

Climate Proofing Infrastructure in Bangladesh

The Incremental Cost of Limiting Future Inland Monsoon Flood Damage

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Abstract

Two-thirds of Bangladesh is less than 5 meters above sea level, making it one of the most flood prone countries in the world. Severe flooding during a monsoon causes significant damage to crops and property, with severe adverse impacts on rural livelihoods. Future climate change seems likely to increase the destructive power of monsoon floods. This paper examines the potential cost of offsetting increased flooding risk from climate change, based on simulations from a climate model of extreme floods out to 2050. Using the 1998 flood as a benchmark for evaluating additional protection measures, the authors calculate conservatively that necessary capital investments out to 2050 would total US\$2,671 million (at 2009

prices) to protect roads and railways, river embankments surrounding agricultural lands, and drainage systems and erosion control measures for major towns. With gradual climate change, however, required investments would be phased. Beyond these capital-intensive investments, improved policies, planning and institutions are essential to ensure that such investments are used correctly and yield the expected benefits. Particular attention is needed to the robustness of benefits from large-scale fixed capital investments. Investments in increased understanding of risk-mitigation options and in economic mobility will have especially high returns.

This paper—a product of the Environment and Energy Team, Development Research Group—is part of a larger effort in the World Bank to understand potential impacts of climate change and adaptation cost. Policy Research Working Papers are also posted on the Web at <http://econ.worldbank.org>. The author may be contacted at sdasgupta@worldbank.org.

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1. Introduction

Bangladesh is one of the most flood prone countries in the world. Analysis of past flood records indicates that about 21 percent of the country is subject to annual flooding and an additional 42 percent is at risk of floods with varied intensity (Ahmed and Mirza, 2000). Although annual regular flooding has traditionally been beneficial by providing nutrient laden sediments and recharging groundwater aquifers, the country often experiences severe flooding during the monsoon that causes significant damage to crops and properties and has adverse impacts on rural livelihoods and production. A classified list of all floods in Bangladesh reveals the country has experienced 21 *above-normal* floods, of which 4 were *exceptional* and 2 *catastrophic* since 1954.⁸ The most recent *exceptional* flood in 2007 inundated 62,300 sq km of land (42% of the total) and caused severe damage to lives and property. This flood caused 1,110 deaths, submerged 2.1 million ha of standing crop land, completely destroyed 85,000 houses, damaged 31,533 km of roads and affected 14 million people. The estimated loss of assets from this flood alone is US \$ 1.1 billion.

In general, the relative severity of the impacts from *above-normal* floods in Bangladesh has decreased substantially since the 1970s as a result of improved macroeconomic management, increased resilience of the poor, and progress in disaster management and flood protection infrastructure. The 1974 flood was a 1 in 9 years event which resulted in damages of 7.5% of GDP. In comparison, the 1998 flood was a 1 in 90 years event, inundating nearly twice the area but resulting in damages of 4.8% of GDP. The increased resilience of Bangladesh to floods is also apparent when recent GDP and agricultural growth rate trends are examined with respect to the timing of flood events. Until the 1990s, GDP and agricultural growth rates sharply declined following major flood events. However, the relative effects of major floods have diminished

⁸ A flood with inundation area exceeding 21% of the total land area of Bangladesh has been classified as *above-normal*. *Above normal* floods have been further decomposed into four categories: *moderate*, *severe*, *exceptional* and *catastrophic* depending on the extent of inundation area being 21%-26%, 26% - 34%, 34%-38.5% and greater than 38.5% of the total land area respectively Mirza (2002).

after 1990.⁹ In fact, growth rates remained positive after the *exceptional* 1998 flood, which resulted in damages of nearly 4.8% of GDP. Changes in cropping patterns (shift from deepwater “aman” rice to “boro” rice), adequate reserves of food grains, and increase in rice imports by both the public and private sectors have all contributed to diminishing the relative impact of major flood events.

These recent gains may be at risk if the severity of floods increases with climate change. Across the 16 General Circulation Models (GCM) and 3 emission scenarios considered by the fourth assessment report of the Inter Governmental panel of Climate Change (IPCC AR4), a clear consensus exists on a warming trend in the larger Ganges Brahmaputra Meghna (GBM) basin in South Asia where Bangladesh is located; with increases of 1 to 3° C by 2050. For precipitation in the GBM basin, estimated changes differ widely across models. Most GCM’s, however, estimate increases in rainfall during the monsoon season in the 2050s – up to 20% more from July to September. All else equal, this increasing trend of monsoon rainfall will increase the extent of flooding in Bangladesh.

Given the pervasive impacts of climate-related risks on monsoon flooding over time, the government of Bangladesh has highlighted severe monsoon floods as a significant hazard and ensuring adequate flood protection infrastructure as a “pillar” of the Climate Change Strategy and Action Plan (GoB, 2009). Currently, systematic studies of the cost of climate proofing infrastructure are scarce in Bangladesh. Analytical work has been confined to relatively limited sets of locations and adaptation measures. Yet, the government has already invested over \$10 billion (at constant 2007 prices) in flood management embankments and emergency shelters to make the country more climate resilient and less vulnerable to natural disasters.¹⁰ This paper is an attempt to narrow the knowledge gap by providing itemized estimates of adaptation cost for roads, railways, embankments and drainage infrastructure to intensified monsoon flood in a changing climate out to 2050. In the absence of detailed location-specific data on the functional status of existing infrastructure and the current risk of overtopping and break downs during a

⁹ Despite several major disasters, Bangladesh remains among few countries that have avoided a single year of negative growth since the 1990’s.

¹⁰ The government recognizes climate change is an environmental as well as a developmental issue; and is committed to protect the country from its adverse impact and maintain a stable growth path of the country.

monsoon flood, the focus of this paper is to avoid further damage from additional inundation due to climate change.

In order to estimate cost of climate proofing infrastructure, this paper has followed a 3-step procedure:

1. Demarcation of a potential inundation zone from monsoon flood and projection of inundation depth under a baseline (without climate change) and in a changing climate scenario;
2. Identification of critical impact elements: population and infrastructure exposed to additional inundation risk in a changing climate;
3. Quantification of adaptation in infrastructure that will be required to avoid damage from additional inundation in a changing climate and costing of adaptation.

The itemized cost estimates for climate proofing infrastructure developed in this paper could help spur the Government of the People's Republic of Bangladesh to develop adaptation plans now in order to avoid future losses from monsoon flood amplification. For the international community, this paper presents a detailed bottom-up methodology to estimate the adaptation cost to intensified floods in a changing climate. The approach integrates information on climate change, assets at risk, growth projections and cost estimates. The cost estimates presented in this paper may also shed light in climate negotiations as a prototype of adaptation cost to extreme weather events.

