

THE WORLD BANK

BANGLADESH Development Series



67845



The Cost of Adapting to Extreme Weather Events in a Changing Climate

The Cost of Adapting to Extreme Weather Events in a Changing Climate

BANGLADESH
Development Series
Paper No. 28

THE WORLD BANK

December, 2011





The World Bank

World Bank Office Dhaka

Plot - E-32 , Agargaon,
Sher-e-Bangla Nagar,
Dhaka- 1207, Bangladesh
Tel: 880-2-8159001-28
Fax: 880-2-8159029-30
www.worldbank.org.bd

World Bank

1818 H Street, N.W.
Washington DC 20433, USA
Tel: 1-202-4731000
Fax: 1-202-477-66391
www.worldbank.org

All Bangladesh Development Series (BDS) publications are downloadable at:

www.worldbank.org.bd/bds

Standard Disclaimer:

This volume is a product of the staff of the International Bank for Reconstruction and Development/The World Bank. The findings, interpretations, and conclusions expressed in this paper do not necessarily reflect the views of the Executive Directors of the World Bank or the governments they represent. The World Bank does not guarantee the accuracy of the data included in this work. The boundaries, colors, denominations and other information shown on any map in this work do not imply any judgment on the part of the World Bank concerning the legal status of any territory or the endorsement or acceptance of such boundaries.

Copyright Statement:

The material in this publication is copyrighted. The World Bank encourages dissemination of this work and will normally grant permission to reproduce portion of the work promptly.

Map Credits:

The maps published in this report were produced by the Institute of Water Modeling (IWM) (Figs. 2.1, 2.2, 4.1, 4.3, 5.1 and Box 1.2) and the Center for Environmental and Geographic Information Services (CEGIS) (Fig 5.2).

Cover Photo: Quddus Alam/DrikNEWS/Majority World

Back Cover Photo: Palash Khan/Drik/Majority World

Design & Print: Progressive Printers Pvt. Ltd.

Foreword

Global warming is expected to have severe consequences for developing countries prone to extreme weather events. Projections by the Intergovernmental Panel on Climate Change and the World Meteorological Organization suggest an increase in the frequencies and/or intensities of climate extremes in the 21st century. Some recent examples illustrate how severe the consequences of such extreme weather events can be: heavy floods in Australia and Brazil in 2011; extreme winter weather throughout Europe in 2010; Russia's heat wave in 2010; devastating floods in Pakistan, India, China, and Mozambique in 2010; and super cyclones in Myanmar in 2008 and Bangladesh in 2007.

Adaptation to increased risks of severe weather events, as well as other impacts of climate change, is essential for development. Adaptation will require climate-smart policies and investments to make countries more resilient to the effects of climate change, including losses of property, habitat, infrastructure, and lives. Country governments and their citizens, as well as development partner institutions and climate negotiators, need a better understanding of the potential damage due to climate change and adaptation costs to formulate effective adaptation to extreme weather events.

To shed light on potential damage from extreme weather events and adaptation costs, World Bank staff and experts from the Institute of Water Modeling and the Center for Environmental and Geographic Information Services in Bangladesh have conducted a study on the potential intensification of inland monsoon floods and cyclones for Bangladesh in a changing climate. This study is timely and of prime importance as it identifies vulnerable populations and infrastructure, quantifies outstanding deficits in dealing with current climate-related risks, and estimates the cost of adaptation to avoid further damage due to climate change.



John Henry Stein
Sector Director
Sustainable Development
South Asia



Ellen Goldstein
Country Director
Bangladesh

Acknowledgments

This report was prepared by a team consisting of Maria Sarraf (Task Team Leader), Susmita Dasgupta (Lead Environment Economist), and Norma Adams (Editor). The team would like to thank Naomi Ahmad, Faria Selim, Luis Andres, Ainun Nishat, Mehrin A. Mahbub, Khawaja Minnatullah, and Sayeeda Salim Tauhid for their valuable input.

