Global Environmental Change 18 (2008) 490–500

Contents lists available at ScienceDirect

Global Environmental Change

journal homepage: www.elsevier.com/locate/gloenvcha

Impacts of climate change and sea-level rise on cyclonic storm surge floods in Bangladesh

Mohammed Fazlul Karim [a,*], Nobuo Mimura [b,1]

[a] CSIRO Davies Laboratory, University Road, Townsville, QLD 4814, Australia
[b] Department Civil and Env. Engineering, Ibaraki University, Hitachi, Ibaraki 316-8511, Japan

ARTICLE INFO

Article history:
Received 27 October 2006
Received in revised form
7 May 2008
Accepted 19 May 2008

Keywords:
Cyclone
Storm surge
Flood
Climate change
Sea-level rise
Adaptation
Bangladesh

ABSTRACT

This paper describes the impacts of sea surface temperature (SST) rise and sea-level rise (SLR) on cyclonic storm surge flooding in western Bangladesh. A calibrated numerical hydrodynamic model was used to simulate surge wave propagation through the rivers and overland flooding. The model was calibrated with base condition (present climate), and then eight flooding scenarios of plausible future conditions were assessed by considering increased surge heights. Flooded area, flooding depth and surge intrusion length were computed by superimposing the predicted maximum water level information on a digital elevation model (DEM). This analysis showed that for a storm surge under 2 °C SST rise and 0.3 m SLR, flood risk area would be 15.3% greater than the present risk area and depth of flooding would increase by as much as 22.7% within 20 km from the coastline. Within the risk area, the study identified 5690 km^2 land (22% of exposed coast) as a high-risk zone (HRZ) where flooding of depth 1 m or more might occur, and people should move to nearby cyclone shelters during extreme cyclonic events. Predicted area of HRZ is 1.26 times the currently demarcated HRZ. It was estimated that 320 additional shelters are required to accommodate people in the newly identified HRZ. This information would be of value to policy and decision makers for future shelter planning and designing shelter heights.

1. Introduction

Flooding due to tropical cyclones is one of the most devastating natural hazards in Bangladesh. The coastal region of Bangladesh is particularly vulnerable to cyclonic storm surge floods due to its location in the path of tropical cyclones, wide and shallow continental shelf and the funnelling shape of the coast (Das, 1972). Cyclone-duced storm surges in this region typically originate in the central and southern parts of the Bay of Bengal or in the Andaman Sea. Due to the shallow continental shelf, the surge amplifies to a considerable extent as it approaches land and causes disastrous floods along the coast (Murty et al., 1986). In addition, the coastal areas of Bangladesh comprise low-lying and poorly protected land which supports a large population. All the ingredients for a major cyclone disaster are present and such disasters have occurred several times in the past and claimed hundreds of thousands of lives notably in 1970 and 1991 (Haque, 1997). A brief summary of historic cyclones (wind speeds above 150 km/h) that made landfall along the coast of Bangladesh and caused catastrophe in terms of coastal flooding and human casualties is given in Table 1. The country is likely to be affected by more intense cyclonic events in the foreseeable future due to climate change and sea-level rise (SLR). This is of great concern, since the location and geography of Bangladesh makes it not only particularly susceptible to the effects of climate change, but also extremely hard to protect. The consequences of climate change lead to an increase in the cyclone-prone area and put a large number of people at risk. However, over the last decade the country's capacity to deal with cyclones has improved considerably with the establishment of a cyclone warning and evacuation system. For example, cyclone Sidr in 2007 claimed far fewer lives (approx. 3500) than the 1970 and 1991 cyclones, which killed at least 500 000 and 138 000 people, respectively. At present, people in the flood risk areas are directed by the forecasting and warning centre to evacuate to refugee shelters. Unfortunately, the capacity of exiting shelters is not adequate to accommodate all the people in the flood risk areas. Moreover, any increase in risk area due to climate change and SLR will increase the required number of shelters.

All of the existing cyclone shelters are located in the high-risk zone (HRZ), which is that part of flood risk area where there is a

* Corresponding author. Tel.: +61 7 4753 8580; fax: +61 7 4753 8600.
E-mail addresses: Fazlul.Karim@csiro.au (M.F. Karim), mimura@mx.ibaraki.ac.jp (N. Mimura).
[1] Tel.: +81 294 385169; fax: +81 294 385268.

0959-3780/$ - see front matter Crown Copyright © 2008 Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.gloenvcha.2008.05.002

Table 1
List of major cyclones that made landfall to Bangladesh and associated coastal storm surges and casualties since 1960 (Source: IWM, 2005; Ali, 2000)

Landfall date	Location of landfall	Maximum wind speed (km/h)	Maximum surge height (m)	Death
30 Oct 1960	Chittagong-Cox's Bazar	208	6.1	5179
09 May 1961	Bhola, Noakhali	160	3.0	11 468
28 May 1963	North of Chittagong	203	3.7	11 520
11 May 1965	Barisal, Noakhali	162	4.0	19 279
15 Dec 1965	Cox's Bazar	210	3.7	873
23 Oct 1966	Noakhali, Chittagong	145	6.7	850
12 Nov 1970	Chittagong	222	10.6	300 000
25 May 1985	Chittagong	154	4.3	4264
29 Nov 1988	Khulna	160	4.4	1498
29 Apr 1991	Chittagong	225	6.1	138 000
02 May 1994	Cox's Bazar	215	3.3	188
19 May 1997	Chittagong, Feni	225	4.6	126
26 Sep 1997	Chittagong	150	3.0	155
16 May 1998	Chittagong, Cox's Bazar	165	2.5	12
15 Nov 2007	Barguna, Patuakhali	220–250	6.0	3500

possibility of flood depth reaching 1 m or more (Chowdhury, 2003). The boundary of the HRZ was originally established based on inundation depth during the 1991 cyclone. The stilt heights of existing shelters were designed based on a study of Bangladesh University of Engineering & Technology (BUET) and Bangladesh Institute of Development Studies (BIDS) (BUET and BIDS, 1993). The study recommended stilt heights of 3.5–7.0 m based on the location of a shelter with respect to the coastline. However, the impact of SLR and/or intensification of cyclonic events under increased sea surface temperature (SST) were not considered in that study. As a low-lying country, Bangladesh is considered as one of the most vulnerable countries in the world to climate change and SLR (IPCC, 2007). The country is experiencing rising sea level along its coast (SMRC, 2003; Unnikrishnan et al., 2006) due to global SLR and the subsidence of the Ganges delta (Alam, 1996; Haque, 1997). The impacts of SLR are profound throughout the western coastal zone as it is low lying and the coastal lands are subsiding (Mohal et al., 2007). SLR can also cause the relative decrease of existing shelter heights with respect to mean sea level (MSL). Recent climate studies also predicted intensified tropical cyclones and associated storm surges with an increase in SST (Emanuel, 2005). It is very likely that any increase in surge height at the coast will lead to an increase in flooded area and spatial flooding depth. In fact, significantly increased flooding scenarios were predicted in an early study of Karim et al. (2005) that incorporated some of the climate impacts. If this occurs, the boundary of the present HRZ area will be shifted further inland. Additional shelters would therefore be necessary to accommodate the people in the newly identified HRZ. At the same time, increased flood depth threatens the safety of existing shelters. In this study, we have addressed some of those issues by predicting flooding scenarios for different plausible climate conditions. For an average climate condition by 2050, the boundaries of the risk area and the HRZ were established, and then the number of shelters to accommodate people in the HRZ was re-estimated.

2. Study area and cyclonic surges

2.1. Location and geophysical environment

Bangladesh is one of the major disaster-prone countries in the world due to its geographical setting. It is a part of the Bengal Basin, one of the largest geo-synclinals in the world. The country is well within the tropics, bounded between 20°34′–26°38′N and 88°01′–92°41′E comprising an area of 147 570 km^2. Its coastline is 710 km long, which lies along the Bay of Bengal. About 80% of the country's land is the floodplains of three large rivers, the Ganges, the Brahmaputra and the Meghna. The country has very flat and low-lying land, except in the northeast and southeast regions. Only 10% of Bangladesh is 1 m above MSL and one-third is under tidal influence. The Himalayan range is to its north and its southern coast is at the northern tip of the Bay of Bengal, which converges near the coast like a funnel towards the Meghna estuary. All these geo-physical settings make the country vulnerable to natural disasters among which tropical cyclones are the most serious (Ali and Chowdhury, 1997).