The remainder of the paper is organized as follows: Section 2 describes the history of monsoon flood in Bangladesh. The future of monsoon flood in a changing climate is presented in Section 3. Section 4 summarizes the modeling and simulation to determine the impact of climate change on magnitude of floods and resulting vulnerable area and population. Section 5 describes the cost of climate proofing infrastructure in the flood plains, and Section 6 concludes the paper.

2. History of Monsoon Floods in Bangladesh

At present, Bangladesh faces serious flooding that may submerge over 60% of the country every 4 to 5 years (GoB, 2009). Flooding in Bangladesh is a result of a complex set of factors. Most of Bangladesh is located in the delta of three large rivers, the Ganges, the Brahmaputra and the Meghna. Uncertain trans-boundary flow, the low and flat topography of Bangladesh, heavy rainfall during monsoon season, high vulnerability of the country to tidal waves and cyclonic storm surges and congested drainage channels contribute to the inundation problem. Records indicate that Bangladesh was affected by a significant number of *above-normal* floods during 1890 and 2007. Time-series analysis indicates *above-normal* flooding in Bangladesh has not followed any regular pattern historically. A period of fairly frequent flooding 1892-1922 was followed by a relatively few *above normal* floods (1923 -1973), and, then, the frequency of *above-normal* floods is showing an increasing trend since 1950 (Hofer and Messerli, 2006). Specifically, Bangladesh has experienced 2 *catastrophic*, 4 *exceptional*, 4 *severe* and 11 *moderate* floods during 1950 - 2009. See Figure 1 for the extent of *above-normal* flooding in Bangladesh since 1950.

Table 1 summarizes key statistics for the *exceptional* and *catastrophic* floods since 1954. Inundation extents of recent floods reveal the affected area may exceed even two-thirds of the total area of Bangladesh during severe floods. The *exceptional* flood of 1998 was the worst on record and lasted from the first week of July to the third week of September and was the most severe both in-terms of depth and duration. It inundated nearly 70% of the total lands and caused severe damages to lives and properties. This flood alone caused 918 deaths, flooded nearly 100,000 km² that included 6000 km² of standing crop lands, affected 31 million people and impacted the property of about 1 million households. It also damaged 16,000 km of roads and 6,000 km of embankments. (See Table 1.)

Bangladesh has a number of “hard” (capital intensive) and “soft” (policies and institutions) measures in place to protect the population and assets in the floodplains. For example, “hard” measures include river embankments, emergency shelters, early warning systems and disaster relief operations; and “soft” measures include design standards and building codes for

infrastructure¹¹, countercyclical shifts in cropping patterns to offset agricultural losses immediately following the flooding. The people of Bangladesh also have adapted over generations to reduce exposure to flood risks and to maintain their livelihoods. For example, in areas where inundation is a risk, people have raised their houses on mounds above the normal flood level, and adjusted their cropping patterns to take advantage of the flood water. Rural roads and other infrastructure, such as schools, and medical centers, are also raised above normal flood level, where it is feasible. While these measures have significantly reduced damages and losses from floods over time, especially in terms of deaths and injuries, the challenge now that Bangladesh faces is to scale up the investments to prevent the potential drastic consequences of climate change.

3. Flooding in a Changing Climate

The IPCC AR4 and research conducted on the future climate of South Asia is indicating climate change will increase the vulnerability of Bangladesh to severe floods.

The IPCC AR4 predicted that monsoon rainfall will increase this century in South Asia resulting in higher flows in the rivers of Bangladesh from Nepal, India, China and Bhutan (IPCC 2007). Although Bangladesh accounts for only 7% of the GBM basin area, it drains the entire GBM basin (1.72 million km²) because of its location at the mouth of the basin. Hence, the timing, location, and extent of flooding in Bangladesh depend on the rainfall in the entire GBM basin.¹²

Mirza and Dixit (1997) have estimated that a 2°C warming combined with a 10 percent increase in precipitation would increase runoff in the GBM Rivers by 19, 13, and 11 percent respectively. In Bangladesh, increased depth of flooding will be pronounced in the lowlands and of the Faridpur, southwest Dhaka, Rajshahi, Pabna, Comilla, Sylhet, and Mymensingh greater districts. In a more recent study, Mirza et al., 1998 reported that an increase in precipitation over the GBM basins of about 5 percent combined with a temperature increase of around 1°C could result in up

¹¹ Bangladesh Water Development Board (BWDB) has developed design manuals for embankment and flood control & drainage infrastructures.

¹² On average, an annual water flow of 1,350 billion cubic meters of the GBM basin drains through Bangladesh. In addition, nearly 80 percent of the country's annual precipitation occurs during the summer monsoon season, when these rivers have a combined peak flow of 180,000 m³/second, the second highest in the world.

to a 20 percent increase in area flooded in Bangladesh. Severity of extreme floods, such as the 20-year flood event, is estimated to increase marginally. Another study conducted in 1998 concluded that an increase in monsoon rainfall by 11 and 20 percent will increase surface runoff by 20 to 45 percent in Bangladesh (Ahmed and Alam, 1998).¹³ For Bangladesh alone, the median predictions of 16 General Circulation Models for three emission scenarios considered by the IPCC AR4 point to a warming of 1.55° C and an increase in precipitation of 4% by 2050 (Yu et al. 2010).¹⁴ In sum, the warmer and wetter climate predicted for the GBM basin by most of the climate-related research indicates vulnerability of Bangladesh to severe monsoon floods will increase with climate change.

4. Exposure to Inundation Risk

In order to assess potential change in the extent and depth of inundation in a changing climate, this research conducted flood modeling for two scenarios. The 1998 exceptional flood event (see Box 1) with a return period of 90 years has been considered as the baseline scenario. It is the counterfactual against which future climate change risk is measured. For the climate change scenario, changes in the monthly precipitation and temperature predicted by the GCM- MIROC 3.2 under the A2 emission scenario have been considered.¹⁵ Since flooding in Bangladesh depends on the rainfall in the entire GBM basin, predictions of precipitation and temperature between 1998 and 2050 for each 50km x 50 km grid covering GBM basin from the MIROC 3.2 have been applied to the historical monthly averages for 1998 to approximate the monthly precipitation and temperature over the entire GBM basin in 2050.

Inundation risk exposure for each scenario is then determined in four steps.

First, the Ganga Brahmaputra Meghna model in the MIKE BASIN platform, developed at the Flood Forecasting and Warning Centre (FFWC) of Bangladesh Water

¹³ An Earlier study indicates that a 10 percent increase in monsoon precipitation in Bangladesh could increase runoff depth by 18 to 22 percent, resulting in a sevenfold increase in the probability of an extremely wet year (Qureshi and Hobbie, 1994).

