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# Global warming and changes in the probability of occurrence of floods in Bangladesh and implications

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**Abstract**

Bangladesh is very prone to flooding due to its location at the confluence of the Ganges, Brahmaputra and Meghna (GBM) rivers and because of the hydro-meteorological and topographical characteristics of the basins in which it is situated. On average, annual floods inundate 20.5 per cent area of the country and this can reach as high as about 70 per cent during an extreme flood event. Floods cause serious damage to the economy of Bangladesh, a country with a low per capita income. Global warming caused by the enhanced greenhouse effect is likely to have significant effects on the hydrology and water resources of the GBM basins and might ultimately lead to more serious floods in Bangladesh. The use of climate change scenarios from four general circulation models as input into hydrological models demonstrates substantial increases in mean peak discharges in the GBM rivers. These changes may lead to changes in the occurrence of flooding with certain magnitude. Extreme flooding events will create a number of implications for agriculture, flood control and infrastructure in Bangladesh. 

*Keywords:* Bangladesh; Flood; Ganges; Brahmaputra and Meghna; Global warming; Probability of occurrence; Implications

## 1. Introduction

Bangladesh is located at the confluence of three large rivers the—Ganges, Brahmaputra and Meghna (Fig. 1). About 92.5 per cent of the combined basin area of the three rivers lies outside of the country. Furthermore, 80 per cent of the annual rainfall occurs in the monsoon (June–September) across the river basins. Therefore, Bangladesh is forced to drain out huge cross-border monsoon runoff together with its own runoff through a network of rivers. Most of the time, the volume of generated runoff exceeds the capacity of the drainage channels and this makes it one of the most flood-vulnerable countries in the world. Flooding in Bangladesh is highly dependent on the magnitude and pattern of precipitation in the three river basins. Results from general circulation models (GCMs) indicate that future warming, due to an enhanced greenhouse effect, may increase monsoon precipitation in South Asia. This may lead to increase in peak discharges of the major rivers and may eventually exacerbate the flooding problem in Bangladesh. Global warming may also effect the characteristics of floods in other ways. This article presents a sensitivity analysis of possible changes in the probability of occurrence of floods in Bangladesh and its implications, in terms of characteristics of floods and damage due to changes in precipitation, as projected by four GCMs. Section 2 discusses flood problems in Bangladesh, with particular focus on flood types, characteristics of peak discharge, flood duration and recession and flood damage. Section 3 discusses linkages between global warming and floods. Possible changes in occurrence of peak discharges are analysed in Section 4 and future likely implications are illustrated in Section 5.

## 2. Flood problem in Bangladesh

The extensive low-lying flat flood plain of the three principal rivers and their numerous tributaries and distributaries is the main physiographic feature of the country. About 60 per cent of the country is lower than 6 m above the sea level, with an average river gradient of 6 cm/km in the delta (USAID, 1988; GOB, 1992). As a result of the flat topography of the floodplain about 20.5

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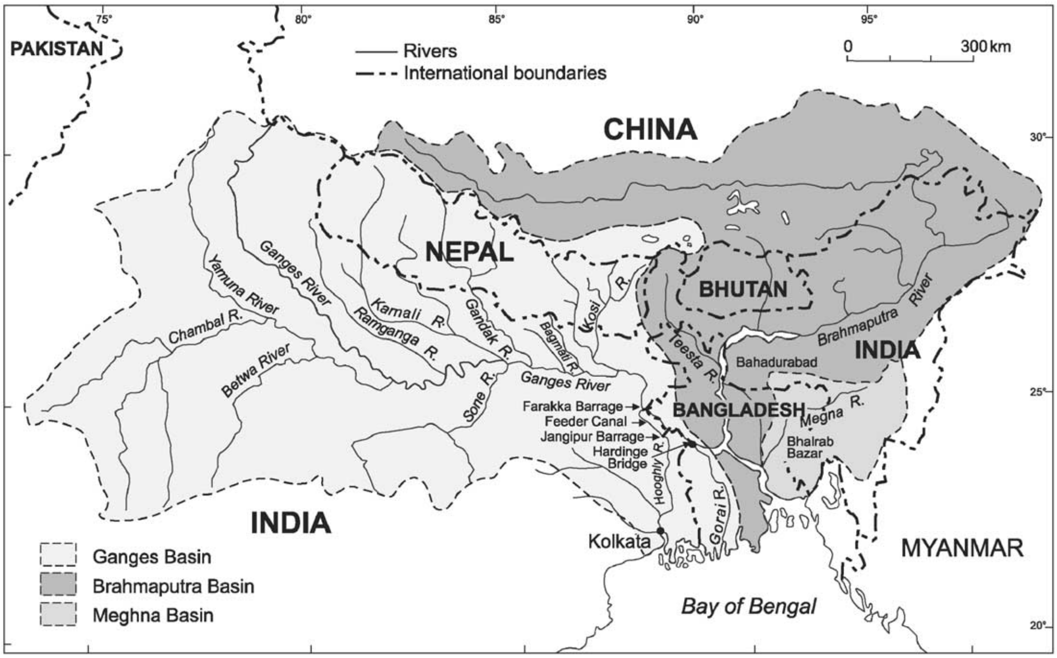


Fig. 1. The Ganges, Brahmaputra and Meghna basins.

per cent of Bangladesh (3.03 million ha) is flooded annually by many types of floods (Mirza et al., 2002; Chowdhury et al., 1996). In extreme cases, floods may inundate about 70 per cent of the country (Fig. 2) as occurred in 1998. The area flooded in Bangladesh during the period 1954–1999 is presented in Fig. 3. It shows that more area inundated in Bangladesh during the period 1980–1999 than that of the period 1960–1980. The former period was characterised by two catastrophic and one exceptional floods. Estimates of flood damage were also high in recent decades due to depth and duration of flooding.

### 2.1. Flood types

Bangladesh generally experiences four main types of floods: flash floods, riverine floods, rain floods and storm-surge floods. *Flash floods* occur in the eastern and northern rivers, along the borders of Bangladesh. They are characterised by a sharp rise in water level and high water flow velocity, a result from exceptionally heavy precipitation occurring over neighbouring hills and mountains in India. *Riverine floods* from the spilling of major rivers and their tributaries and distributaries generally rise and fall slowly over 10–20 days or more and can cause extensive damage to property and the loss of life. Depth and extent of floods and associated damage are extensive when the major rivers reach their peaks simultaneously. *Rain floods* are caused by high-intensity local rainfall of long duration in the monsoon.