In Bangladesh the coastal zone has been delineated based on three criteria, namely the limits of tidal fluctuation, salinity intrusion and cyclone risk. The coastal zone comprises 19 administrative districts encompassing a land area of 47 201 km^2 (32% of total area of the country). It has been broadly classified as an exposed zone that demonstrates the above three criteria, and as an interior coast that demonstrates one or two criteria (Islam, 2004). Based on geomorphologic characteristics, the coastal zone is divided into three distinct coastal regions, namely the western, central and eastern regions as shown in Fig. 1. The scope of this study was limited to the western coastal zone, which is particularly vulnerable to storm surge floods. The western coastal zone (also known as Ganges Tidal Plain) consists of nine exposed districts having a land area of 25 504 km^2 (65% of total exposed zone) and 541 people per square kilometre, and four interior districts having a land area of 6238 km^2 (79% of total interior zone) and 853 people per square kilometre (BBS, 2005). About 4520 km^2 of land (18% of western coastal zone) is currently demarcated as HRZ where surge flooding may exceed 1 m flood (BUET and BIDS, 1993). The western coastal zone is a low-lying deltaic plain and is characterized by wide rivers and estuaries that allow sea surges to propagate faster and to intrude far inland (Barua, 1991). There are six major estuarine rivers (as shown in Fig. 1) having widths of several kilometres and depth in the range of 20–30 m. Low land elevation, large estuary opening and poor defences against floods are some of the major causes of disastrous surge flooding in this region (SMRC, 1998).

2.2. Storm surge and coastal flooding

Storm surges are atmospherically forced oscillation of the water level in a coastal or inland water body. The surges are generated mainly by wind stresses and, to a lesser extent, falling atmospheric pressure that produces a rise in water level at the

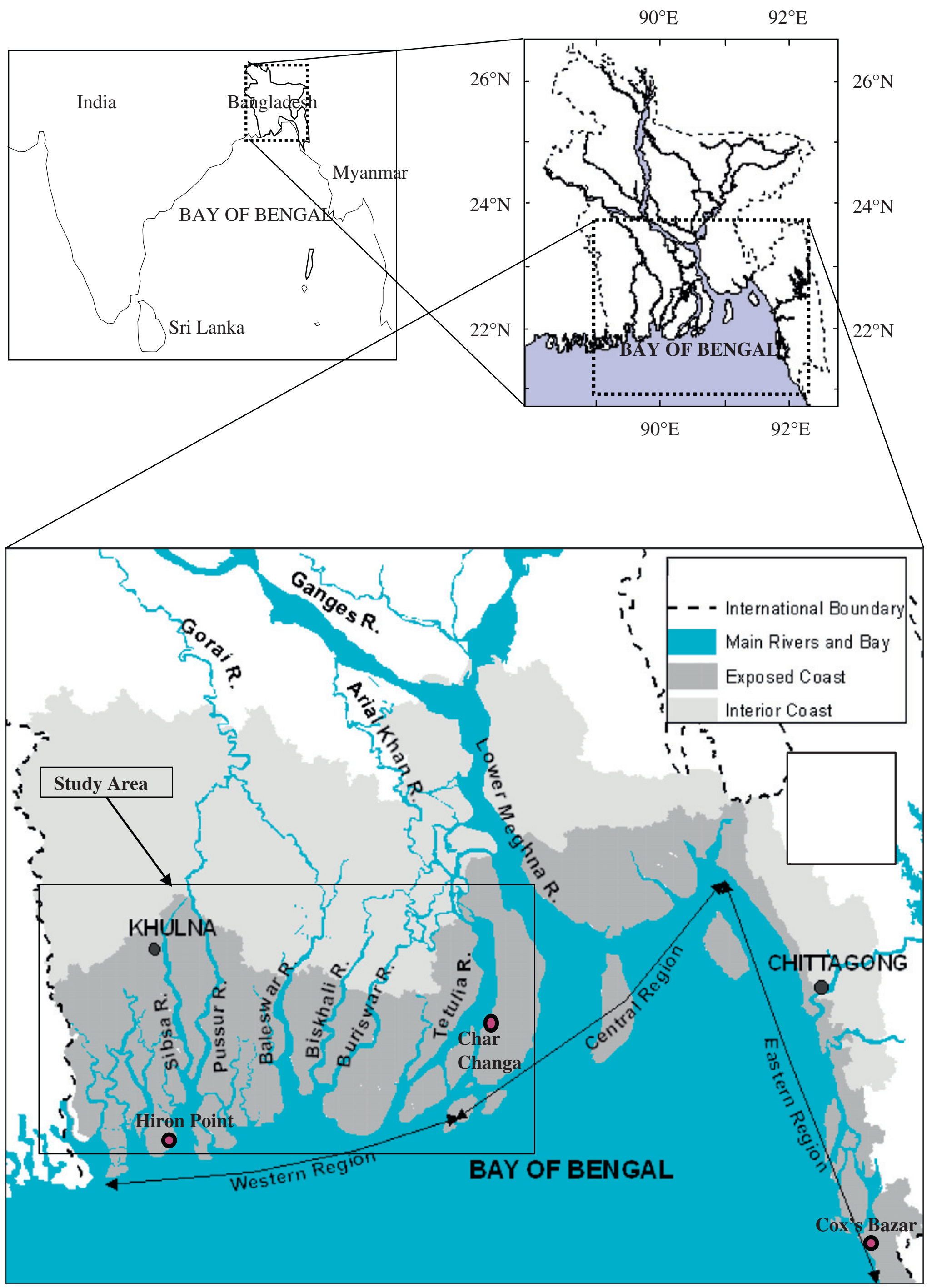

Fig. 1. The coastal regions of Bangladesh and major rivers in the western coastal zone.

rate of approximately 1 cm per hPa fall in pressure (McInnes et al., 2002). Storm surges have wave periods ranging from a few minutes to a few days and are categorised as long gravity waves in the same category as tidal waves (Murty, 1984). The tide is an astronomical phenomenon that is caused by the gravitational attraction of the moon and the sun on the earth, while the storm surge is a meteorological phenomenon. Cyclones in the Bay of Bengal generally occur in the pre-monsoon (April–May) or post-monsoon (October–November) seasons. The Bay of Bengal has favourable conditions for the formation of tropical cyclones, and about 149 cyclones have crossed the Bangladesh coast between 1891 and 1998. Since 1970, four severe cyclones with maximum wind speeds greater than 220 km/h and associated surges more than 4 m high have hit Bangladesh (November 1970, April 1991, May 1997 and November 2007). In probabilistic terms, Bangladesh is prone to at least one major tropical cyclone every year (Haque, 1997). The most destructive element of a cyclone is its accompanying surge. There is little that can withstand a great mass of onrushing water often as high as 6 m. In Bangladesh, the maximum value of storm surge has been reported to be as high as 13 m (SMRC, 1998). The western coastal zone is particularly vulnerable to surge flooding due to its low-lying land and very poor defences against surge waves. In the past, surge flooding was reported in excess of 60 km inland (Chowdhury, 2003). The effect of a storm surge is particularly severe when its arrival coincides with high tide. In fact, this coincidence occurred several times in the past when large coastal areas flooded to more than 5 m depth (IWM, 2005). Notably, the cyclone of 1970 produced an extreme water level 10 m above MSL as it hit the coast during high spring tide and caused inundation to every low-lying coastal area (SMRC, 1998).