¹⁴ The resolution of the models varies with about 5 grid boxes typically covering Bangladesh. The national values are weighted averages, with the weights equal to the percentage of each grid that is within Bangladesh.

¹⁵ The MIROC 3.2 has been used in this research to approximate potential extreme effects as it results in the largest increase in runoff among the GCMs for Bangladesh.

Development Board (BWDB) in 2006 has been used to simulate the trans-boundary flows with estimates of runoffs generated from basins of three major rivers: Ganges, Brahmaputra, Meghna.¹⁶

Second, the National Flood Model of Bangladesh developed by the FFWC of BWDB has been used to generate flood levels, inundation extent and duration for the extreme flood events in Bangladesh during the monsoon period for each 300m x 300m grid.

The National Flood Model operates a real time numerical model based on one dimensional fully hydrodynamic model (MIKE 11 HD), and is linked to a rainfall-runoff model (MIKE 11 RR). The rainfall runoff model comprises 157 sub-catchments having a total area of 122,437 sq. km. Rainfall data from more than 200 rainfall stations and potential evapotranspiration data of around 30 evaporation stations have been used in the model. The hydrodynamic model, on the other hand, includes all important rivers and *khals* of Bangladesh (10,235 km), floodplain routing channels (1,147 km) and link channels. It is based on the existing national DEM for Bangladesh and model simulations included all existing flood protection measures like flood embankment and flood control and drainage infrastructure in Bangladesh.¹⁷

Third, the daily inundation depth results are synthesized to determine the highest inundation depth for each grid point during the monsoon period, and areas vulnerable to floods of a minimum duration of 24 hours are identified.

Finally, for the subsequent economic analysis, risk exposure zones are formed by grouping grid points into the five flood risk zones.

¹⁶ For this research, the model was updated by the Institute of Water Modeling (IWM) with river alignments of GBM basins using available physical maps of India, Nepal, Tibet; and sub catchments of the GBM basins were re-delineated using the Digital Elevation Model (DEM) based on SRTM-version 3. The model has been first calibrated using round the year hydrological feature of 2005 and validated for two subsequent years 2006 and 2007. Then the model was further updated using most recent data of last hydrological year 2009.

¹⁷ Bathymetries of the rivers have been updated incorporating the available latest cross-sections and bathymetries of floodplain routing channels are taken from national land terrain model developed in FAP (Flood Action Plan) 19.

Figure 2 depicts the flood risk exposure map of Bangladesh, as measured by the highest inundation levels for a 24-hour duration from the simulations, under the baseline and the climate change scenarios respectively. While the duration of a flood is an important metric for determining its impact, models to reliably determine the duration of a flood beyond a few days are not currently available. The choice of 24 hours duration is based on the potential severe damages that road infrastructure, flood embankments and rural houses usually are subject to from floods of such duration.¹⁸ Construction of flood maps of longer duration was not feasible within the resource constraints of the study. (See Figure 2.)

The flood risk exposures under the two scenarios are summarized in Table 2. Under the baseline scenario, 45% of land is under at least 0.3 m of water (see Table 2). Under the climate change scenario, the total flooded area increases by 4%; exposing more inhabitants, assets and activities at risk. More importantly, the inundation depth increases in most flooded areas, increasing the level of risk to which these areas are exposed. Areas inundated to depths greater than 0.9m increases from 34% of the total area under the baseline scenario to 40% under the climate change scenario. The distribution of land based on inundation levels at the peak period is approximately the same as those for the 24 hour duration flood.

The number of inhabitants exposed to inundation risk of different depths under the two scenarios is estimated by overlaying the inundation risk map with the population map for 2001 using Geographic Information System (GIS) software. About 23 million people lived in rural areas with estimated inundation depths greater than 0.3 meter in 2001.¹⁹ Urban migration is expected to offset increases in the population by 2050 resulting in a decline in the number of rural inhabitants exposed to inundation risk to 19.2 million. An additional 1.9 million live in the newly inundated areas under the climate change scenario resulting in a total of 21.1 million rural inhabitants that are exposed to risk of inundation greater than 0.3 meter by 2050.²⁰ This represents a 9% increase

¹⁸ Urban floods and flash floods are not accounted for in this analysis.

¹⁹ The exposed population count is estimated at the thana level, which is the lowest administrative unit, using the population density and the total area that falls into each risk zone. The total exposed population count is the sum of the exposed population across all thanas.

²⁰ The rural and urban population growth rates to 2050 are applied uniformly to existing rural and urban areas respectively.

relative to the 2050 baseline scenario, but a decrease of about 9% relative to the population at risk currently. (See Table 3.)

Most people living in inundated areas, however, are likely to be exposed to higher inundation depths under the climate change scenario. The estimated population exposed to inundation depths greater than 0.9 meter is expected to increase from 13.6 million under the baseline scenario to 16.6 million under the climate change scenario, implying an increase of 22%. Correspondingly, this is offset by a 19% decrease in the population living in areas with inundation depth less than 0.9 meter.

It should be noted that the estimates of population exposed in 2050 are based on 1.15% annual expected growth rates²¹ in the rural and urban populations, which are applied uniformly across the country. These projections do not account for a) autonomous adaptation by rural households in response to changing flood risk conditions or b) the implementation of the land use and coastal zone management policies which the government has started to put in place over the past decade.

5. Infrastructure Exposed to Additional Inundation Risk and Adaptation Cost

The infrastructure assets considered for the analysis includes: national highways, regional highways, feeder roads-type A, feeder roads-type B, railways, bridges, embankments and drainage systems. In order to estimate the cost of climate proofing infrastructure, the additional flood inundation risk due to climate change has been determined for each 300m x 300m grid by taking the difference in inundation depth between the baseline and climate change scenarios using GIS software. Figure 3 shows a map of the areas with additional inundation risk.²² Visual inspection suggests the areas with large expected changes in inundation depth are spread out across the country. (See Figure 3.)

²¹ Projection of population is based on the assumption that Bangladesh is expected to attain replacement fertility in 2021 (BBS, 2007)

²² These represent just the additional risk due to climate change and not the total risk from flooding.

Area estimates indicate although climate change is likely to increase inundation depth in about half of the country, the inundation depth increases are less than 15 cm for most areas. Increases in inundation depths larger than 15 cm are likely to occur in only 544 sq km or less than 0.5% of Bangladesh. (See Table 4.)

Current spatial distribution of infrastructure provided the starting point for identifying infrastructure that are likely to be exposed to additional inundation risk due to climate change in 2050. The best available spatially-disaggregated maps and data for these assets have been acquired from various public sources including Bangladesh Railways, Bangladesh Water Development Board, Local Government Engineering Department, Center for Environmental and Geographic Information Services (CEGIS), Public Works Department, Roads and Highways Department, Water Resources Planning Organization and the World Bank. The stock of infrastructure in 2050 is projected by applying expected changes²³ in the Bangladesh economy uniformly across the country. The additional inundation exposure risk zones due to climate change are overlaid on the infrastructure map using GIS software to determine the assets exposed to additional inundation risk.