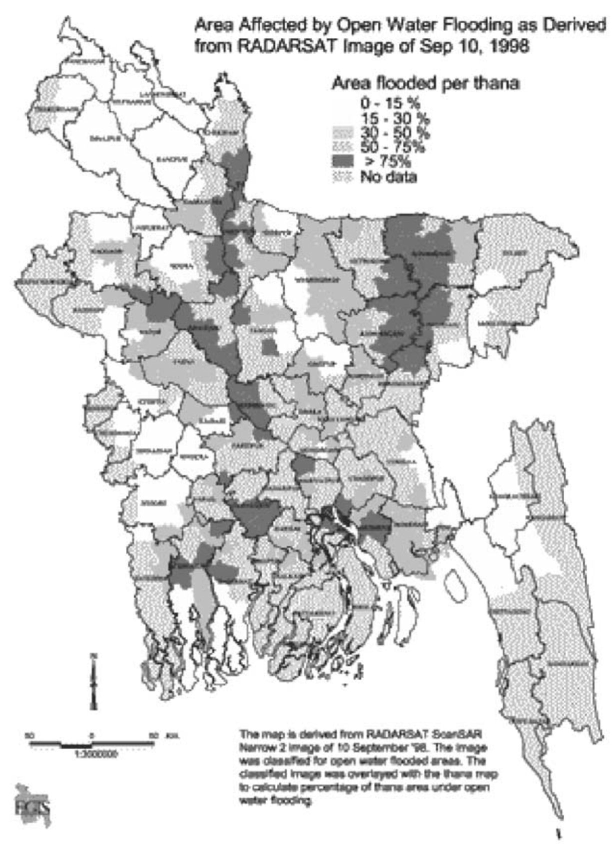


Fig. 2. The 1998 flood in Bangladesh, which inundated more than two-thirds of the country. Source: Environment and Geographic Information Systems (EGIS, 1998).

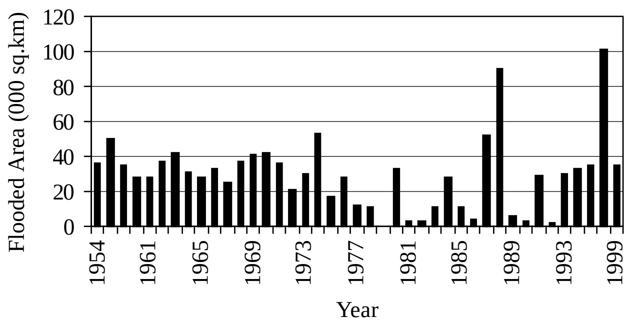


Fig. 3. Flooded area in Bangladesh during 1954–1998.

From year to year, the extent and depth of rain water flooding varies with the monsoon, depending on the amount and intensity of local precipitation and current water levels in the major rivers that control drainage from the land. *Storm surge floods* occur in the coastal area of Bangladesh, which consists of large estuaries, extensive tidal flats, and low-lying islands. Storm surges generated by tropical cyclones cause widespread damage to property and the loss of life in coastal area. Floods in Bangladesh have also been classified based on the extent of inundation, respective return periods and level of physical damage (MPO, 1987; FEC, 1989; Mirza, 1997) (Table 1).

Table 1
Flood classifications (in terms of area inundated, chances of occurrence and physical damage) in Bangladesh

| Types of floods | Parameters | | | |
|---|---|---|---|---|
| | Range of flooded area (sq. km) | Range of per cent inundation | Probability of occurrence* | Physical parameters affected |
| Normal flood | 31,000 | 21 | 0.5 | Hampers normal human activities<br>Cropping pattern is adjusted with inundation<br>May increase soil fertility<br>Economic loss is minimum |
| Moderate flood | 31,000–38,000 | 21–26 | 0.3 | Hampers human activity moderately<br>Damage limited to crops<br>Economic loss is moderate<br>Evacuation not necessary. People take their own measures |
| Severe flood | 38,000–50,000 | 26–34 | 0.10 | Hampers human activities severely<br>Damage is mainly to crops, infrastructure (roads, railways, power, telecommunications, etc.) and certain urban centres<br>Economic loss is higher<br>Requires evacuation<br>Requires relief operation |
| Catastrophic flood | 50,000–57,000 | 34–38.5 | 0.05 | Hampers human activities very severely<br>Extensive damage to crops of all types of lands, cultured fisheries, lives and property in both urban and rural centres, all types of infrastructure, etc.<br>Requires extensive relief operation<br>Very high economic loss<br>Requires international support |
| Exceptional flood | > 57,000 | > 38.5 | 0.05 | Hampers human activities exceptionally<br>Extensive damage to crops of all types of lands, cultured fisheries, lives and property in both urban and rural centres, all types of infrastructure, etc.<br>Requires extensive relief operation<br>Disrupts communication<br>Closing of educational institutions<br>Exceptional economic loss<br>Usually requires international support |

*Probability of occurrence was calculated based on area flooded during 1954–1999.

### 2.2. Characteristics of peak discharge

The characteristics of peak discharges of the Ganges, Brahmaputra and Meghna rivers are unique in terms of magnitude and timing of occurrence. Precipitation patterns of the river basins highly influence their characteristics. For example, although the basin area of the Brahmaputra River is about half of that of the Ganges River, mean annual peak discharge of the former is considerably higher than the latter (Table 2). Note that the Brahmaputra River drains a high-precipitation area in South Asia. The coefficient of variation (CV) of peak discharge of the Ganges is higher than that of the other two major rivers that demonstrates a slightly higher uncertainty in precipitation regime. On the other hand, the CV of peak discharge of the Brahmaputra and Meghna rivers indicates similar precipitation pattern in their basin areas.