The report combines the results of two studies: *Vulnerability of Bangladesh to Cyclones in a Changing Climate*, prepared by Susmita Dasgupta, Mainul Huq, Zahirul Huq Khan, Manjur Murshed Zahid Ahmed, Nandan Mukherjee, Malik Fida Khan, and Kiran Pandey; and *Climate Proofing Infrastructure in Bangladesh*, prepared by Susmita Dasgupta, Mainul Huq, Zahirul Huq Khan, Md. Sohel Masud, Manjur Murshed Zahid Ahmed, Nandan Mukherjee, and Kiran Pandey. Both studies were prepared under the World Bank-supported Economics of Adaptation to Climate Change Program.

The team would like to acknowledge the financial support provided by the Bangladesh Climate Change Resilient Fund (BCCRF), funded by the Department of International Development of the United Kingdom, the Embassy of Denmark in Bangladesh, the European Commission, the Swedish International Development Cooperation Agency, and the Swiss Agency for Development and Cooperation.

Abbreviations and Acronyms

BCCSAP	Bangladesh Climate Change Strategy and Action Plan
BMD	Bangladesh Meteorological Department
BWDB	Bangladesh Water Development Board
CEGIS	Center for Environmental and Geographic Information Services
EACC	Economics of Adaptation to Climate Change
GBM	Ganges, Brahmaputra, and Meghna
GCM	General Circulation Model
GIS	Geographic Information System
IPCC	Intergovernmental Panel on Climate Change
IWM	Institute of Water Modelling
MIROC	Model for Interdisciplinary Research on Climate
RCM	Regional Climate Model
VSL	Value of Statistical Life

Currency Equivalents

2009 US\$1 = 70 Bangladesh takas (Tk.)

Vice-President	Isabel M. Guerrero
Country Director	Ellen A. Goldstein
Sector Director	John Henry Stein
Sector Manager	Herbert Acquay
Task Team Leader	Maria Sarraf

Contents

Executive Summary	xiii
Chapter 1. Monsoon Floods and Cyclones	01
Exposure to monsoon floods	01
Exposure to cyclones	03
Building resilience over the years	05
Added risk of climate change	06
Moving forward	06
Study objective and scope	06
Chapter 2. Added Inundation from Inland Monsoon Floods in a Changing Climate	09
Added risk of climate change	09
Changes in potential inundation zones and depths due to climate change	10
Population at risk	13
Chapter 3. Adaptation Cost: Inland Monsoon Floods	15
Infrastructure at added risk of monsoon flood inundation due to climate change	15
Roads	15
Cross-drainage road facilities	17
Railways	17
River embankments	18
Coastal polder drainage	18
Scour protection	19
Cost of added inundation from inland monsoon floods	19
Chapter 4. Added Inundation from Cyclones in a Changing Climate	21
Added risk of climate change	21
Changes in potential storm-surge zones and depths due to climate change	22
Coastal population at risk	24

Chapter 5. Adaptation Cost: Cyclones	25
Infrastructure at added risk of storm-surge inundation due to climate change	25
Height enhancement of coastal polders	26
Afforestation protection of sea-facing polders	27
Multipurpose cyclone shelters	27
Cyclone-resistant private housing	28
Strengthened early warning and evacuation system	29
On further infrastructure investment	29
Cost of added inundation from cyclones and related storm surges	29
Chapter 6. Toward Adaptation and Investment Planning	31
References	33
Appendix: Impact of a 10-year-return-period Cyclone in Bangladesh by 2050	37

Tables

Table 1	Total adaptation cost for inland monsoon floods (at 2009 prices)	xvi
Table 2	Total adaptation cost for cyclones and associated storm surges by 2050 (at 2009 prices)	xvii
Table 2.1	Inundation-area estimates out to 2050	11
Table 2.2	Additional inundation depths with climate change	12
Table 2.3	Vulnerable population estimates for inland monsoon floods	13
Table 3.1	Length of road (km) at added risk of inundation from climate change by 2050	16
Table 3.2	Adaptation cost by road type (million US\$)	17
Table 3.3	Railway tracks at risk of inundation by 2050 with climate change	17
Table 3.4	Itemized cost of raising river embankments (million US\$)	18
Table 3.5	Total adaptation cost for inland monsoon floods	20
Table 4.1	Vulnerable population estimates for cyclonic storm surges	24
Table 5.1	Estimated cost of enhancing height of coastal embankments (million US\$)	27
Table 5.2	Total adaptation cost for cyclones and associated storm surges by 2050	30
Table A-1	Cost (US\$) to enhance height of coastal embankments	39
Table A-2	Added potential damage and loss from an average cyclone-induced inundation in a changing climate by 2050 (\$2009 prices)	41

