

McBride, J.L., 1995, "Tropical cyclone formation" - In Global Perspectives on Tropical Cyclones", WMO/TD-No. 693, Tropical Cyclone Programme, Report No. TCP-38, WMO, Geneva, Switzerland.

Mott MacDonald Int. Ltd. and others, 1993, "Assistance to Ministry of Relief in Coordination of Cyclone Rehabilitations, UNDP (BGD/91/021)", Final Report, Vol. II: Natural Disasters Affecting Bangladesh, Ministry of Relief, Government of Bangladesh.

Murty, T.S., Flather, R.A. and Henry, R.F., 1985, "Storm surges in the Bay of Bengal", IOC/UNESCO Workshop on Regional Cooperation in Marine Science in the Central Indian Ocean and Adjacent Seas and Gulfs, Colombo, 8-13 July, 1985, Workshop Report No. 37, Supplement, Intergovernmental Oceanographic Commission, 205-227.

Neumann, C.J., 1993, "Global overview", Chapter 1, Global Guide to Tropical Cyclone Forecasting, WMO, Geneva, Switzerland.

Plate, E.J., 1995, "Risk management of coastal structures", Keynote Speech, 4th Int. Conf. Coastal and Port Engg. in Developing Countries, COPEDEC IV, Rio de Janeiro, Brazil.

Proudman, J., 1955, "The propagation of tide and surge in an estuary", Proc. R. Soc. Lond., A, **Vol. 231**, 8-24.

Sener, Ingenieria, Y., Sistemas, S.A. and others, 1996, "Cyclone shelter preparatory study, Stage I: Feasibility Phase", Final Report, BGD/7-3000/91/419-04, Commission of the European Communities, Brussels.

Sinha, P.C., Dube S.K. and Roy G.D., 1985, "Influence of river on the storm surges in the Bay of Bengal, Proc. International Workshop on Operational Applications of Mathematical Models (Surface Water) in Developing Countries, New Delhi, India, 26 February-1 May 1985.

UNCRD, 1991, "Cyclone damage in Bangladesh", United Nations Centre for Regional Development, Nagoya, Japan, 41-45.

UNDRO, 1991, "Mitigating natural disasters", A manual for policy makers and planners, UNDRO, New York.

Venkateswarlu, B., 1987, "Extreme wind hazards in Asia", Proc. US- Asia Conf. on Engineering for Mitigating Natural Hazards Damage, ed. P. Karasudhi, P. Nutalaya and A.N.L. Chiu, A1-1-A1-14, Bangkok.

Warrick, R.A., Bhuiya, A.H., Mitchell , W.M., Murty, T.S. and Rasheed, K.B.S., 1994, "Sea level changes in the Bay of Bengal", Briefing document No. 2, Bangladesh Unnayan Parishad (BUP), Dhaka, Bangladesh, 24 p.

Yim, W.W.S., 1995, "Implications of sea level rise for Victorian harbour", *Hong Kong J. Coastal Res.*, Special Issue.