Discharge of the Brahmaputra River starts rising in March due to snow melt in the Himalayas while the Ganges discharge begins to rise in early June with the onset of the monsoon (Fig. 4). Monsoon rainfall occurs in the Brahmaputra and Meghna basins earlier than the Ganges basin due to the pattern of progression of the monsoon air mass. The former two river basins also experience high rainfall due to their orographic features (Mirza, 1997). The flood peaks of the Brahmaputra River occur in July and August, while the peaks in the Ganges occur in August and September (Fig. 4). Analysis shows that peak discharge in the Ganges River occurred 45 per cent of the time in August and that for the Brahmaputra River 35 per cent of the time. This indicates a real likelihood of simultaneous floods in the Ganges and Brahmaputra rivers should be fairly common. Distribution of timing of peak discharges of these two rivers shows that one group (0–10 days) occurred 22 per cent of the time over a 28-year period (Mirza, 1997). In 1998, the peak discharges in the Brahmaputra and Ganges occurred only 2 days apart. As a result, the entire central region of Bangladesh near the confluence point of the two rivers suffered an unprecedented flood. A similar simultaneous occurrence of peak flows of the two rivers also occurred in 1988 that also caused a devastating flood.

Table 2
Characteristics of peak discharge ($m^3/s$) of the major rivers in Bangladesh

| River/station | Basin area (million ha) | Annual peak discharge | | |
|---|---|---|---|---|
| | | Mean | CV | Observed maximum |
| Ganges (Hardinge Bridge) | 109.50 | 54,000 | 0.19 | 80,230 |
| Brahmaputra (Bahaduarabad) | 57.90 | 67,000 | 0.17 | 98,600 |
| Meghna (Bhairab Bazar) | 8.02 | 14,000 | 0.17 | 19,900 |

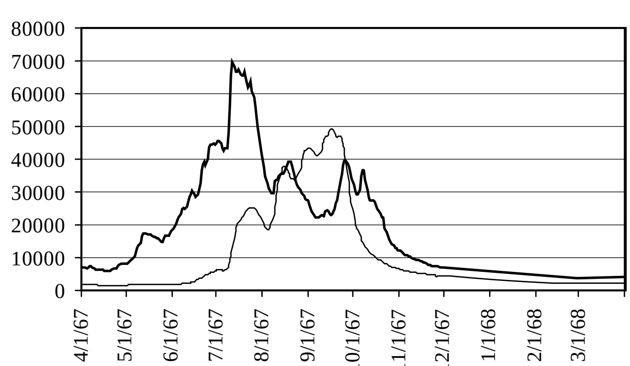


Fig. 4. Hydrographs of the Ganges (lighter solid line) and Brahmaputra (thicker solid line) rivers for the typical water year 1967–68. The values are in $m^3/s$. Data source: Bangladesh Water Development Board (BWDB).

### 2.3. Flood duration and recession

Duration and recession of a flooding in Bangladesh depend on many factors. They include: inflow of water from the upstream areas, rainfall in basin areas within Bangladesh, tidal activity, simultaneous occurrence of flood peaks in the major rivers and their propagation to the confluence, etc. In 1998, flood peaks stayed for a record 66 and 68 days above the danger levels in the Brahmaputra and Meghna rivers, respectively. Water levels in the Ganges River remained above the danger level for 27 days. In 1988, the duration of floods above the danger levels for the Brahmaputra and Meghna rivers was 27 and 68 days, respectively. In the Ganges River, water levels stayed above danger level for 23 days (BWDB, 2000). Although the magnitudes of peak discharges of the major rivers were almost equal in 1998 and 1988, longer duration of floods in 1998 was attributed to drainage congestion around the confluence of the Ganges and Brahmaputra rivers caused by high tidal activity and subsequent backwater effect (Ahmed and Mirza, 2000).

### 2.4. Flood damage

The 1987 flood completely or partially damaged 2.06 million houses (or 16.67 per cent of the total national housing). The 1988 flood had displaced and affected an estimated 45 million people and destroyed or partially damaged 12.8 million houses. The 1998 flood affected about 31 million people in 52 out of the 64 districts in Bangladesh. An estimated 2.4 million houses were completely or partially destroyed. Estimated damage

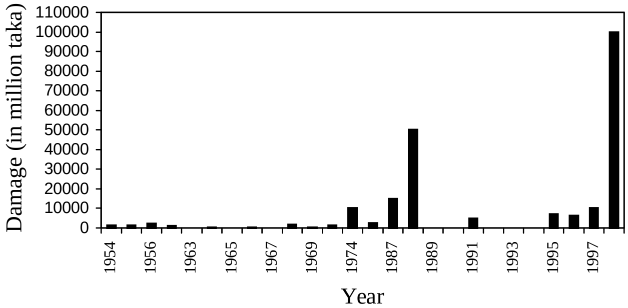


Fig. 5. Estimated flood damage in Bangladesh during 1954–1998.

caused by floods during 1954–1998 is shown in Fig. 5. Among these, the 1998 flood damage was the worst in history, totaling in the range of US$ 2–2.8 billion (ADRC, 2000; GOB, 1998). During the period 1954–1999, floods killed 11,571 people in Bangladesh, of which 7109 people were killed during the floods of 1987, 1987 and 1988 (Mirza et al., 2002).

In Bangladesh, agricultural crop and dwellings each account for roughly 30 per cent of the total flood related damage (FEC, 1989). Damage to infrastructure, such as roads, railways, and water works accounts for the remaining 40 per cent. Besides the impact on physical infrastructure, the damage to socio-economic activities is also significant. Floods cause a devastating effect on large segments of the population especially those are poor. Victims are temporarily deprived of their main income and/or forced to sell their assets or take loans to rebuild their houses (Islam, 2000).