Figures

Figure 2.1	Comparison of risk-exposure zones for 24-hour duration floods	11
Figure 2.2	Change in inundation depths across Bangladesh	12
Figure 4.1	Tracks of major cyclones in 1960-2009 spanned Bangladesh's entire coastline.	22
Figure 4.2	Five cyclone tracks span Bangladesh's entire coastline under the climate-change scenario.	23
Figure 4.3	High risk area by 2050 in a changing climate (Source: IWM)	23
Figure 5.1	In a changing climate, 33 sea-facing and 26 interior polders will likely be overtopped by 2050.	26
Figure 5.2	Spatial locations of existing cyclone shelters in coastal areas	28

Boxes

Box 1.1	History of Inland Monsoon Floods	02
Box 1.2	History of Cyclones and Related Storm Surges	04

Executive Summary

Bangladesh is one of the most climate vulnerable countries in the world. Situated in the delta of the Ganges, Brahmaputra, and Meghna (GBM) rivers, the country is exposed to a range of river and rainwater flood hazards due to climate variability, the timing, location, and extent of which depend on precipitation in the entire GBM basin. The country's topography is extremely low and flat, with two-thirds of its land area less than 5 m above sea level. Low-lying coastal districts along the Bay of Bengal are particularly vulnerable to tidal flooding, cyclones, and related storm surges. Given that the current population of 150 million is expected to reach about 230 million by 2050*, any further intensification of climatic variability will affect the country in a significant way.

Climate change will likely increase the exposure of densely populated, low-lying areas to intensified flooding and cyclones. Since 1954, Bangladesh experienced 21 above-normal floods, 4 of which were exceptional and 2 catastrophic. The scientific consensus for the GBM basin is a projected temperature rise of 1-3°C and 20 percent more monsoon rainfall by 2050, suggesting that Bangladesh will be exposed to more severe inland flooding. The country is also a global hotspot for tropical cyclones. A severe cyclone strikes the country every three years, on average. Increase in ocean surface temperature and rising sea levels are predicted to intensify

cyclones. Cyclonic storm surges are expected to cover an additional 15 percent of coastal area, with greater inundation depth. Without strengthening coastal polders, 6-8 million people could be displaced by 2050 if sea-level rise is higher than currently projected.

The Government of Bangladesh is fully committed to global climate-change advocacy and action, having already invested heavily in adaptation measures and policies. In recent decades, the government has invested more than US\$10 billion to protect its population and assets in the floodplains. Such measures as strengthening river embankments, building emergency cyclone shelters, and developing a world-class, community-based early warning system have significantly reduced the loss of life and livelihoods and property damage caused by extreme weather events. Notwithstanding that climate change may put all the recent gains in resilience at incredible risk.

The government recognizes intensification of inland monsoon flooding and tropical cyclones in a changing climate as major climate hazards requiring a rapid, strategic response. The Bangladesh Climate Change Strategy and Action Plan (BCCSAP), adopted prior to the Copenhagen Summit in 2009, identified inland monsoon flooding and tropical cyclones accompanied with storm surges as two of the three major climate hazards facing the country.

* The estimate is based on a 1.15-percent annual population growth.

Taking into account projected population growth, the government acknowledges that disaster preparedness and resilience must be scaled up to maintain the country's stable growth path and thus avoid jeopardizing the livelihoods and long-term health of the Bangladesh people.