The generation and propagation of cyclonic storm surges in the Bay of Bengal and flooding in the coastal regions of Bangladesh have been investigated quite extensively since the 1970s. Various studies (e.g. IWM, 2005; Azam et al., 2004; Madsen and Jakobsen, 2004; CSPS, 1998; Flather, 1994) predicted storm surges and associated flooding along the coast due to direct overtopping of the surge wave over the coastline. However, impacts of climate change and SLR were not included in those studies. Even though there are a fairly good number of studies on climate modelling (e.g. Mirza et al., 2003; Ahmed and Alam, 1999), studies of coastal flooding under climate change conditions are still limited. Among the few studies, Ali (2000) predicted storm surges along the coast of Bangladesh for several climate scenarios but flooding was not investigated in that study. While IWM (2005) assessed coastal flooding by incorporating some aspects of climate impacts, lateral surge flooding due to riverbank overtopping was not considered. It is well known that the surge wave declines very quickly overland due to strong resistance by land cover. In contrast, surge waves move much faster through rivers due to less resistance to flow (Madsen and Jakobsen, 2004). The propagating surge through the river overtops the riverbank and causes lateral flooding along the river (Chowdhury and Karim, 1996). In the past, lateral surge flooding was recorded approx. 60 km inland, while direct surge flooding over the coastline was limited to a few kilometres (WARPO, 2001; MCSP, 1992). In this study, surge intrusions through the river were investigated using a river network model. The flood-prone areas were identified by superposing computed maximum water level and a digital elevation model (DEM). The study established a boundary of surge flooding and then identified an area of high risk within the flooded area where there is a possibility of flooding depths in excess of 1 m.

3. Climate change impacts assessment

3.1. Observation and future climate scenarios

Over the past 100 years, the broad region encompassing Bangladesh has warmed by about 0.5 °C. Observed data indicate that the temperature is generally increasing in the monsoon season (June–August). Average monsoon maximum and minimum temperatures show an increasing trend annually at the rate of 0.05 and 0.03 °C, respectively (Ahmed and Alam, 1999). There are various estimates of temperature rise in Bangladesh. One estimate (e.g. Ahmed and Alam, 1999) is that the average increase in temperature would be 1.3 °C by the year 2030 and 2.6 °C by the year 2075 with respect to the base year 1990. The seasonal variation of temperature will be more in winter than in summer: 1.3 °C in winter and 0.7 °C in summer for 2030 and 2.1 °C for winter and 1.7 °C for summer for 2075. A study of the Organisation of Economic Co-operation and Development has compared the results of 17 General Circulation Models (GCMs) for Bangladesh in order to assess changes in average temperature and precipitation. It has selected 11 out of the 17 models which best simulate the current climate over Bangladesh. The models were run with the IPCC B2 scenarios to assess the future climate. All climate models predicted a steady increase in temperature for Bangladesh, with little inter-model variances (Agrawala et al., 2003). Based on the results of available climate studies, the National Adaptation Program of Action (NAPA) recommended 1.0, 1.4 and 2.4 °C temperature rises by the years 2030, 2050 and 2100, respectively (MOEF, 2005).

3.2. Sea-level rise

SLR along the coast of Bangladesh is another critical variable that may amplify the vulnerability to global climate change. The meteorological research council of the South Asian Association for Regional Cooperation carried out a study on relative SLR in the Bay of Bengal based on 22 years (1977–1998) measured sea-level data and observed that sea levels at Hiron Point, Char Changa and Cox's Bazar (refer to Fig. 1 for locations) have been rising by 4.0, 6.0 and 7.8 mm/year, respectively (SMRC, 2003). The results reveal that the rate of SLR along the coast of Bangladesh is much higher than the global rate of 1.0–2.0 mm/year in the last century. However, the relative sea level in the Bay of Bengal is influenced by local factors such as tectonic setting, sediment load and deltaic subsidence (Warrick et al., 1996). As outlined by Alam (1996), the Ganges–Brahmaputra delta is subsiding at a rate of 2–4 mm/year. There is no specific regional scenario for eustatic SLR in the Bay of Bengal. The Bangladesh country study (Agrawala et al., 2003) put the range at 30–100 cm by 2100, while IPCC projected 26–59 cm global SLR under scenario A1F1 (Meehl et al., 2007). In an earlier study, potential SLR in Bangladesh was predicted as 30–150 cm by 2050 (DOE, 1993). Based on IPCC reports and available SLR studies, the NAPA for Bangladesh recommended SLRs of 14, 32 and 88 cm for the years 2030, 2050 and 2100, respectively (MOEF, 2005).

3.3. Frequency and intensity of cyclones

The formation of tropical cyclones is strongly influenced by SST of the underlying ocean or, more specifically, by the thermal energy available in the upper ocean waters. The role of SST in the genesis and intensification of tropical cyclones has been analysed in many studies (e.g. Emanuel, 1987; Saunders and Harris, 1997). Theoretically, any rise in SST will cause more frequent and intense cyclones. However, this phenomenon is not fully supported by an analysis based on observed cyclones in the Bay of Bengal (Ali, 2000). This study considered all kinds of tropical cyclones formed in the Bay of Bengal between 1877 and 1995, but it showed no corresponding increase of cyclone frequency even though increasing temperature was observed. However, studies of intensification of cyclones in the Bay of Bengal have shown that the frequency of intense cyclones during November has been increasing (SMRC, 2003). In another study, Unnikrishnan et al. (2006) reached a similar conclusion while analysing the outputs from the UK Hadley Centre GCM (HadRM2) for the northern Indian Ocean.

There is a large uncertainty in the future changes in tropical cyclone frequency predicted by climate models forced with future greenhouse gas concentrations. The changes in frequency of storms simulated by models are often smaller than those due to natural variability. The IPCC (2007) concluded that the results of GCM experiments on storm frequencies are inconclusive. In the case of cyclone intensity, it is more likely that an increase in SST will be accompanied by a corresponding increase in cyclone intensity. Emanuel (1987) has explained the significance of SST in the increase of cyclone intensity and established relationships between minimum sustainable central pressure and maximum wind speed as a function of SST. If the IPCC (2007) standard of a lower bound of 2 °C and an upper bound of 4.5 °C rise in temperature by 2100 is considered, the corresponding increases in maximum cyclone wind speed using Emanuel's table (Emanuel, 1987) are 10% and 25%, respectively, relative to the present threshold temperature of 27 °C in the Bay of Bengal. However, the above cyclone intensification has not yet been confirmed by observations and/or numerical experiments. The possibility of any increase in peak intensities has potentially serious implication for a country already vulnerable to cyclonic storm surges. A potential implication would be that future storm surges might be even higher than those that are observed currently, due to the combined effects of temperature increasing and sea-level rising.

4. Method of simulation

4.1. Prediction of storm surge

A number of studies investigated storm surges in the Bay of Bengal using numerical models (e.g. IWM, 2005; Madsen and Jakobsen, 2004; Flather, 1994; Dube et al., 1986; Murty et al., 1986; Das, 1972) and empirical models (e.g. Chowdhury, 1994; MCSP, 1992) as part of the adaptation to cyclonic surges in Bangladesh. However, the impacts of climate change and SLR were not considered in those studies. As predicted by Emanuel (2005), any increase in SST will cause intensification of tropical cyclones. This phenomenon should be included in any future prediction of cyclonic storm surges. Ali (2000) is one of the few studies that predicted cyclone-induced surges at the coast by incorporating SST rise and SLR into the cyclone model. The main inputs to the cyclone model are minimum sustainable central pressure and the maximum wind speed as a function of SST. Table 2 shows the surge heights for a total of nine climate scenarios correspond to three SSTs and three sea levels. Scenario I represents the base condition, while Scenario V is considered as an average climate condition by 2050. It shows that storm surge height may increase as much as 21% if SST rises by 2 °C (Scenario II) and 49% if SST rises by 4 °C (Scenario III). Another analysis based on continental shelf length and wind speed (Chowdhury, 1994) also produced similar surge heights at the coast. These predictions are relatively large compared with the results of Mitchell et al. (2006) in which they predicted 0.5–0.7 m increase in surge height of a 50-year return period storm surge. It is interesting to note that surge height reduces by 7% if SLRs by 1.0 m, but SST remains unchanged (Scenario VII). The reason is that the amplification of the surge is less if the water depth is increased, due to the differences in bottom friction on the propagating waves.