## 3. Global warming and floods in Bangladesh

Over the last 100 years, global mean surface temperature (the average of near surface air temperature over land, and sea surface temperature) has increased by 0.4–0.8°C. This value is 0.15°C larger than that estimated by the Second Assessment Report (SAR) of the Intergovernmental Panel on Climate Change (IPCC) for the period up to 1994. The additional increase in temperature is because of the relatively high observed temperature during 1995–2000 and application of improved methods for processing the data (IPCC WG I, 2001). Analysis of *mean annual* temperature over India during the period 1901–1982 indicates about 0.4°C warming (Kothyari and Singh, 1996). The warming is found to be more pronounced on the west coast, the interior peninsula and the north central (Ganges basin) and northeast regions (Brahmaputra and Meghna basins). Pant and Kumar (1997) analysed a slightly longer time-series (1881–1997) data for temperature for India and found a significant warming of 0.57°C. In the Bangladesh region, from the latter part of the last century, there has been, on average, an overall warming

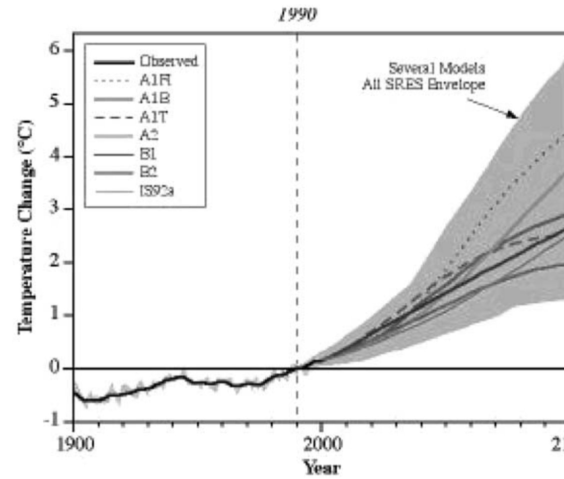


Fig. 6. Observed and projected global climate.

of about 0.5°C, comparable in magnitude to the observed global mean warming (Warrick and Ahmad, 1996).

Mirza et al. (1998) analysed long-term annual precipitation records of meteorological sub-divisions of the Ganges, Brahmaputra and Meghna river basins and found no general significant change, with slight exceptions in a few meteorological sub-divisions. No distinct long-term trends were noticed in precipitation records at the 78 stations distributed across Nepal (Shrestha et al., 2000). However, Rackhecha and Soman (1994) found a more than 10 per cent increase in 1–3 day extreme precipitation over a small area in the Brahmaputra basin in India. Thus, in the last 100 years, broadly speaking, there has been no discernible increasing or decreasing trend in annual precipitation in the greater Himalayan region (McLean et al., 1998; Lal and Aggarwal, 2001).

Over the period 1990–2100, the global average surface temperature is projected to increase by 1.4–5.8°C (Fig. 6). These results are for the full range of 35 SRES scenarios, based on a number of climate models (IPCC WGI, 2001). Similarly, based on global model simulations and for a wide range of scenarios, global average water vapour concentration and precipitation are projected to also increase during the 21st century (IPCC WGI, 2001). Most of the GCMs are in general agreement about increases in precipitation over the region of South Asia. Lal and Aggarwal (2001) simulated daily rainfall in the CCSR/NIES A-O GCM corresponding to the year 2050. The analysis suggests an intensification of the monsoon rainfall over central India and an enhancement in the summer monsoon precipitation variability in each of the four SRES marker emission scenarios. Recent studies (Kitoh et al., 1997; Lal and Harasawa, 2001) confirm an increase in the inter-annual variability of daily precipitation in the Asian summer monsoon with increased greenhouse gas concentrations in other A-O GCMs as well. An

Table 3
Changes in precipitation under various warming scenarios and corresponding mean peak discharge

| GCM | $\Delta T$ (°C) | Ganges $\Delta P$ (%) | Ganges Mean peak discharge ($m^3$/s) | Brahmaputra $\Delta P$ (%) | Brahmaputra Mean peak discharge ($m^3$/s) | Meghna $\Delta P$ (%) | Meghna Mean peak discharge ($m^3$/s) |
|---|---|---|---|---|---|---|---|
| CSIRO9 | 2 | 8.5 | 57790 | −0.5 | 64853 | 4.5 | 15171 |
| | 4 | 17.0 | 62900 | −1.0 | 64840 | 9.0 | 16267 |
| | 6 | 25.5 | 68010 | −1.5 | 64827 | 13.5 | 17378 |
| HadCM2 | 2 | −2.8 | 50963 | 7.2 | 70308 | 9.7 | 16017 |
| | 4 | −5.6 | 49240 | 14.4 | 75757 | 19.4 | 17971 |
| | 6 | −8.4 | 47523 | 21.6 | 81199 | 29.1 | 19927 |
| GFDL | 2 | 4.6 | 55419 | 7.2 | 67487 | 11.3 | 16844 |
| | 4 | 9.2 | 58159 | 14.4 | 70107 | 22.6 | 19614 |
| | 6 | 13.8 | 60898 | 21.6 | 72728 | 33.9 | 22412 |
| LLNL | 2 | 0.5 | 52996 | 1.4 | 65385 | 7.7 | 15958 |
| | 4 | 1.0 | 53312 | 2.8 | 65904 | 15.4 | 17842 |
| | 6 | 1.5 | 53628 | 4.2 | 66423 | 23.1 | 19740 |

examination of the frequency distribution of daily monsoon rainfall over India in the model-simulated data suggests that the intensity of extreme rainfall events is likely to be higher in future, a consequence of increased convective activity during the summer (Lal and Aggarwal, 2001).

As floods in Bangladesh are caused by intense monsoon precipitation over the basin areas of the Ganges, Brahmaputra and Meghna rivers, future changes in precipitation regime have four distinct implications. *First*, the timing of occurrence of floods may change, with a possible change in the seasonality of the hydrological cycle. This implies that onset and withdrawal of monsoons may be delayed or advanced. Presently, monsoons break in the middle of June and withdraw by the middle of September. A 1-month delay in the monsoons means it will not end until the middle of October, but the duration will remain unchanged. *Second*, an increase in monsoon precipitation in the Ganges, Brahmaputra and Meghna basins may increase the magnitude, frequency, depth, extent and duration of floods. *Third*, timing of peaking in the major rivers may also change that may change the likelihood of synchronisation of flood peaks of the major rivers. *Fourth*, increased magnitude, depth and duration of floods will bring a dramatic change in land-use patterns in Bangladesh. Mirza (1997) analysed the implications of global warming on magnitude, frequency, depth and extent of flooding in Bangladesh with the aid of empirical models and the MIKE11-GIS simulation model.[1] For this purpose, standardised precipitation change scenarios for per degree global warming from the CSIRO9, UKTR, GFDL and LLNL GCMs were derived by determining the difference of changes ($2 \times CO_2 - 1 \times CO_2$) and then dividing by the overall climate sensitivity of each GCM (Hulme, 1994). The precipitation scenario was scaled for various magnitudes of temperature change. These scenarios were then used in a series of empirical models developed between annual precipitation and annual mean discharge and annual mean and peak discharge for the three rivers to determine changes in mean peak discharge (Table 3). The present analysis has included scenarios from the HadCM2 model by replacing the UKTR model, as it is now considered to be out of date. Overall, the analysis demonstrates significant changes in the mean annual peak discharges of the Ganges, Brahmaputra and Meghna rivers for various warming scenarios.