Study objective

Given the uncertain magnitude and timing of the added risks from climate change, it is essential to identify the costs of climate-proofing Bangladesh's critical infrastructure from intensified monsoon floods and cyclonic storm surges. Previously, few if any detailed studies have been developed on the costs of climate-proofing the country's infrastructure assets from inland monsoon floods and cyclones. Most analytical work to date has been confined to case studies, with relatively limited sets of locations, impacts, and adaptation measures.

This study aims to fill that knowledge gap by providing detailed vulnerable population estimates and estimates of the incremental costs of asset adaptation out to the year 2050. It is part of a larger World Bank-supported study, entitled Economics of Adaptation to Climate Change (EACC), funded by the governments of the United Kingdom, the Netherlands, and Switzerland. This 2010 study takes the BCCSAP as its starting point, building on and strengthening the analytical models and quantitative assessment tools used to support the plan's research and management theme. Two of the four discrete areas developed for analysis and quantification under the EACC study are inland monsoon floods and tropical cyclones and related storm surges.

For these two climate hazards, this study integrated information on climate change, population and assets at risk, growth projections, and cost estimates. In each case, the first step was to demarcate the potential inundation zone and projected depth of inundation for a baseline scenario without climate change and one with climate change. The next step was to identify the critical populations and infrastructure exposed to the added risk of inundation in a changing climate. The final step was to quantify the cost of adapting these assets to avoid further damage due to climate change.[†]

Inland monsoon floods

For inland monsoon floods, the 1998 exceptional flood, with a 90-year return period, was taken as the baseline scenario. This flood—the most severe on record in terms of both duration and inundation depth—was the counterfactual against which future climate change risk was measured. For the scenario with climate change, the MIROC 3.2 General Circulation Model, under the A2 emissions scenario of the Intergovernmental Panel on Climate Change which results in the largest increase in runoff for Bangladesh, was used to predict changes in monthly precipitation and temperature between 1998 and 2050. To approximate the monthly precipitation and temperature over the entire GBM basin in 2050, projections for each 50 km x 50 km grid covering the basin was applied to the historical monthly averages for 1998.

Risk exposure out to 2050 was identified under both the baseline and climate-change scenarios. Transboundary flows and estimated runoffs from the GBM basin were simulated using models developed at the Flood Forecasting

[†] Given the lack of detailed, location-specific data on the functional status of existing infrastructure and the current risk of overtopping and breakdowns during a disaster, the focus of this analysis is to avoid further damage from additional inundation due to climate change.

and Warning Centre of the Bangladesh Water Development Board. The national flood model was used to generate flood levels, extent of inundation, and duration of extreme flood events during the monsoon period. The results of daily inundation depth were synthesized to determine the highest depths during the monsoon period, identify the most vulnerable areas, and group them into five risk-exposure zones. Under the baseline scenario, 45 percent of land would be under at least 0.3 m of water. **Under the climate-change scenario, the total flooded area would increase by 4 percent, and in most flooded areas, inundation depth would also rise.**

To determine the number of people exposed to inland monsoon floods under the two scenarios at various inundation depths, the flood risk exposure map was overlaid on the 2001 population map, using Geographic Information System (GIS) software. In 2001, about 23 million people lived in rural areas with estimated inundation depths greater than 0.3 m. By 2050, that number is expected to fall to 19.2 million, owing to urban migration. However, the area inundated is likely to expand with climate change, with an additional 1.9 million lives affected by the newly inundated areas. **In a changing climate, therefore, a total of 21.1 million rural people would be at risk of inundation depths greater than 0.3 m, and most people living in inundated areas would be exposed to higher depths.**[‡]

To estimate the cost of climate-proofing infrastructure-railways, river embankments, and drainage structures-the added risk of flood inundation due to climate change was determined, using GIS software. Areas with large expected changes in inundation depth are spread out across Bangladesh. Although climate

change is likely to increase inundation depth in about half of land area, depths greater than 15 cm are expected to occur in less than 0.5 percent of the country. Current spatial distribution of infrastructure was taken as the starting point for identifying which assets would be most vulnerable to the added risk of inundation by 2050.