4.2. Model setup and calibration

A 1-D numerical hydrodynamic model was developed to simulate surge wave propagation through the rivers and over land. Since we used 1-D model, flow over the land was considered as an additional part of the main channel. The effective overland flow area was calculated based on water depth as the momentum of water remains insignificant if the water depth is very small. A methodology after McDowell and O'Connor (1977) was followed to calculate effective river-land flow section which is commonly termed as conveyance area. The discharge and water level at each computational point were then calculated by solving continuity and momentum equations. The river and estuarine systems in the study area were established using GIS-based land topography maps and DEM.

The model is based on long wave equations (Sorensen, 1993) for one-dimensional flow. The governing equations are the continuity equation (mass balance) and momentum equation. These equations were solved numerically using an implicit finite difference scheme known as the 6-point Abbott scheme (Abbott and Ionescu, 1967). The transformations of these equations into a set of finite difference equations were performed in a computational grid consisting of alternating flow, Q and depth, h points. Q points were always placed midway between two adjacent h points, while the distance between two consecutive h points varied in the range of 2–5 km. The completion of a computational cycle requires the specification of boundary data at the inland and seaward ends of a river system. In the present setup, discharges were specified at all inland boundaries and water levels are specified at all seaward boundaries (river mouths).

The river network setup consists of four major river systems namely Pussur-Sibsa, Baleswar, Biskhali-Buriswar and Tetulia as shown in Fig. 1. A total of 23 river branches (4 in Pussur-Sibsa, 8 in Baleswar, 4 in Bishkhali-Buriswar, and 7 in Tetulia), 320 cross-sections covering a total schematized length of 1278 km and 11 junctions were modelled. Each river system was bounded by a water level boundary at the river mouth (seaward boundary) and one or more discharge boundaries at the upstream ends. The discharge boundary was located far beyond the surge intrusion limit to avoid any influence of upstream flow. In fact, during the past cyclonic events, upstream flows were insignificant to create any influence on surge flooding (IWM, 2005).

The model was calibrated for the cyclone of September 1997 when surge heights of 3–5 m were recorded. Details of the model calibration can be found in Karim et al. (2005). Predictions of surge intrusion length and flooding area were made for an extreme condition when peak surge coincides with high spring tide. For this condition, the vertical displacement of water level is the highest and the surge intrusion length is maximum. Such an extreme occurred during the cyclone of November 1970 and caused excessive flooding all along the coast (Flather, 1994; MCSP, 1992). To estimate flooding scenarios, we considered the worst condition of surge wave coinciding with a spring tide.

4.3. Scenarios of surge flooding

Flooding scenarios were assessed for a total of nine input surges (Scenario I to Scenario IX, refer to Table 2). At first, time

Table 2
Storm surges under different SLR and SST rise conditions (Scenario I represents base condition that corresponds to wind speed and central pressure as observed during the 1991 cyclone) [Derived from Emanuel (2005) and Ali (2000)]

Climate scenarios	SLR (m)	SST rise (°C)	Wind speed (km/h)	Central pressure (hPa)	Surge height (m, MSL)
Scenario I	0.0	0	225	926	7.6
Scenario II	0.0	2	246	924	9.2
Scenario III	0.0	4	274	921	11.3
Scenario IV	0.3	0	225	926	7.4
Scenario V	0.3	2	246	924	9.1
Scenario VI	0.3	4	274	921	11.3
Scenario VII	1.0	0	225	926	7.1
Scenario VIII	1.0	2	246	924	8.6
Scenario IX	1.0	4	274	921	10.6

variation of surface elevations at the seaward boundary was generated by an algebraic summation of astronomical tide and a storm surge (meteorological tide). The Bay of Bengal has a substantial tidal range reaching around 6.0 m at Calcutta, and adjacent to Sandwip Island, but around 3.0 m along the western coast (Barua, 1991; Murty and Henry, 1983). In this study, an average astronomical tidal range of 3.0 m was considered to generate ordinates of tide levels. A triangular shape hydrograph having a period of 12 h was used to generate time series of storm surge data as recommended by Chowdhury and Karim (1996). The period of storm surges in the Bay of Bengal varies in the range of a few hours (e.g. As-Salek, 1998; Flather, 1994; Dube et al., 1986). The worst condition was considered by assuming the coincidence of surge peak with tide peak. A typical example of seaward boundary data is presented in Fig. 2 for an extreme water level 9.2 m above MSL, made up of a 7.7 m surge over a 3.0 m astronomical tidal range (Scenario II). For each setup, the model was run for 30 h (two and half wave cycles) with a 15 s time interval. The propagation of surge wave was simulated separately through each river system.

Surge residuals at different computational points were computed from the time history of water surface elevations. Flooding area under each river system was then estimated by superimposing the maximum water surface elevation data over the DEM. The limit of surge intrusion was considered at a location where there was a surge residual of 0.2 m. A typical example of the time variation of water surface elevations at four interior computational points in the Pussur River is shown in Fig. 3 for an input surge as described above (refer to Fig. 2). The timing of surge landfall at the coast is shown on the time axis (at 15 h). The results show the arrival of the peak surge and corresponding water surface elevation at different locations. For this example there is a surge residual of 2.4 m at 50 km inland. However, over bank flooding depends on the water level in the river with respect to the riverbank level. The results give an indication of how the surge dies with distance and time. The rate of surge height reduction with distance was also evaluated. For the example in Fig. 3, surge height reduced by 1.09 m between 20 and 30 km, 0.66 m between 30 and 40 km, and 0.47 m between 40 and 50 km. The reduction in surge height is exponential as expected.

Another example in Fig. 4 shows water surface envelops (surge profiles) along the Baleswar River for three input surges that correspond to the base year (Scenario I), 2 °C temperature rise (Scenario II) and 4 °C temperature rise (Scenario III). It also shows the elevation of the riverbank with respect to MSL. The average bank slope is 1:50 000, illustrating the very flat topography in the region. The difference between water level and bank level gives

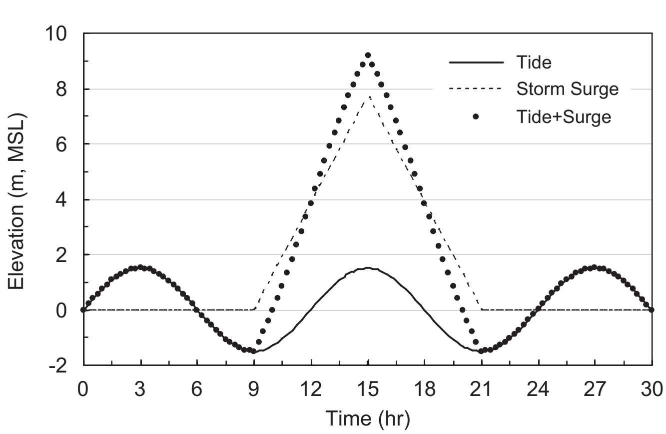

Fig. 2. A typical example of time variation of water surface elevations at a seaward boundary for a net surge of 7.6 and 3.0 m tidal range (Scenario I).

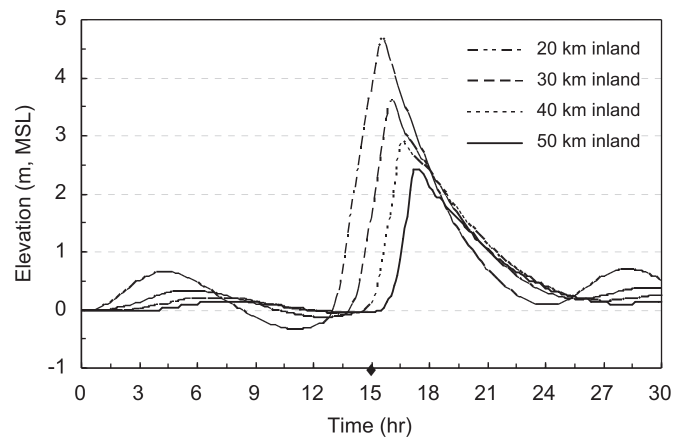

Fig. 3. Time variation of computed water surface elevations at four interior sections along the Pussur River for an input surge of 9.2 m (Scenario II). ◆: Denotes time of landfall.