## 4. Changes in occurrence of floods

Changes in the magnitude of a mean annual flood imply that the return period or probability of occurrence of extreme floods will also change. For the present analysis, possible future changes in the magnitudes and return periods of such events, as a consequence of climate change are examined, assuming that the coefficient of variation of future floods remains unchanged. The standard deviations of the peak discharge values for the three rivers were altered by the proportion of change projected to occur in the respective mean peak discharge under climate change scenarios. For the present analysis, a 20-year flood was selected for the Ganges, Brahmaputra and Meghna rivers at their

[1] An interface of the MIKE11 model developed by the Danish Hydraulic Institute (DHI) with GIS. The model is maintained by the Surface Water Modelling Centre (SWMC), Dhaka, Bangladesh.

respective discharge measurement stations, Hardinge Bridge, Bahadurabad and Bhairab Bazar.[2]

For flood frequency analyses, the Gumbel Type I distribution (EV1) has been recommended for the major rivers in Bangladesh (GOB, 1992). Accordingly, the EV1 distribution was applied for estimating the current and future 20-year return period peak discharge for the Ganges, Brahmaputra and Meghna rivers. The EV1 probability distribution function is

$$F(x) = \exp\left[-\exp\left(-\frac{x-u}{\alpha}\right)\right] - \infty \leqslant x \leqslant \infty, \tag{1}$$

where $F(x)$ is the probability of an annual maximum $Q \leqslant x$ and $\alpha$ and $u$ are location parameter and scale parameters, respectively. After defining $s$ as standard deviation and $\bar{x}$ as mean, the expressions for $\alpha$ and $u$ are as follows:

$$\alpha = \frac{\sqrt{6}s}{\pi}, \tag{2}$$

$$u = \bar{x} - 0.5772\alpha \tag{3}$$

with a finite sample, the mean and standard deviation can be estimated from the moments of the data sample. A probability model now can be obtained by substituting the value of $\alpha$ and $u$ in Eq. (1).

Annual peak discharge data for the period 1965–1992 were used to determine the mean and standard deviation. The computed 20-year floods for the Ganges, Brahmaputra and Meghna rivers are 67,984, 86,687 and 18,996 $m^3/s$, respectively. The computed mean peak discharge values for the three rivers under the various climate change scenarios were then used to determine the changes in the probability of occurrence of the magnitude of the 20-year flood. The results of the analysis are shown in Table 4 and in Figs. 7–9.

### 4.1. The Ganges River

The Ganges is the driest basin of the three large river basins. While the CSIRO9, GFDL and LLNL GCMs project an increase in mean precipitation in the basin, the HadCM2 model indicates a slight decrease in precipitation, under all warming scenarios. Overall, the scenarios demonstrate comparatively smaller increases in precipitation in this area, compared to the Brahmaputra and Meghna river basins. Scenarios from the CSRIO9 model indicate the largest possible increases in peak discharge of the Ganges River. Therefore, changes in the probability of exceedence of the 20-year floods for this GCM are expected to be highest among all GCMs. For example, it can be seen from Table 4 that, for a 2°C

[2] Floods of higher return periods exceeded the range of the data used for the development of the mean-peak discharge empirical models. Therefore, they were not considered for spatial flood coverage and depth of inundation. The 20-year floods have often been used as the basis for water resource planning in Bangladesh (MPO, 1987).

Table 4
Changes in the probability of exceedence of a current 20-year flood for the Ganges, Brahmaputra and Meghna rivers under the climate change scenarios

| GCM | $\Delta T$ (°C) | Ganges | | Brahmaputra | | Meghna | |
|---|---|---|---|---|---|---|---|
| | | $T$ | $p$ | $T$ | $p$ | $T$ | $p$ |
| CSIRO9 | 2 | 9.2 | 0.11 | 19.9 | 0.050 | 11.86 | 0.08 |
| | 4 | 4.5 | 0.22 | 19.94 | 0.050 | 7.16 | 0.14 |
| | 6 | <2.33 | >0.42 | 19.97 | 0.050 | 4.41 | 0.23 |
| HadCM2 | 2 | 28.2 | 0.035 | 9.8 | 0.10 | 6.82 | 0.15 |
| | 4 | 41.2 | 0.024 | 5.5 | 0.18 | 3.15 | 0.31 |
| | 6 | 61.8 | 0.016 | 3.4 | 0.29 | 1.85 | 0.53 |
| GFDL | 2 | 13.1 | 0.08 | 15.05 | 0.07 | 5.56 | 0.18 |
| | 4 | 8.7 | 0.11 | 11.41 | 0.09 | <2.33 | >0.42 |
| | 6 | 5.8 | 0.17 | 8.69 | 0.12 | <2.33 | >0.42 |
| LLNL | 2 | 19.0 | 0.052 | 18.80 | 0.053 | 8.25 | 0.12 |
| | 4 | 18.1 | 0.055 | 17.83 | 0.056 | 3.63 | 0.28 |
| | 6 | 17.3 | 0.057 | 16.87 | 0.059 | <2.33 | >0.42 |

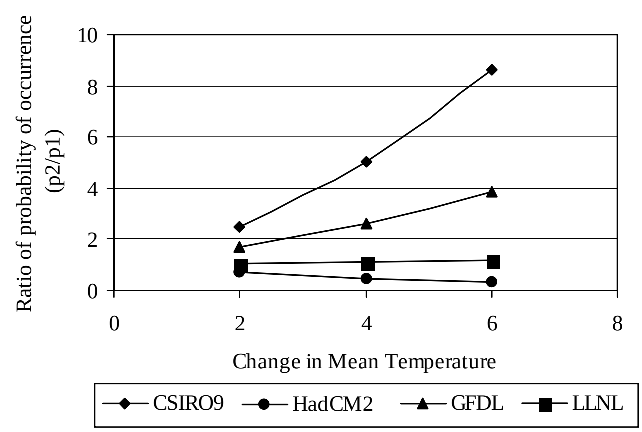


Fig. 7. Ratio of the future and present probability ($P_2/P_1$) of the magnitude of the 20-year flood for the Ganges River.