The infrastructure stock exposed in each inundation risk zone for drainage structures, e.g. culverts is a count of the number of assets located in that risk zone. For assets with a large spatial extent (e.g., roads, railways and embankments) the exposure estimate is measured by the spatial extent of the assets, in kilometers.

Roads

All national and regional roads in Bangladesh were designed to be built above the highest flood level with a return period of 50 years, and feeder roads were designed above normal flood levels (Siddiqui and Hossain 2006). Still, these standards were not sufficient to prevent large losses in road infrastructure during recent major floods. For example, road damages accounted for 15% of the total damages or about 0.7% of GDP during the 1998 flood (Islam and Mechler 2007).

²³ These include population and income growth and structural shifts in the economy away from agriculture and towards industry and services.

Hence, the concern is increase in inundated area and inundation depths due to climate change will further increase the inundation risks of roads.

This paper has estimated the length of roads (km) exposed to additional inundation risk due to climate change for different types of roads from the GIS overlays of the maps of additional inundation risk zones with the existing road maps for each category. Bangladesh already has one of the densest road networks in the world, leaving little room for extensive growth in the road network in future. In absence of long term planning for additional new roads, this exercise has assumed that total lengths of roads in Bangladesh will increase by another 25% over the existing stock by 2050. The assumed 25% expansion of the road network is applied uniformly across the existing network.²⁴

Table 5 summarizes the total kilometers of roads likely to be exposed to various degrees of additional inundation due to climate change. Computation indicates less than 2% of roads in 2050 will be subject to more than 1 meter of additional inundation due to climate change, while almost all (87%) will be inundated by up to 0.5 meters due to climate change. (See Table 5.)

The total cost of raising roads to avoid further inundation due to climate change has been calculated using DBS=Wearing Course 50 mm thick on average (Taka 8,350 per m³), DBS-Base Course 50 mm thick on average (Taka 7,899 per m³), Aggregate Base Type I- 100 mm (Taka 2,819 per m³), Aggregate Base Type II- 100mm (Taka 2,232 per m³), roadway excavation (Taka 184 per m³) and earth fill from borrow pit (Taka 124 per m³).²⁵ Table 6 documents the total adaptation cost of the entire road network to offset the additional inundation risk due to climate change for different types of roads. (See Table 6.)

The estimated cost for elevating the entire road network to offset additional risk due to climate change is Tk 148.56 billion or \$2.12 billion. National and regional roads account for about 12% of the total costs, while the remaining 88% is required for rural and feeder roads.

²⁴ Currently quality of road is poor in Bangladesh; most new investments in the road infrastructure are likely to be for upgrading roads to higher standards for instance by paving unpaved roads rather than for expansion.

²⁵ US \$1 = BGD Taka 70

Cross-Drainage Facility for Roads

Roads in Bangladesh do not have adequate drainage facilities for flood water. The natural flow of flood water currently is obstructed due to inadequate number of culverts and regulators to allow cross-drainage. In a changing climate, the problem of drainage is likely to worsen with increased volume of flood water. It would be necessary to increase the number of drainage structures, including culverts and regulators to facilitate the drainage of the extra flood water. In addition, some existing culverts need to be raised to facilitate the free flow of water.

Climate change is expected to increase the deeply inundated areas (greater than 0.9 meters) by an additional 7,736 sq km.²⁶ Each drainage structure of size 1.5mX1.8m can approximately drain a 10 sq km area that costs Taka 15 million. As a result, 775 new drainage structures will be required to drain the additional deep inundated areas in a changing climate; at a total cost of Taka 11,625 million or US\$ 166.07 million. It has been further estimated that a total of 315 additional culverts are to be raised to avoid additional inundation from climate change at a cost of Taka 1 million per culvert.²⁷ Hence, the total cost of raising culverts will be Taka 315 million or US\$ 4.5million.

Railways

The rail network of Bangladesh has not changed significantly during past fifty years. Aside from doubling the railway track between Dhaka and Chittagong in the next few years, Bangladesh Railways does not have any other plans for changing its network for the foreseeable future. Hence, for this analysis, the rail network in 2050 is assumed to be the same as now with the planned expansion between Dhaka and Chittagong; and the length of railways (km) exposed to additional inundation risk due to climate change for different types of tracks of rail has been determined based on GIS overlays of the maps of additional inundation risk zones with the existing railway maps. Table 7 summarizes the estimates. Exposure estimates indicate that less than 2% of railway tracks in 2050 will be subject to more than 1 meter of additional inundation due to climate change, while almost all (85%) will be subject to 0.5 meters of additional

²⁶ These are areas with the F2-F4 classifications.

²⁷ Rebuilding the flat part cost Tk. 700,000 on average, and other remodeling cost are Tk. 300,000.

inundation due to climate change; and nearly all of the tracks that are at additional risk from climate change are meter gauge tracks.²⁸ (See Table 7.)

Raising rail tracks entails six tasks: (i) the removal and replacement of the ballast, (ii) the removal and replacement of rail and other heavy iron works, (iii) the dismantlement of and replacement of tracks, (iv) the earth work with sand, (v) the procurement of 15% ballast & spreading, and (vi) the mechanical tamping at four stages. The cost per kilometer for raising railway tracks 0-0.5 meter for different gauges of tracks are shown in table 8. The cost for broad gauge and double gauge are US\$ 38,886 per km while the cost for meter gauge is to some extent lower at US\$ 29,212 per km. (See Table 8.)

The cost of earthwork generally increases when rail tracks are to be raised more than 0.5 m. The cost of earthwork per km of rail track are US\$ 20,539 and US\$ 16,821 respectively for Broad or double Gauge, and Meter gauge if tracks are to be raised by 0.5- 1m. Taking all these itemized cost into account, the estimated total Cost of raising railway track to offset additional risk due to climate change is US\$ 27 million. Cost of raising Broad gauge tracks, Meter gauge tracks and double gauge tracks are US\$ 10 million, US\$ 6 million and US\$ 11 million respectively.

River Embankments

Structural measures such as embankments and water regulating structures have dominated water and flood management practices in Bangladesh. Bangladesh Water Development Board (BWDB) currently maintains a total of 9,943 km of embankments, 5,111 km of drainage canals and 13,949 flood control/regulating structures (BWDB, 2006). Embankments are used to protect agricultural land, major cities and small towns from the 10-year, 15-year, 50-year return period floods respectively. Discussions with the BWDB officials point out that the length of embankments is not expected to expand beyond what currently exists through 2050.