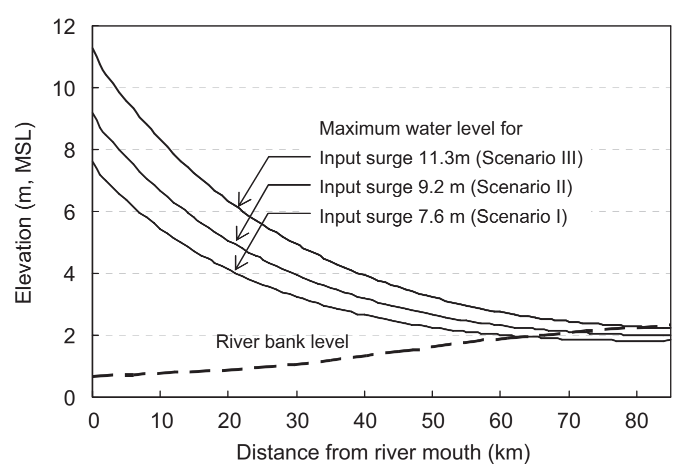

Fig. 4. Computed water surface envelop along the Baleswar River for different SSTs (Scenario I: base condition, Scenario II: surge corresponding to 2 °C temperature rise, Scenario III: surge corresponding to 4 °C temperature rise).

the flooding depth at a particular location. It can be seen that a surge equivalent to that which occurred during the 1991 cyclone would produce over bank flooding up to 60 km inland (Scenario I). It is predicted that over bank flooding would occur as much as 69 km inland for a surge that corresponds to Scenario II, while the intrusion reached up to 78 km inland for a surge that corresponds to Scenario III. These intrusion lengths are 15% and 30% higher than that in Scenario I. There is a trend of exponential decay of surge height for all scenarios. The reason is the strong surface resistance to flow as the wave propagates over land. The results confirm that surge height over the land reduces significantly within a few kilometres from the coastline. Surge wave, however, propagates a large distance through the rivers as the resistance to flow is small in rivers.

The area of flooding was estimated by superposing computed maximum water levels and the DEM using ArcView GIS software. At first, the number of cells in the flooded zone was identified. The product of cell size (200 m × 200 m) and number of flooded cells is the area of flooding. The assessment was done separately for each river system. The cumulative sum of flooded areas under different river systems identifies the total flood-prone area. A brief summary of computed flood-prone areas and intrusion lengths is presented in Table 3 for Scenario I, Scenario II and Scenario III. It can be seen that the flooding area increases by 12.6% for a surge

Table 3
Predicted surge intrusion length and flooding area under different SST rise, while sea level remains unchanged

River name	Input surge 7.6 m (Scenario I)		Input surge 9.2 m (Scenario II)		Input surge 11.3 m (Scenario III)	
	Intrusion distance (km)	Flooded Area (km^2)	Intrusion distance (km)	Flooded Area (km^2)	Intrusion distance (km)	Flooded Area (km^2)
Passur-Sibsa	56	1265	63	1388	72	1509
Baleswar	62	1441	69	1590	78	1776
Biskhali-Buriswar	47	1154	54	1318	62	1442
Tetulia	50	1047	58	1228	66	1392
Total	–	4907	–	5524	–	6119

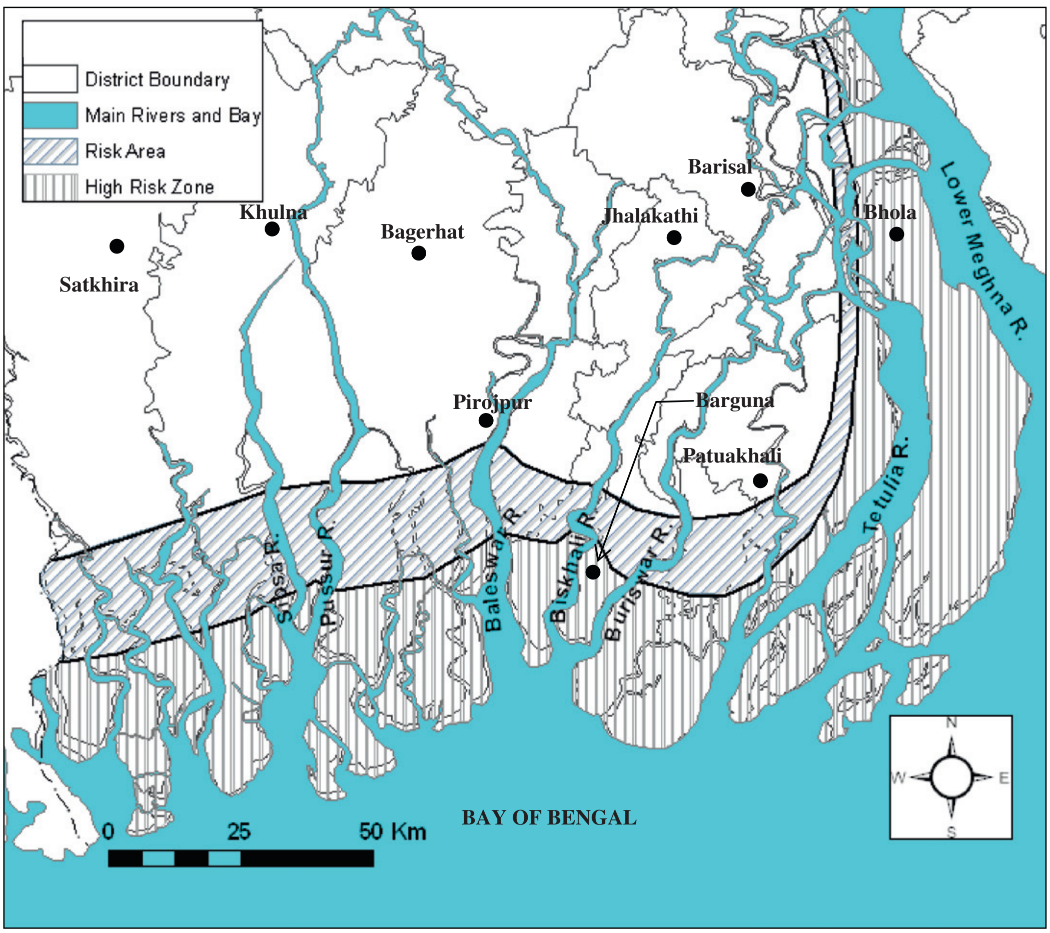

Fig. 5. Flood risk map corresponds to a typical projected climate (Scenario V: 2 °C temperature rise and 0.3 m SLR).

that corresponds to 2 °C temperature rise (Scenario II) and by 24.5% for a surge that corresponds to 4 °C temperature rise (Scenario III) if sea level remains unchanged. The results show that the maximum surge intrusion occurred along the Baleswar River. The area of flooding is also large in this river system. This is because of the large opening at the entrance and relatively higher water depth in this river.

Impact assessments were carried out in terms of potential risk areas under different climate conditions. The risk area was identified by a boundary line that represents the maximum limit of surge intrusion length. The methodology is briefly described here. At first the points where the surge produced a water level same as the riverbank level were located. Then, all those points were connected based on land level data, so that the boundary line maintains the same elevation over land. The area in between this boundary line and the coastline represents the area at risk. However, within this risk area there are some places that may not inundate due to higher elevations or barriers. The estimated risk areas are 9548, 10 988 and 11 628 km^2, which correspond to Scenario I, Scenario II and Scenario III, respectively. An assessment was made to identify flood risk for an average climate condition by 2050 (i.e. Scenario V). It was estimated that 11 008 km^2 land would be under flood risk, a 15.3% increase compared with present risk area. Fig. 5 shows that the areas of coastal districts belong to risk area and HRZ. It is apparent that the surge wave intrudes the furthest into the Baleswar River, which is the largest river in terms of inlet opening and water depth. This study set the boundary of HRZ where there was a possibility of 1 m or more flooding. The area of the HRZ was computed as 5690 km^2, which is 1.26 times the currently demarcated HRZ. People should move to a nearby shelter from this area whenever a cyclone is warned as recommended in the national water management plan (WARPO, 2001).