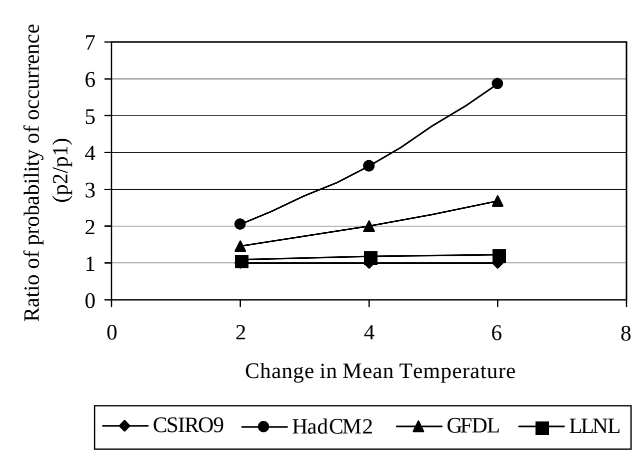


Fig. 8. Ratio of the future and present probability ($P_2/P_1$) of the magnitude of the current 20-year flood for the Brahmaputra River.

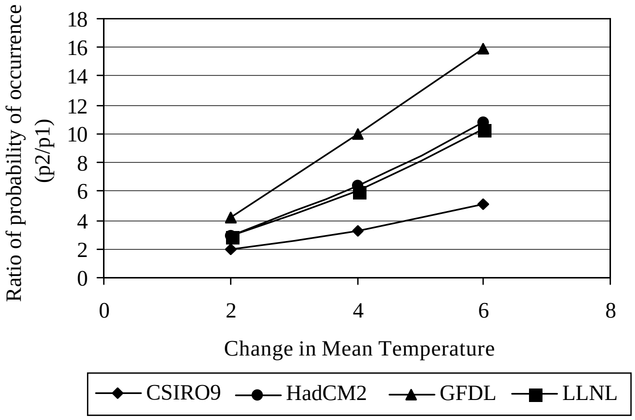


Fig. 9. Ratio of the future and present probability ($P_2/P_1$) of the magnitude of the 20-year flood for the Meghna River.

global temperature rise, the probability of exceedence of a current 20-year flood may change from $p = 0.05$ to 0.12, under the CSIRO9 scenario. In other words, a particular magnitude of the flood would be about 2.5 times more likely to occur than at present ($P_2/P_1$, as shown in Fig. 7). The HadCM2 model indicates the least change in the exceedence probabilities of the current 20-year flood.

With increases in precipitation, the future mean flood volume eventually equals the current 20-year flood volume. This occurs when $P_2/P_1 = 8.2$. With the CSRIO9 model, the magnitude of future mean flood exceeds the current 20-year flood at about a 6°C rise in global mean temperature.

### 4.2. The Brahmaputra River

The Brahmaputra basin is wetter than the Ganges but drier than the Meghna basin. The HadCM2, GFDL and LLNL models are in agreement about increases in precipitation in the basin. On the other hand, the CSIRO9 model shows a very slight decrease in precipitation. The GFDL model project the highest increase in precipitation and the LLNL the lowest.

The highest change in the probability of a current 20-year flood for the Brahmaputra River is associated with the GFDL model, followed by the HadCM2 model. For the scenarios associated with the CSIRO9, no change in probability of exceedence is expected. However, the relative changes in exceedence probabilities are smaller than those for the Ganges and the Meghna Rivers (as indicated by the ratio of $P_2/P_1$ (Fig. 8).

### 4.3. The Meghna River

The Meghna is the wettest river basin among the three. Mean annual precipitation is 3.5 times higher than the Ganges and about 1.5 times higher than the Brahmaputra. All four GCMs project substantial increases in precipitation. The HadCM2 model shows the highest increase in precipitation while the CSIRO9 the lowest.

For the Meghna basin, the changes in probability of exceedence implied by the HadCM2 and LLNL model results are similar and are very large. Thus, with a 6°C warming, the chance of the current 20-year flood magnitude occurring or being exceeded in any given year increase by a factor of 10 (Fig. 9). Thus, for both these GCMs (HadCM2 and LLNL), the future mean flood may exceed the current 20-year flood at a 6°C rise in temperature (Table 4 and Fig. 9). On the other hand, for the GFDL model, this situation may be expected with only a 4°C increase in temperature. The CSIRO9 model predicts the smallest changes in the probability of exceedence.

## 5. Future implications

Possible changes in mean flood discharge of the Ganges, Brahmaputra and Meghna rivers in Bangladesh may generate significant implications in terms of hydrological characteristics and economic and physical damage to the area. The general hydrological characteristics of Bangladesh floods are discussed in Section 2 and may be substantially changed. *First*, possible changes in mean and standard deviation may introduce a shift in the distribution of floods. Thus, variability may also change and a large uncertainty may be expected. *Second*, the magnitude of a flood volume for any return period may also change. As a result, the likelihood of occurrence of a flood of any return period will also change. *Third*, if the magnitude of a mean flood will increase, duration of a flooding will also increase subject to no change in drainage capacity of the major rivers and other estuarine factors that might influence the pattern of drainage. Any increase in mean flooding may also cause substantial damage to agriculture, housing and settlements and infrastructure.