GIS overlays of the maps of additional inundation risk zones and existing embankments indicates a total of 5,421 km of embankments will be subject to various degrees of additional

²⁸ In Bangladesh, railway tracks are classified into two categories: broad gauge and meter gauge. There are a few tracks which can be used for either broad gauge or meter gauge trains.

inundation due to climate change. Of this, 5,088 km (94%) will be exposed to an additional inundation depth of up to 0.5 m and 29 km (less than 1%) to more than 1 meter.

The total cost for raising embankments to offset the additional risk due to climate change is Taka 6,727 or US\$ 96 million. This cost has been calculated using cost estimates available from the BWDB for earth work (Taka 125/ m³), compaction (Taka 60/ m³), and turfing (Taka 25/ m²). Table 9 provides the itemized cost of height enhancement of affected embankments for various inundation depths. As expected, the bulk of the costs is for the required earthwork. (See Table 9.)

Drainage within Coastal Polders

Bangladesh has 123 coastal polders (i.e., areas with a dyke) to protect low lying coastal areas against flood and salinity intrusion. Water regulators are used to prevent drainage congestion in coastal polders.²⁹ The higher precipitation level during the monsoon and the rising sea level under the climate change scenario is expected to increase drainage congestion in coastal polders.

For this analysis, trial simulations were conducted with 4 coastal polders to determine the average number of additional vents necessary for draining water if the water level inside the polder increases due to climate change conditions and creates drainage congestion. Each simulation consisted of adjusting the length of opening under the climate change scenario to reduce the water depth inside each polder to the level under the baseline scenario. The adaptation measure is the additional length of opening needed to ensure same drainage conditions under both scenarios. Additional numbers of vents are computed by dividing the length of opening with 1.52 m (i.e. width of each vent). The 4 trials indicate 7, 17, 24, and 51 additional vents are needed to reduce water levels under the climate change scenario down to the levels under the baseline scenario.

Estimates further indicate a total of 1,475 additional vents, each costing Taka 20 million will be required to drain the expected extra monsoon flood water from the polders identified to face

²⁹ At present, not all existing water regulators in coastal polders are operational. The costs of rehabilitating existing structures or adding new ones to meet the drainage needs under the baseline scenario are not part of adaptation cost to climate change.

increased drainage problem under the climate change scenario. Hence, the estimated total cost of additional drainage regulators in the coastal areas is Taka 29,500 million or US\$ 421.4 million.

Scour Protection

Past experience indicates unprotected river banks erode with the increase in the maximum discharge along the rivers (CEGIS, 2010). In a changing climate, expected change in flooding with an augmented maximum discharge will lead to increased erosion at the unprotected river banks and aggravate scour depths even where the river bank protection exists. The BWDB has estimated that the maximum discharge in the Ganges, the Brahmaputra and in the Meghna rivers will increase by 17%, 20% and 8% respectively due to climate change which in turn will result in increase in scour depth by 1.87 meter, 0.96 meter and 1.13 meter respectively (BWDB, 2003).³⁰ Increase in scour depth will lead to increase in yearly operation and maintenance cost of existing river bank protection works due to additional requirement of launching apron. The yearly operation and maintenance cost of the existing bank protection projects is expected to increase by 6.8% in order to provide additional protection against scouring.

On average, BWDB's requirement was Taka 1,045 million (US\$ 14.9 million) for protection against scouring for the past two years. Due to climate change, annual scour protection cost is expected to increase to Taka 1,116 million (US\$ 15.9 million), an increment of Taka 71 million (US\$ 1.0 million) per year.³¹

In summary, the costs of protecting roads, railways, embankments and drainage infrastructure against the additional risk of inundation from inland monsoons resulting from climate change by 2050 are recapitulated in Table 10. It should be noted that these estimates provide a lower bound on the actual costs of adaptation as they do not include additional adaptation required in urban areas and currently unprotected riverbanks. Inspection reveals over four-fifths of the total adaptation cost is for raising the height of the road network. Additional drainage structures in

³⁰ Lacey's formula was used for estimating scour depth

³¹ Absence of relevant data prevented estimation of erosion at the unprotected river banks.

coastal areas account for an additional 14% of costs, while the remaining measures account for less than 5% of the total cost of adaptation for inland flooding. (See Table 10.)

It should also be noted that infrastructure investments are long-lived, expensive and yield large benefits when designed appropriately. Hence, it is essential to develop appropriate standards commensurate with the likely climate risks over the expected lives of the assets and to update them over time based on new research results that become available. For example, the prospect of more intense precipitation has implications for unpaved roads, especially in rural areas, which are vulnerable to being washed away by floods and heavy rainfall. Single-lane sealed roads have a higher capital cost, but they provide a more reliable all-weather network with lower maintenance costs. As research makes the risk of flooding in a location more apparent, the design standards for roads in these areas need to be increased accordingly. Similarly, the embankments need to be strengthened beyond their current protective capacity as the added risk from floods becomes more certain.

6. Conclusion

Bangladesh is a flood prone country. Severe floods result in significant damages to the economy on a regular basis. The scientific evidence available to date indicates that climate change may intensify monsoon rainfall and further exacerbate the inundation problem. At present, systematic studies of climate proofing of infrastructure to potential additional inundation due to climate change is scarce in Bangladesh; this research is an attempt to narrow the gap.

This paper presents an assessment of the vulnerability of Bangladesh to intensified monsoon rainfall – as predicted by the MIROC 3.2 under the A2 emission scenario – out to 2050. Hydrological and hydrodynamic models have been used to delineate additional inundation extent and change in inundation depths due to climate change. Geographic overlays have been used to identify vulnerable population and infrastructure. Also, the paper quantifies the changes in the infrastructure that will be required to offset additional inundation in a changing climate and the cost of adaptation to the future (2050) climate.

At present, 45% of the area of Bangladesh is exposed to extreme monsoon flooding. Although the inundation area estimates indicate a potential addition to the extent of inundation by 4%, the entire area at risk (nearly half of the country) is expected to encounter higher inundation depths due to climate change. Bangladesh being a densely populated country, these will translate to significantly larger damages to assets and economic activities than what the small areal share of additional inundation may suggest.³² The government of Bangladesh recognizes intensification of monsoon flood is an environmental as well as a developmental issue, and is committed to protect the country from its impact and maintain a stable growth path of the country. Ensuring adequate flood protection infrastructure has been identified as a “pillar” of the Climate Change Strategy and Action Plan of Bangladesh. The estimates reported in this paper indicate that **the cost of adaptation for the railways, road network, embankments and drainage infrastructure to offset additional inundation due to climate change alone is US\$ 2.7 billion.**³³ This cost estimate is conservative (and hence provides a lower bound) as it does not include the additional adaptation required in urban areas and unprotected river banks. It should also be noted that the cost of full climate proofing of infrastructure is compounded by the fact that the country has an outstanding adaptation deficit and there exist substantial risks from severe flooding even in the current climate. In the absence of information on location-specific data on the functional status of existing infrastructure and the current risk of overtopping and breakdowns during a monsoon flood, adaptation deficit could not be quantified in this analysis.