The impacts of SLR were assessed in terms of surge intrusion length and flooding depth. As predicted, increased SST produces an increase in surge height at the coast if sea level remains unchanged. Increased surge, on the other hand, produces longer intrusion length and larger flooded area. However, any increase in sea level causes an increase in water depth, which in turn reduces surge amplification near the coast. The resultant effects of these two phenomena, however, always produces large flooding depths near the coast even though flooding area or intrusion length may reduce in some circumstances. Fig. 6 traces the maximum water surface elevation for 1.0 m SLR and no SLR that correspond to surge heights of 8.6 m (Scenario VIII) and 9.2 m (Scenario II), respectively. It can be seen that the combined effect of temperature rise and SLR produces larger flooding depth near the coast. However, surge height further inland is less for the SLR condition.

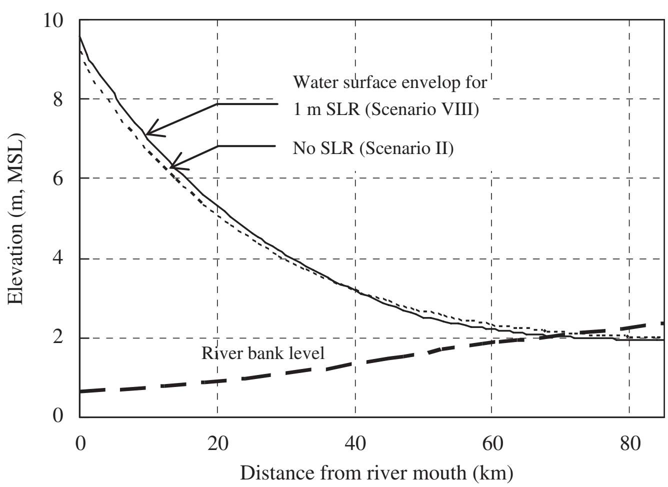

Fig. 6. Maximum water surface elevation along the Baleswar River due to concurrent increase in sea level and SST (Scenario II: corresponding to 2 °C temperature rise but no SLR, Scenario VIII: corresponding to 2 °C temperature rise and 1 m SLR).

Note that the coastline was assumed at the same location for both scenarios, whereas, in reality, the coastline may shift landwards if SLRs and this may lead to some changes in results.

5. Vulnerability assessment and preparedness

5.1. Population at risk

The people who live in the exposed coast are considered as vulnerable partly or fully to surge flooding. The administrative districts Satkhira, Khulna, Bagerhat, Barguna, Patuakhali, Jhalkhati, Pirojpur, Barisal and Bhola are located in the exposed coast (refer to Fig. 5). The land area of these administrative units is 25 504 km^2 (17% of area of Bangladesh) and it is the home of approx. 14 million people (10% of country's population), with an average population density of 541 km^2 (BBS, 2005). A brief scenario of population distributions in the coastal areas is presented in Fig. 7 in terms of population density. The density of coastal population is 78% of average population density of the country. In the western zone, population density is slightly less compared with the rest of the coastal zone. One of the reasons for this is the high vulnerability to surge flooding as well as some other problems such as salinity, water logging, etc. The population near the coast is even sparser than the inner parts as the lands are less productive. However, a significant number of transitory people come to the coastal areas during the fishing season from the inner parts of the country. We have therefore assumed the same population density throughout the exposed coast (i.e. 541 persons per sq. km). As predicted in the above analyses, the risk areas are 9548, 10 988 and 11 628 km^2, which correspond to Scenario I, Scenario II and Scenario III. If no population growth is considered, then the corresponding populations at risk are 5.2, 5.9 and 6.3 million based on the population density in 2005. In contrast, if we consider the present population growth of 1.4% (BBS, 2005) and if the climate remains unchanged, then 6.8 million people will be at risk in 2025 and 12.7 million people will be at risk in 2050. Based on the present growth rate, it was estimated that 11.1 million people would be at risk for an average climate condition by 2050 (Scenario V). The study identified 5690 km^2 of land as the HRZ for Scenario V. About 3.1 million

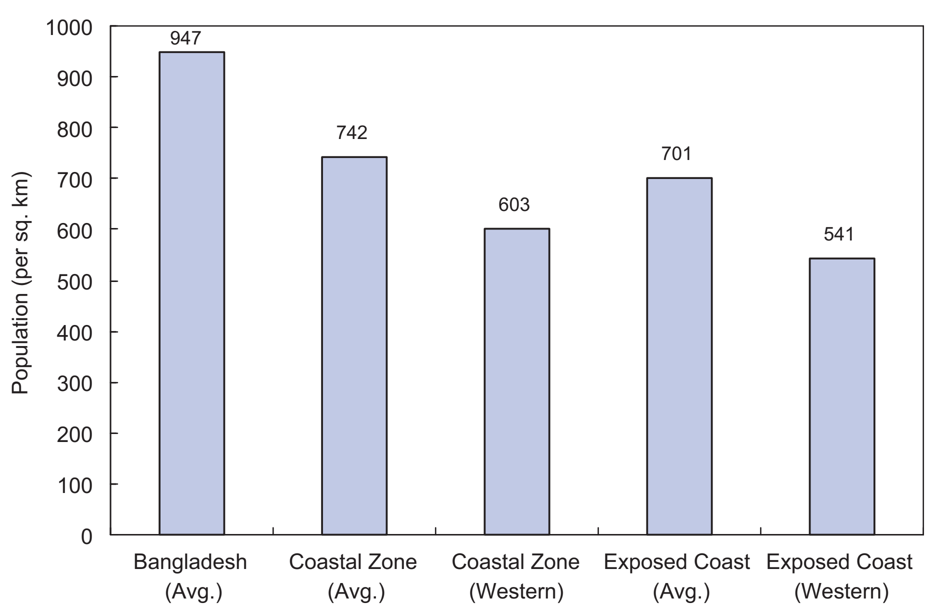

Fig. 7. Population density in the coastal regions of Bangladesh (BBS, 2005).

people are currently living in this area and the number will be 5.7 million by 2050, if we consider present population growth.

5.2. Preparedness measures

Since 1960 the government of Bangladesh (GoB), in association with international donor agencies and non-government organizations (NGOs), has initiated a number of activities to minimize the human casualties and damage to properties due to cyclonic surges. As a part of the adaptation measures, a large number of refugee shelters have been constructed to provide temporary shelter to the people living near the coast. Construction of embankments is another adaptation measures to protect coastal land from tidal flooding and to impede surge intrusion to the land. Even if storm surges overtop the embankments, the wave energy as well as surge height behind the embankments reduces to a considerable extent. The GoB, with community participation, is running a large afforestation project, the 'Coastal Greenbelt Project', to slow down surge waves and to stabilize coastal land. Among others, a large number of NGOs are working in the coastal zone to reduce the vulnerability and to increase the resilience of coastal community. One such example is the 'Reducing Vulnerability to Climate Change Project' of CIDA-CARE (CDP, 2004). Above all, a good cyclone forecasting and warning system is a precondition to save the lives of people living in the coastal areas. During a recent cyclone in 2007 and also in 1997 millions of people saved their life by taking shelter in nearby refugee shelters as they received timely warning. However, the forecasting and warning system needs further improvements and additional shelters are needed to accommodate all the people at risk. This paper focuses on these two items in details, while other adaptations measures are discussed in a separate paper.

5.2.1. Cyclone forecasting and warning system

Bangladesh suffered from forecast failures several times in the past. Up to 1997 there were plenty of forecast failures that caused huge casualties. For example, there was ample warning prior to the 1991 cyclone that a cyclone might strike, but few people were convinced of the severity of it until they saw the rising water level. Analysts of the cyclone later found that many false alarms were issued prior to that event which lowered the citizen's trust in the warning system (Haque, 1997). In recent years, with the technical assistance from the USA and Japan, the cyclone forecasting system in Bangladesh has been improved substantially and it has saved hundreds of thousands of lives during the cyclones of 1997 and 2007 with the dissemination of accurate and timely warnings. The development of an accurate and timely forecasting system has been ongoing for several years, but much more needs to be done to prepare for a future event.