### 5.1. Monsoon, floods and crop damage

Agriculture is the one of the most important sectors of the economy of Bangladesh. Although the share of agriculture in total GDP has declined over the last three decades (from about 47 per cent during the seventies to about 40 per cent during the eighties and further to 30 per cent in the late 1990s), the economy still remains essentially agrarian in nature, with the agriculture sector employing more than 70 per cent of the rural labour force. Within agriculture, crops predominate, with a share of more than 75 per cent of value added in the sector. Within the crop sector, food grain (rice and wheat) claims about 80 per cent share of total acreage and 75 per cent share in total gross value production

(Sahabuddin, 2000). The remaining 25 per cent contribution comes from fishery, forestry and livestock subsectors. Due to limited arable land resources and high demand for food for a fast growing population, agriculture will continue to be a highly important sector for Bangladesh in the future.

In Bangladesh, there are two main cropping seasons (*kharif* and *rabi*) and three-growing seasons (aus, aman, boro). The kharif season coincides with the rainy season and the rabi season with the dry season. Both seasons can be divided into two parts: Kharif-I includes the pre-monsoon season and most of the monsoon while kharif-II includes the later part of the monsoon and post-monsoon time. The rabi season includes the cool winter period when dry season crops (such as wheat) are grown, and a second part, which includes the hot pre-monsoon, during which *boro* paddy is grown (Fig. 10).

Rice is highly dependent on the onset, retreat and magnitude of monsoon precipitation (Brammer et al., 1996) and land classes (Table 5). Seed bed preparation, plantation and growth of Aman rice crop in Kharif-II season is dependent on the timely arrival of monsoons, normal rainfall and non-occurrence of high floods. Broadcast rice varieties in the lowland areas can sustain normal floods but may suffer damage if the rate of rise of flood water is $>4$–$5\,cm/day$. High-yielding aman rice varieties are very susceptible to floods as they are unable to keep up with the pace of growth with increasing depth of flood water. Fig. 10 demonstrates that preparation of seed bed in medium to medium high lands in the Brahmaputra basin coincides with the occurrence of first peak discharge in July. Sowing of aman crop in the basin may be hampered by the arrival of a possible second peak in August–September. The flood peak in

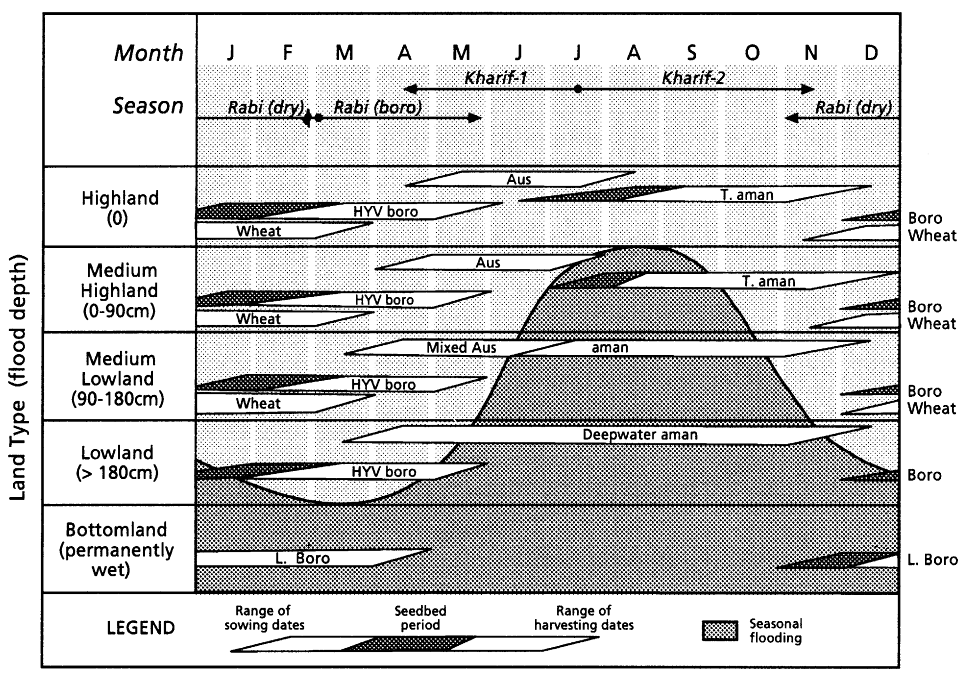


Fig. 10. Crop calendar in relation to monsoon flooding.

Table 5
Various land classes in Bangladesh and crop suitability

| Land type | Range of inundation depth | Crop suitability |
|---|---|---|
| Highland ($F_0$) | $<30\,cm$ (flood free) | Land suited to HYV Transplanted *aman* in monsoon, wheat and HYV boro in *rabi* season |
| Medium highland ($F_1$) | 30–90 cm (shallow flooded) | Land suited to local varieties of aus and Transplanted aman in monsoon; wheat and HYV boro in *rabi* season |
| Medium lowland ($F_2$) | 90–180 cm (moderately flooded) | Land suited to Broadcast *aman* in monsoon; wheat and HYV *boro* in *rabi* season |
| Lowland ($F_3$) | $>180\,cm$(deeply flooded) | Land suited to Broadcast *aman* in monsoon; HYV *boro* in *rabi* season |

Source: MPO (1986).

the Ganges basin in August–September may affect sowing of the aman crop. Floods are also detrimental to monsoon vegetables for the reason that most vegetables are unable to cope with flooded conditions.

Supply of moisture by monsoon rain to medium highlands and highlands helps in the cultivation of winter vegetables and *rabi* crops. However, in a high flood year, delayed drainage of flood water may delay planting and may result in a reduction in production. On the other hand, Bangladesh usually receives a good harvest of *boro* crop preceded by a high flood in the previous year, due to a good supply of moisture and the growth of blue–green algae (Chowdhury et al., 1996).

Floods in Bangladesh cause damage to crops in different proportions. On average, yearly crop damage could be about 0.5 million tons (Paul and Rasid, 1993). However, during an exceptional flood such as that of the magnitude observed in 1998, crop damage was estimated in the range of 2.2–3.5 million tons (GOB, 1998; Ahmed, 2001). During the floods of 1987 and 1988, crop damage was estimated at 1.32 and 2.10 million tons, respectively. High crop damage caused by the floods in 1998 was due to the long duration of floods above the danger levels.