It should also be taken into account that the evaluation of the “hard” adaptation investments in this paper has been done within a framework of appropriate development policies and efficient institutional arrangements. Good policies, planning, and institutions are essential to ensure that more capital-intensive measures are used in the right circumstances and yield the expected benefits. As a general rule, investments—such as flood embankments—designed to protect vulnerable assets should always be subjected to careful consideration. The construction of an embankment is followed, almost by definition, by accumulation of physical capital in the shadow of the embankment because it is considered “safe.” However, as the tragedy of New Orleans

³² Vulnerable population estimates suggest there will be a 9% increase in population at risk of flooding but a 22% increase in population exposed to inundation depth greater than 0.9 meter in a changing climate.

³³ The climate is expected to change gradually; hence required investments for adaptation can be phased.

dramatically illustrated, a sufficiently extreme event will breach an embankment. The combination of increasing severity of extreme events, high costs of providing physical protection, and accumulation of capital behind such barriers can mean that the expected value of losses, including human suffering, may not be reduced—either at all, or by as much as expected by investments in protection. Physical measures to prevent suffering must be complemented by long-term measures such as education, job training, and migration designed to reduce reliance on resources and assets whose value may be eroded by climate change. Adaptation should not attempt to resist the impact of climate change, but rather it should offer a path by which accommodation to its effects is less disruptive and does not fall disproportionately on the poor and the vulnerable.

The long-term challenge in Bangladesh is to move people and economic activity into less climate-sensitive areas and to seek a strategic balance between protecting existing populations and encouraging the mobility of future populations. In 2050, the number of people living in cities in Bangladesh is expected to triple, while the rural population will fall by 30 percent. Current government policies will determine where this urban population will settle and how prepared it will be to adapt to a changed climate. Many households have moved further inland, partly due to higher perceived risk, but strengthened embankments may change these perceptions, leading to increased exposure. Good policy needs to encourage future populations to move away from high natural risk areas, avoiding perverse incentives to remain in high-risk areas and adopting positive incentives to promote settlements and urban growth in low-risk areas. Strengthened education in rural areas is also critical for rural migrants to be prepared for productive lives in new urban areas.

Last but not the least, it should be mentioned that strengthened regional cooperation in South Asia is essential to cope with climate change in the long run. Given the location of Bangladesh at the mouth of the GBM basin, a longer term adaptation strategy has to include the development of institutions and mechanisms for transboundary negotiations of water resources with the neighboring countries located in the GBM basin. Cooperation on the sharing of water with neighboring countries in the GBM basin is not a new issue for Bangladesh, but it is one whose importance may be greatly increased by climate change. As the stakes rise, effective steps taken

now to promote and strengthen the cooperative management of the shared resources can not only provide immediate benefits to all parties but can also prevent the need for expensive and possibly disruptive solutions in the future.

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Table 1: Recent *exceptional* or *catastrophic* Floods

Year	1974	1987	1988	1998	2004	2007
Affected area ('000 sq km)	53	57	90	100	56	62
Percentage of Total Land of Bangladesh under Inundation	37%	40%	63%	69%	39%	42%
Affected Population (million)	30	30	47	31	33	14
Fatalities	28,700	1,657	2,379	918	285	1,110
Houses damaged ('000s)	na	989	2,880	2,647	895	1,000
Roads damaged (km)	na	na	13,000	15,927	27,970	31,533
Crops damaged (million ha)	na	na	2.12	1.7	1.3	2.1
Asset losses (million US\$)	936	1,167	1,424	2,128	1,860	1,100
GDP current (million US\$)	12,459	23,969	26,034	44,092	55,900	68,400
Asset losses as % GDP	7.5	4.9	5.5	4.8	3.3	1.6
Return Period (years)	9	13	55	90	12	14

Source: Islam and Mechler (2007), BWDB (2007)

Table 2: Inundation Area Estimates

	Baseline Scenario		Climate Change Scenario		Change due to Climate	
	Km ²	% of Total Area	Km ²	% of Total Area	Km ²	% of Total Area
Flood Free	69,439	52%	64,550	49%	(4,889)	(3%)
F0 (0.1m-0.3m)	2,950	2%	2,251	2%	(699)	
F1 (0.3m-0.9m)	14,123	11%	11,975	9%	2,148	(2%)
F2 (0.9m-1.8m)	19,118	14%	20,723	15%	1,605	1%
F3 (1.8m-3.6m)	22,115	16%	26,153	19%	4,038	3%
F4 (>3.6m)	5,777	4%	7,870	6%	2,093	2%
Total Flooded Area (F1+F2+F3+F4)	60,750	45%	66,362	50%	5,588	5%

Table 3: Vulnerable Population Estimates

Flood Level	(a) Population in 2001 ^a exposed to inundation under base condition	(b) Projected Population in 2050 exposed to inundation under base condition	(c) Projected population in 2005 exposed to inundation with climate change	Percent change between (b) and (c)
F0 (0.1m-0.3m)	1,009,898	843,729	681,031	-19%
F1 (0.3m-0.9m)	6,721,555	5,615,588	4,566,517	-19%
F2 (0.9m-1.8m)	8,490,523	7,093,488	8,108,952	14%
F3 (1.8m-3.6m)	7,105,158	5,936,072	7,543,397	27%
F4 (>3.6m)	669,027	558,945	899,066	61%
Exposed Population to Flood Level F1+F2+F3+F4	22,986,263	19,204,093	21,117,932	9%

^a Population count according to 2001 census

Table 4: Changes in Inundation Depth due to Climate Change- Area Estimates

Additional Inundation Depth due to climate change (cm)	Area (sq km)	Share of total area (%)
No Change	70,249	52.6%
1 – 5 cm	56,102	42.0%
5 – 10 cm	5,841	4.4%
10 – 15 cm	786	0.6%
More than 15 cm	544	0.4%
Total	133,522	100.0%

Table 5: Length of road (km) at additional inundation risk from climate change in 2050

Additional Inundation Depth (m)	Feeder Road-Type A	Feeder Road - Type B	National	Regional	Rural	Total	Share of Total
0 - 0.5	6,175	4,203	998	587	11,065	23,027	87%
0.5 - 1.0	734	515	194	86	1,315	2,844	11%
1.0 - 1.5	72	68	11	6	189	346	1%
1.5 - 2.0	24	19	1	3	89	137	1%
2.0 - 2.5	7	4	0	1	17	30	-
2.5 - 3.0	8	2	1	0	8	19	-
All exposed	7,020	4,810	1,205	683	12,683	26,402	100%
Share of all exposed (%)	27%	18%	5%	3%	48%	100%	