Cyclone warning system in Bangladesh was started in 1966 by the Bangladesh Red Crescent Society (BRCS). After a devastating cyclone in 1970, the BRCS started the cyclone preparedness program (CPP) in 1972 to minimize the loss of lives and property by strengthening the capacity of coastal people in disaster management. The field level work of the CPP is based on 'UNITS', which typically encompasses a village of 2000–3000 people having land area of roughly 2 km^2. The flowchart of volunteer structure under CPP is shown in Fig. 8. The CPP teams presently work in all the coastal districts, but not all the risk-prone areas. The network of CPP is expanding with time, but there are still remote locations where CPP teams have yet to be formed (BRCS, 2005). Moreover, CPP teams have to be formed for the newly identified HRZ as well. Dissemination of cyclone warning in appropriate ways is another important aspect of cyclone disaster management. It is therefore important to improve the existing cyclone warning and dissemination system in all parts of the country. Initiative should be taken to evaluate the existing warning signals and to develop simplified, easily understandable signals and messages that are scientific and realistic. Efforts should be made to ensure that the warnings reach the entire population in the HRZ.

5.2.2. Cyclone shelter

An important and widely acceptable adaptation measures to cyclone disaster in Bangladesh is the construction of refuge shelters commonly known as 'cyclone shelters'. The shelters have

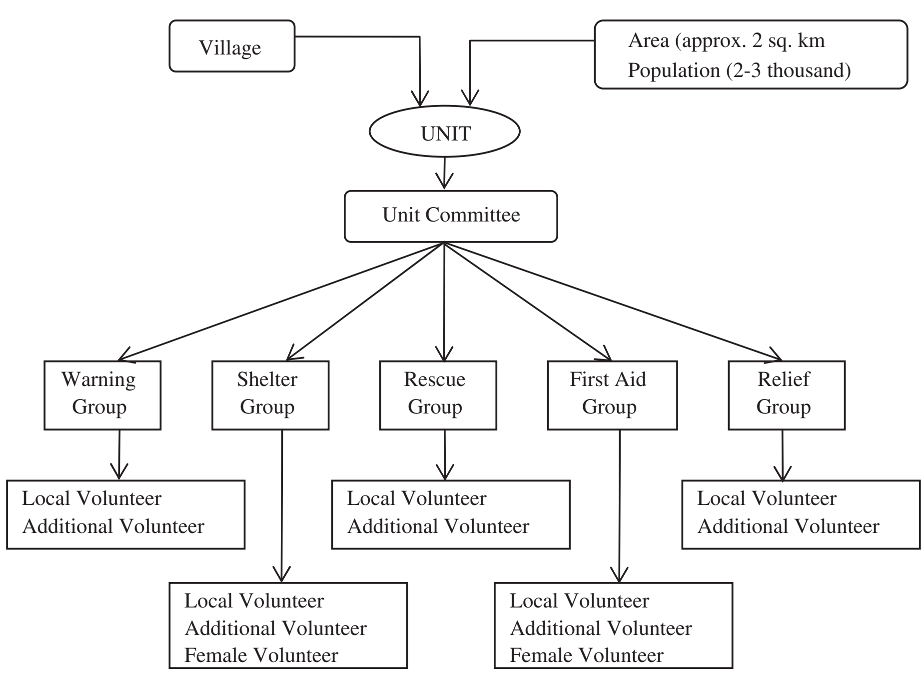

Fig. 8. Flowcharts of volunteer structure of CPP (Cyclone Preparedness Program) team. (There are 2760 units and 33 120 volunteers all over the coastal zones (Source: BRCS, 2005).)

Fig. 9. Typical view of two different types of existing cyclone-shelters in the western coastal zone.

been built since the 1960s, but major constructions were started after the historically worst cyclone of April 1991. In the past decade, Bangladesh has been able to improve its preparation for cyclones with the construction of refuge shelters and the development of cyclone warning and preparedness programs. Bangladesh suffered from very serious cyclones in 1970 and 1991, and in 1997 from a slightly less serious but relatively large cyclone. The shelters that had been built to provide temporary residence during cyclones reduced human loss to 126 in 1997, a dramatic drop on the casualty figures for cyclones of similar ferocity in previous years (Table 1). The recent cyclone of November 2007 was categorised as similar to the 1991 cyclone (second largest in the recorded history), but has taken far fewer lives than 1991s. However, additional shelters are necessary to accommodate the entire population in the risk area.

A cyclone shelter is a building type structure of 2–3 stories of which the first floor is kept transparent to the surge wave, as shown in Fig. 9. Each shelter can accommodate approximately 1000 people under cover and another 1000 people on the roof at most. At present, there are 2133 shelters that are distributed all along the coast (DOE, 2001). Location of a shelter was selected based on the degree of vulnerability and population density. There are 763 shelters in the western coastal zone that can accommodate approx. 1.5 million people (62% of present population in the HRZ). Another 460 shelters are required to accommodate all people in the HRZ. This study identified 1170 km^2 land would be additional to present HRZ by 2050. Consequently, 315 additional shelters are required to accommodate people in the newly identified HRZ if we consider no population growth. A total of 2870 shelters are required to accommodate entire people in the HRZ by 2050 if we consider the present population growth. The Water Resources Planning Organization (WARPO) of Bangladesh proposed another 775 cyclone shelters for 1.6 million people and 1369 raised earth mounds for livestock over the next 25 years (WARPO, 2001) (Fig. 9). An important issue is the estimation of appropriate shelter height so that they can be used safely under increased surge flooding due to global climate change. This study shows significant increase in flooding depth especially near the coast. Moreover, the area is experiencing local subsidence (Alam, 1996). Design heights, therefore, need to be revised to incorporate the effects of bigger surges, subsidence and SLR.

6. Conclusions

Using a hydrodynamic model we estimated storm surge flood risk area with particular reference to western coastal zone of Bangladesh. The study implemented the impacts of SST rise and SLR in terms of intensified surge heights at the coast. As predicted, flooded area, flooding depth and surge intrusion length are substantially larger under intensified surge conditions. Flooding depths, especially within 20 km from the coastline are 30–40% higher with respect to previously estimated depths. This is alarming, because at many locations flood water would inundate first floor of the existing cyclone shelters where people normally take shelter during a cyclonic event. Moreover, additional shelters are required to accommodate people in the newly identified HRZ. The results may have shortcomings as the time variations of surge height at the coast were assumed linear. A non-linear relationship between tide and surge could be further improved the present results. We considered an extreme condition of surge coincidence with high spring tide. This may lead an overestimate of flood risk areas. The outcomes of the present research would set a firm basis for policy and decision makers for future shelter planning and designing safe shelter heights.

Acknowledgements

This study was supported by the Japan Society for Promotion of Science (JSPS). The Institute of Water Modelling, Dhaka, Bangladesh, is gratefully acknowledged for supplying hydraulic and bathymetry data for this research. The authors wish to thank Prof. Jim Wallace of CSIRO and two anonymous reviewers for their valuable comments on an early version of this paper.

References

Abbott, M.B., Ionescu, F., 1967. On the numerical computation of nearly-horizontal flows. Journal of Hydraulic Research 5, 97–117.

Agrawala, S., Ota, T., Ahmed, A.U., Smith, J., Aalst, M.V., 2003. Development and Climate Change in Bangladesh: Focus on Coastal Flooding and the Sundarbans. OECD Publication COM/ENV/EPOC/DAC (2003)3/FINAL.

Ahmed, A.U., Alam, M., 1999. Development of climate change scenarios with general circulation models. In: Huq, S., Karim, Z., Asaduzzaman, M., Mahtab, F. (Eds.), Vulnerability and Adaptation to Climate Change for Bangladesh. Kluwer Academic Publishers, Dordrecht.

Alam, M., 1996. Subsidence of the Ganges–Brahmaputra delta of Bangladesh and associated drainage, sedimentation, and salinity problems. In: Milliman, J.D., Haq, B.U. (Eds.), Sea-Level Rise and Coastal Subsidence: Causes, Consequences, and Strategies. Kluwer Academic Publishers, Dordrecht.