The shortfall of crop production due to floods has many implications. In 1998, the direct impact was estimated to be 5.5 per cent of national agricultural GDP and roughly 1.5 per cent of the total GDP of Bangladesh. Damage to crops has a number of indirect impacts including direct loss in agricultural employment, indirect effects through sectoral linkages, etc. However, if the indirect effects are taken into account, it is estimated that damage amounted to 10 per cent of agricultural GDP and about 3 per cent of the total GDP of the country.

Crop damage by floods and food security is closely inter-linked. Although, during the floods of 1988 and 1998 government of Bangladesh managed to balance the difference between demand and supply of food, this did not necessarily ensure food security at the household level. This is considered a serious problem, even in a normal year in Bangladesh, with half of its population living below the poverty line. Therefore, flood related crop damage and unemployment make a large section of population extremely vulnerable to starvation, malnutrition and even death (Sahabuddin, 2000). In 1974 when a flood damaged about 0.6 million tons of crop and generated a severe unemployment crisis for farm workers, a famine broke out in Bangladesh due to lack of food security. It cost the lives of 1.0–1.5 million people (Alamgir, 1980).

Crop damage during a monsoon is generally a function of flood volume of the Ganges, Brahmaputra and Meghna rivers. In order to examine this, an empirical relationship has been developed between combined peak discharge of the three rivers and the

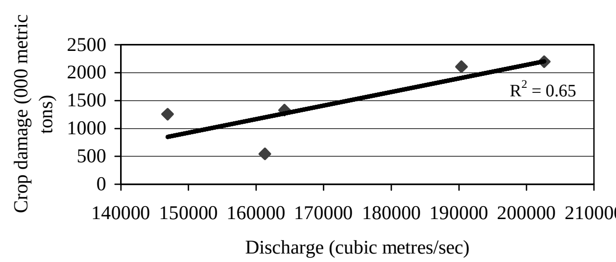


Fig. 11. Empirical relationship between combined peak discharge of the GBM rivers and crop. Damage in Bangladesh. Crop damage = 0.0243 × discharge − 2714.8.

Table 6
Estimated crop damage for future 20-year flood under various warming scenarios

| GCM | $\Delta T$ | Future 20-year flood ($m^3$/s) | | | Combined discharge($m^3$/s) | Estimated crop Damage ( × 000 tons) |
|---|---|---|---|---|---|---|
| | | Ganges | Brahmaputra | Meghna | | |
| CSIRO9 | 2 | 74659 | 86787 | 20524 | 181970 | 1707 |
| | 4 | 81260 | 86770 | 22007 | 190038 | 1903 |
| | 6 | 87862 | 86753 | 23510 | 198124 | 2100 |
| HadCM2 | 2 | 65838 | 94088 | 21669 | 181595 | 1698 |
| | 4 | 63613 | 101379 | 24313 | 189305 | 1885 |
| | 6 | 61394 | 108662 | 26959 | 197015 | 2073 |
| GFDL | 2 | 71596 | 90312 | 22787 | 184695 | 1773 |
| | 4 | 75135 | 93819 | 26534 | 195488 | 2036 |
| | 6 | 78674 | 97326 | 30320 | 206319 | 2299 |
| LLNL | 2 | 68465 | 87499 | 21589 | 177554 | 1600 |
| | 4 | 68874 | 88194 | 24138 | 181205 | 1688 |
| | 6 | 69282 | 88888 | 26706 | 184876 | 1778 |

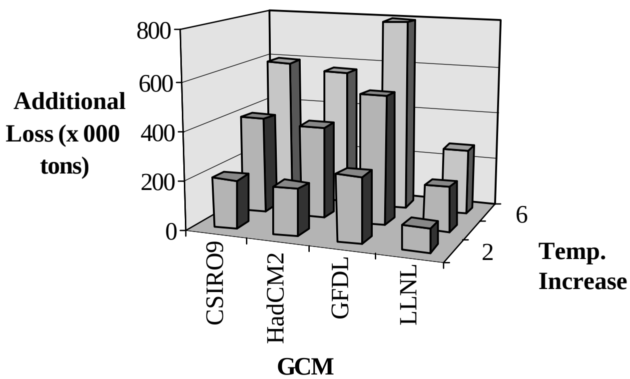


Fig. 12. Difference between estimated current and future crop damage.

amount of crop damage (Fig. 11). It explains about 65 per cent of the variation. Using this relationship, for a current 20-year flood, crop damage in Bangladesh is estimated to be 1.51 million tons.

The empirical relationship has also been used to estimate future crop damage due to changes in 20-year floods under various warming scenarios. The estimated flood discharge for the three rivers and corresponding estimated crop damage is shown in Table 6. The difference between estimated current and future crop damage is shown in Fig. 12. The highest crop damage is expected in the GFDL generated scenarios, followed next by the CSIRO9 model. The lowest crop damage is estimated by the LLNL GCM. Note that crop damage may significantly increase as a result of floods of higher return periods. Thus, for any magnitude of warming, additional damage to crops may increase food insecurity in Bangladesh.

## 6. Conclusions

A sensitivity analysis for 20-year floods for the Ganges, Brahmaputra and Meghna rivers demonstrates a range of possibilities of changes in probability of flood occurrences for various GCM scenarios. The analysis further demonstrates that possible changes in these probabilities of occurrences are not consistent for the three large rivers. The largest changes in probability are expected for the Brahmaputra and Meghna rivers. This implies a greater risk in flood planning and management in Bangladesh in future.

The analysis also demonstrates that crop agriculture in Bangladesh will be at greater risk in a warmer climate than compared to current conditions. Crop cultivation encompasses both human and natural elements. Therefore, adaptation in agricultural systems needs adjustments in human activities, socio-cultural (behavioural) aspects of present and past agricultural practices, and environmental factors in response to the anticipated changes in climate system and its consequential impact (Ahmed, 2001). Since the loss of crop production under warming scenarios could be quite significant, "no adaptation" would mean that the anticipated loss would have to be borne primarily by the poor farmers and the consumers. Concerted efforts are needed to strengthen capacity building in the agriculture sector in Bangladesh in order to reduce crop damage.

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