Table 6: Adaptation cost for roads, by type of road (in million US\$)

Additional Inundation Depth (m)	Feeder Road-Type A	Feeder Road - Type B	National	Regional	Rural	Total	Share of total
0 - 0.5	730.986						92%
0.5 - 1.0	47.114	309.243	144.186	98.329	675.600	1958.343	6%
1.0 - 1.5	6.286	20.843	11.086	8.271	47.843	135.157	1%
1.5 - 2.0	1.043	2.971	2.200	0.500	8.486	20.443	0%
2.0 - 2.5	1.086		0.071	0.157	1.257	2.529	0%
2.5 - 3.0	1.243	0.543	0.071	0.129	1.529	3.357	0%
All exposed	787.757	333.800	157.714	107.486	735.500	2122.257	100%
Share of all exposed (%)	37%	16%	7%	5%	35%	100%	

Table 7: Railway Tracks (km) at risk of inundation due to climate change by 2050

Railway track (in km)	Additional Inundation Depth (m)							Total
	0 - 0.5	0.5 - 1.0	1.0 - 1.5	1.5- 2.0	2.0- 2.5	2.5- 3.0	>3.0	
Meter gauge	173.3	10.8	2.4	1.7	-	-	-	188.1
Broad gauge	205.8	35.0	7.0	-	-	0.4	0.3	248.5
Meter gauge double	224.7	43.0	2.6	0.5	0.3	0.4	-	271.4
Total track	603.8	88.8	11.9	2.1	0.3	0.8	0.3	708.1

Table 8: Cost (in US \$) per Kilometer to raise different railway tracks upto 0.5 meters

Description of cost component	Meter gauge	Broad gauge	Double gauge
Carriage cost			
Removal and replacement of ballast	741	892	892
Removal and replacement of rail & other heavy iron works	463	498	498
Permanent way			
Dismantling and Re-lay of track	12,745	17,039	17,039
Earth work with sand	5,607	6,846	6,846
Procurement of 15% ballast & spreading	6,786	10,143	10,143
Mechanical temping at four stages	2,871	3,468	3,468
Total cost ³⁴	29,212	38,886	38,886

³⁴ Cost of removing & replacement of ballast, cost of removing and replacement of rail & other heavy iron works and cost of dismantling and re-laying of tracks have been counted twice because during the construction work another diversion track will be required to sustain continuous movement of trains.

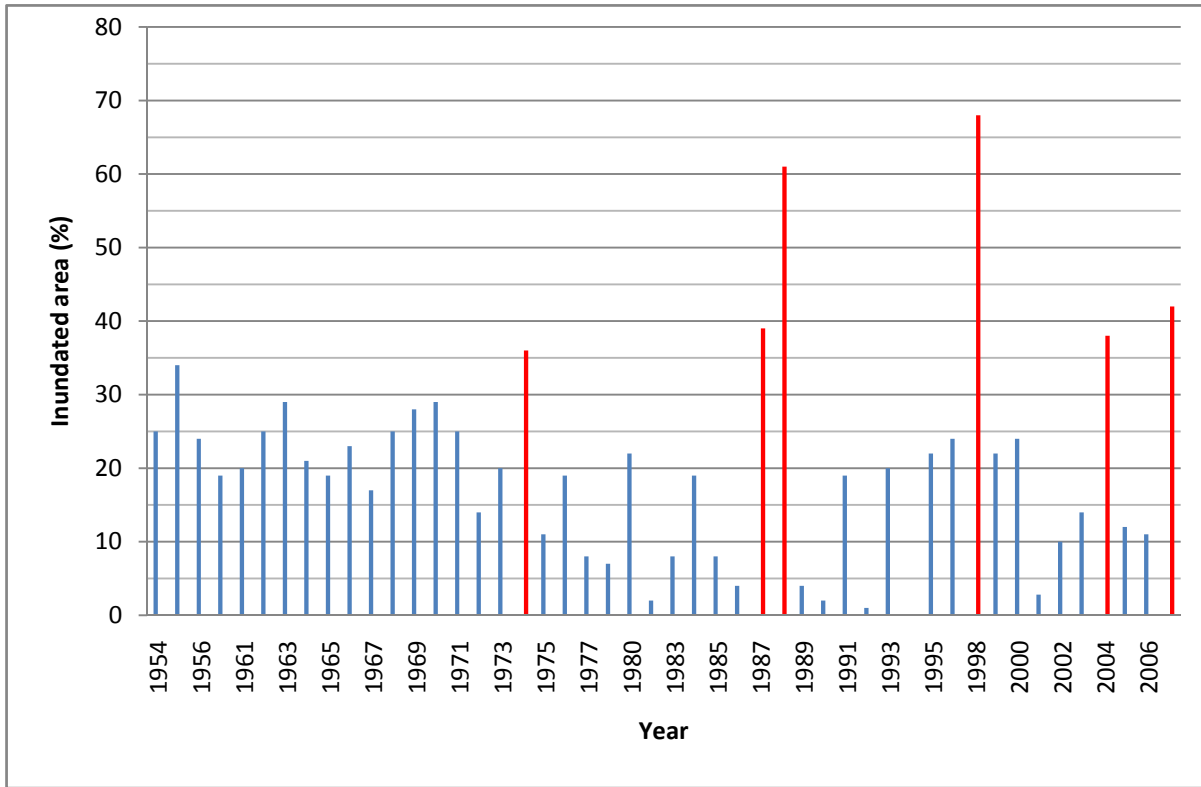
Table 9: Itemized Cost for raising embankments (million US\$)

	Additional Inundation Depth (m)			
	0 - 0.5	0.5 - 1.0	1.0 - 1.5	Total
Earthwork	55	9	1	65
Compaction	26	4	1	31
Turfing	0	-	0	0
Total cost (million Taka)	81	13	2	96

Table 10: Total adaption cost for inland flooding

Description of cost component	Investment (US\$ million)	Recurrent (US\$ million)
Transport – Road height enhancement	2,122	
Transport – Road cross-drainage	5	
Transport – Railway height enhancement	27	
Embankment – height enhancement	96	
Coastal Polders – cross drainage	421	
Erosion Control Programs		1
Total Costs	2,671	1

Figure 1: Extent of above-normal flooding in Bangladesh (1950 – 2009)