Ali, A., 2000. Climate change impacts and adaptation assessment in Bangladesh. Climate Research 12 (2), 109–116.

Ali, A., Chowdhury, J.U., 1997. Tropical cyclone risk assessment with special reference to Bangladesh. MAUSAM (formerly Indian Journal of Meteorology Hydrology and Geophysics) 48, 305–322.

As-Salek, J.A., 1998. Coastal trapping and funnelling effects on storm surges in the Meghna estuary in relation to cyclone hitting Noakhali-Cox's Bazar coast of Bangladesh. Journal of Physical Oceanography 28 (2), 227–249.

Azam, M.H., Samad, M.A., Kabir, M., 2004. Effect of cyclone tract and landfall angle on the magnitude of storm surges along the coast of Bangladesh in the northern Bay of Bengal. Coastal Engineering Journal 46 (3), 269–290.
Barua, D.K., 1991. The coastline of Bangladesh-An overview of processes and forms. In: Proceedings of the Seventh Symposium on Coastal and Ocean Management, ASCE, Long Beach, CA 8-12.
BBS (Bangladesh Bureau of Statistics), 2005. Statistical Yearbook of Bangladesh. BBS, Dhaka, Bangladesh.
BRCS, 2005. Cyclone preparedness program at a glance. Bangladesh Red Crescent Society, Newsletter 3 (30).
BUET and BIDS, 1993. Multipurpose cyclone shelter program. Final Report, Planning Commission, Government of Bangladesh, Dhaka.
CDP (Coastal Development Partnership), 2004. Reducing vulnerability to climate change through awareness, action and advocacy. Coastal Newsletter, Issue 10, CDP, Khulna, Bangladesh.
Chowdhury, J.U., 1994. Determination of shelter height in storm surge flood risk area of Bangladesh coast. Water Resources Journal, ESCAP 182, 93–99.
Chowdhury, J.U., 2003. Flood management in the Ganges tidal plain. International Workshop on Natural Hazards in Coastal Areas, Japan, Paper D-1: 27-33.
Chowdhury, J.U., Karim, M.F., 1996. A risk-based zoning of storm surge prone area of the Ganges Tidal Plain. Journal of Civil Engineering, Institution of Engineering, Bangladesh 24 (2), 221–233.
CSPS (Cyclone Shelter Preparatory Study), 1998. Mathematical Modelling of Cyclone Surge and Related Flooding, Cyclone Risk Area Development Project, vol. I. Bangladesh Disaster Preparedness Center.
Das, P.K., 1972. A prediction model for storm surges in the Bay of Bengal. Nature 239, 211–213.
DOE, 1993. Assessment of the Vulnerability of Coastal Areas to Sea Level Rise and Other Effects of Global Climate Change, Pilot Study Bangladesh. Department of Environment, Government of Bangladesh.
DOE, 2001. Bangladesh: STATE of the Environment 2001. Department of Environment, Ministry of Environment and Forest, Government of Bangladesh.
Dube, S.K., Sinha, P.C., Roy, G.D., 1986. Numerical simulation of storm surges in Bangladesh using a bay-river coupled model. Coastal Engineering 10 (1), 85–101.
Emanuel, K.A., 2005. Increasing destructiveness of tropical cyclones over the past 30 years. Nature 436, 686–688.
Emanuel, K.A., 1987. The dependence of hurricane intensity. Nature 329, 483–485.
Flather, R.A., 1994. A storm surge prediction model for the Northern Bay of Bengal with application to the cyclone disaster in April 1991. Journal of Physical Oceanography 24, 172–190.
Haque, C.E., 1997. Atmospheric hazards preparedness in Bangladesh: a study of warning, adjustments and recovery from the April 1991 cyclone. Natural Hazards 16, 181–202.
IPCC, 2007. Climate Change 2007: Impact, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the IPCC. Cambridge University Press, UK, 976p.
Islam, M.R., 2004. Where Land Meets the Sea—A Profile of the Coastal Zone of Bangladesh. The University Press Ltd., Dhaka, Bangladesh.
IWM, 2005. Impact assessment of climate change on the coastal zone of Bangladesh. Final Report, Institute of Water Modelling, Dhaka, Bangladesh, 37p.
Karim, M.F., Mimura, N., Nobuoka, H., 2005. Management of storm surge flood risk in the coastal region of Bangladesh. In: Proceedings of the First International Conference on Coastal Zone Management and Engineering in the Middle East, Paper No. D-1: 1-7 (in CD ROM).
Madsen, H., Jakobsen, F., 2004. Cyclone induced storm surge and flood forecasting in the northern Bay of Bengal. Coastal Engineering 51 (4), 277–296.
McDowell, D.M., O'Connor, B.A., 1977. Hydraulic Behaviour of Estuaries. Wiley, New York, 292p.
McInnes, K.L., Hubbert, G.D., Abbs, D.J., Oliver, S.E., 2002. A numerical modelling study of coastal flooding. Meteorology and Atmospheric Physics 80, 217–233.
MCSP, 1992. Multipurpose Cyclone Shelter Program. Final Report, vol XI Special Studies, UNDP/World Bank/Govt of Bangladesh Project No. BGD/91/025.
Meehl, G.A., Stocker, T.F., Collins, W.D., Friedlingstein, P., Gaye, A.T., Gregory, J.M., Kitoh, A., Knutti, R., Murphy, J.M., Noda, A., Raper, S.C.B., Watterson, I.G., Weaver, A.J., Zhao, Z.C., 2007. Global climate projections. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.
Mirza, M.M.Q., Warrick, R.A., Ericksen, N.J., 2003. The implications of climate change on floods of the Ganges, Brahmaputra and Meghna Rivers in Bangladesh. Climatic Change 57 (3), 287–318.
Mitchell, J.F.B., Lowe, J., Wood, R.A., Vellinga, M., 2006. Extreme events due to human-induced climate change. Philos. Trans. R. Soc. London. A 364, 2117–2133.
MOEF, 2005. National adaptation program of action. Final Report, Ministry of Environment and Forest, Government of Bangladesh.
Mohal, N., Khan, Z.H., Rahman, N., 2007. Impact of sea level rise on coastal rivers of Bangladesh. In: Proceedings of the 10th International River Symposium and Environmental Flows Conference Brisbane, Australia (in press).
Murty, T.S., 1984. Storm surges-meteorological ocean tides. Canadian Bulletin of Fisheries and Aquatic Sciences 212, 876–897.
Murty, T.S., Henry, R.F., 1983. Tides in the Bay of Bengal. Journal of Geophysical Research 88 (C-10), 6069–6076.
Murty, T.S., Flather, R.A., Henry, R.F., 1986. The storm surge problem in the Bay of Bengal. Progress in Oceanography 16, 195–233.
SMRC, 1998. The Impact of Tropical Cyclones on the Coastal Regions of SAARC Countries and Influence in the Region. SAARC Meteorological Research Center, Dhaka SMRC-No. 1.
SMRC, 2003. The Vulnerability Assessment of the SAARC Coastal Region due to Sea Level Rise: Bangladesh Case. SAARC Meteorological Research Center, Dhaka SMRC-No. 3.
Sorensen, R.M., 1993. Basic Wave Mechanics: For Coastal and Ocean Engineering. A Wiley-Interscience Publication.
Saunders, M.A., Harris, A.R., 1997. Statistical evidence links exceptional 1995 Atlantic hurricane season to record sea warming. Geophysical Research Letter 24 (10), 1255–1258.
Unnikrishnan, A.S., Kumar, K.R., Fernandes, S.E., Michael, G.S., Patwardhan, S.K., 2006. Sea level changes along the Indian Coast: observation and projections. Current Science 90 (3), 362–368.
WARPO, 2001. National water management plan. Main Report, vol. 2, Water Resources Planning Organization, Ministry of Water Resources, Dhaka.
Warrick, R.A., Bhuiya, A.H., Mitchell, W.M., Murty, T.S., Rasheed, K.B.S., 1996. Sea-level changes in the Bay of Bengal. In: Warrick, R.A., Ahmad, Q.K. (Eds.), The Implications of Climate and Sea-level Change for Bangladesh. Kluwer Academic Publishers, Dordrecht.