Source: CEGIS

Figure 2: Flood maps of Bangladesh

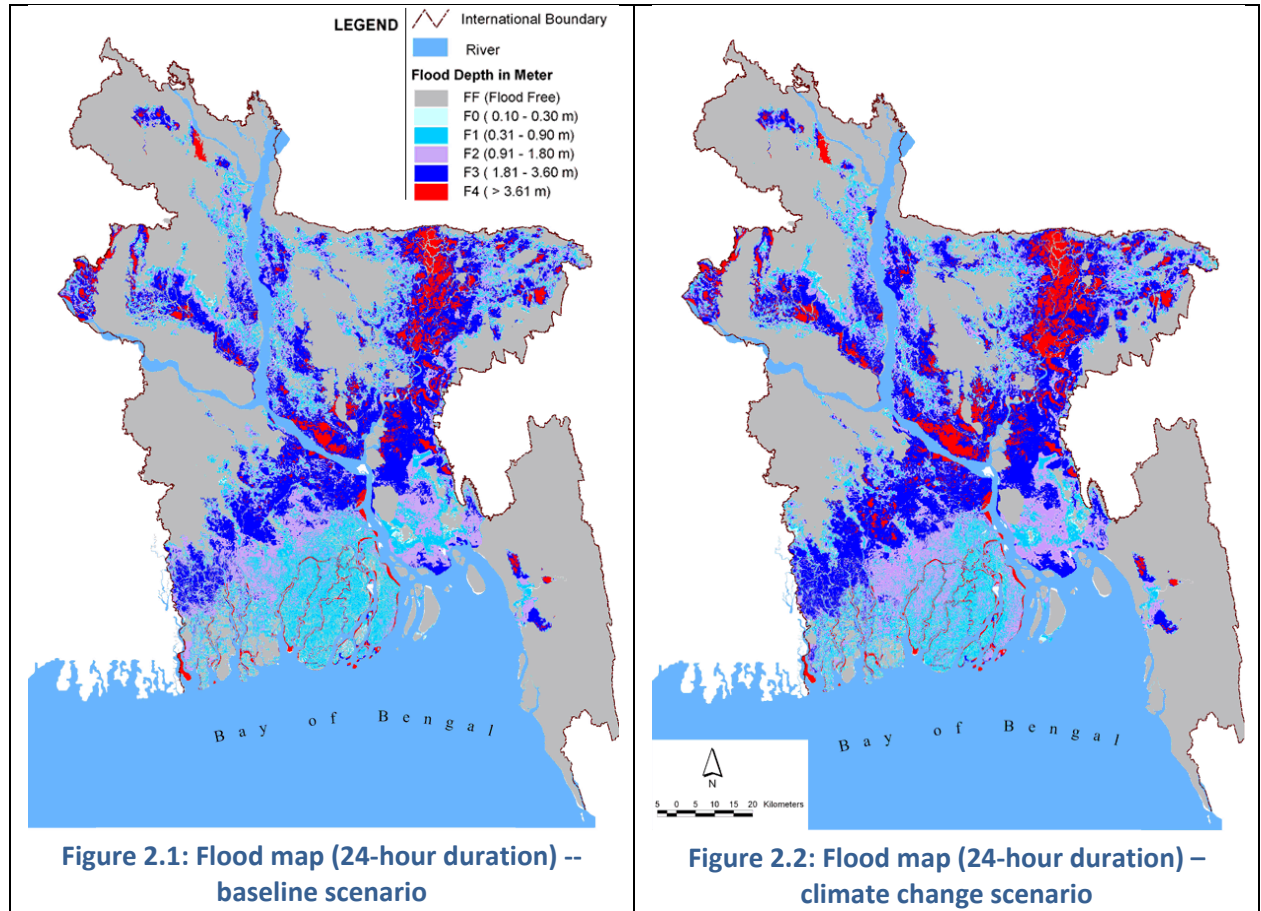
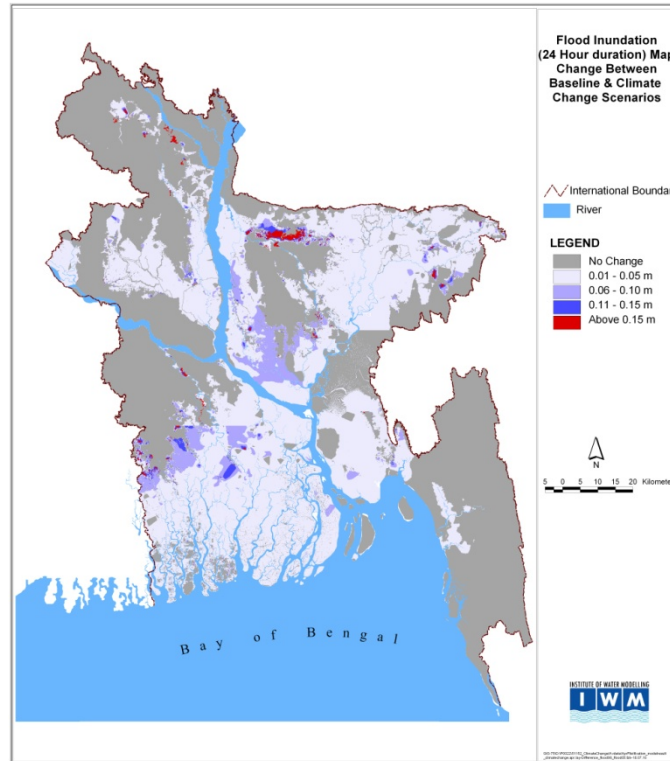


Figure 3: Change in inundation depth due to climate change



The flood of 1998 is the longest-lasting and most devastating flood Bangladesh has experienced in 100 years. In total, 53 of the 64 districts of Bangladesh were affected by floods of differing magnitude; about 50 per cent of the country was under water for up to 67 days, and depth of inundation was estimated to be up to 3 m. In particular, Comilla, Chitagong, Cox's Bazar, Faridpur, Feni, Gaibandha, Hobiganj, Jamalpur, Khagrachari, Kurigram, Lalmonirhat, Manikganj, Mymensingh, Natore, Nilphamari, Pabna, Rajbari, Rajshahi, Rangpur, Sherpur, Sirajganj and Tangail, districts were severely affected.

Flooding prevailed at a stretch from July to mid-September and the situation became critical on (i) July 28 (30 per cent of the country was inundated), August 30 (41 per cent of the country was inundated), and September 7 (when 51 per cent of the country was inundated). The extent of the flooding in Bangladesh on 7 September was probably the greatest of the twentieth century.

Lingering intensive rain throughout Bangladesh during July – August 1998, simultaneous and constant above-danger-level flows of the three major rivers: Ganga, Brahmaputra, Meghna, backwater effects resulting from the synchronization of the peak flow of the three major rivers between September 7 and September 9 and the high tides, the La Nina situation have been identified as the major contributing factors to the devastating flood of 1998. Post disaster damage and loss estimates indicate 31 million people were affected and the floods caused a loss of \$2 billion in Bangladesh.