Cyclones

To approximate cyclonic storm surges in a changing climate by 2050, the study considered a sea-level rise of 27 cm, increased wind speed of 10 percent, and landfall during high tide. Under the baseline scenario, tracks of 19 major historical cyclones that made landfall between 1960 and 2009 were used, along with their observed wind and pressure fields. Simulation modeling was used to generate the extent and depth of inundation from storm surges and associated flooding. Under the climate-change scenario, the same historical cyclones and affected coastal regions were used to simulate potential tracks out to 2050. Overlapping cyclone tracks covered the Sundarban coast, southwestern coast (Sundarban to Patuakhali), Bhola and Noakhali coast in the Meghna Estuary, and eastern coast (Sitakunda to Banshkhali). An artificial track was generated to cover the Sandwip coast and parts of the Noakhali and Chittagong coasts in the central part of the Meghna Estuary. Together, these five tracks were used to determine the inundation zones due to climate change-induced storm surges.

To determine potential future inundation zones by 2050 under the climate-change scenario, the storm-surge model was run for the five cyclone tracks. Based on simulation results, inundation maps for 2050 were generated.

[‡] The estimates for exposed populations in 2050 are based on a 1.15-percent annual growth in rural and urban populations, applied uniformly across the country. These projections do not account for autonomous adaptation by rural households in response to changing flood-risk conditions or the implementation of land-use and coastal zone management policies put in place by the government over the past decade.

Under the climate-change scenario, the vulnerable area would be 55 percent greater than under the baseline scenario, with an additional 2 m of inundation depth.

Currently, cyclonic storm surges expose 8 million people in coastal Bangladesh to inundation depths greater than 1 m. With upswing population growth, that figure would likely increase 68 percent by 2050 under the baseline scenario. **In a changing climate without further adaptation measures, nearly 17 million people would be exposed to inundation depths greater than 1 m, and about 13.5 million to depths greater than 3 m.** To identify the added inundation risk to the extensive infrastructure that protects low-lying coastal areas-polders, cyclone shelters, and early warning and evacuation systems-GIS software was used to overlay the best available, spatially-disaggregated data on current assets and activities with projected inundation zones for 2050 under the two scenarios.

Adaptation cost: Inland monsoon floods

By 2050, an estimated US\$3.3 billion will be required to protect roads, railways, river embankments, and drainage infrastructure against the added inundation from inland monsoon floods due to climate change. Recent major floods have proven that Bangladesh's standards for national and regional roads are

insufficient to prevent large losses of road infrastructure. In addition, the inadequacy of drainage facilities for these roads is likely to worsen in a changing climate in the upfront. Furthermore, climate change will subject most of the country's rail network and river embankments to 0.5 m of added inundation and increase drainage congestion in coastal polders and scour depths of unprotected river banks (Table 1).

More than 83 percent of this adaptation cost, about US\$2.72 billion, is for raising the height of the road network. Additional cross-drainage of coastal polders accounts for another 13 percent, while the remaining measures-river embankment enhancement, railway height enhancement, and road cross-drainage-together account for less than 4 percent of the total cost.

It should be noted that for the climate change scenario considered, these cost estimates for inland monsoon flood protection provide a lower bound on the actual costs of adaptation as they do not include the added adaptation required in urban areas and currently unprotected river banks. Lacking location-specific data on the functional status of existing infrastructure and the current risk of overtopping and breakdowns during a monsoon flood, this analysis could not quantify the adaptation deficit.

Table 1 Total adaptation cost for inland monsoon floods (at 2009 prices)

Cost component	(million US\$)
Road height enhancement	2,718
Road cross-drainage	5
Railway height enhancement	27
River embankment enhancement	96
Cross-drainage of coastal polders	421
Total cost	3,267

Adaptation cost: Cyclones

Despite the extensive infrastructure Bangladesh has in place to protect coastal residents from cyclonic storm surges and tidal waves, it has a current adaptation deficit of US\$2.46 billion.[§] In a changing climate, the greater expanse and depth of the areas inundated will put many more existing structures at risk. By 2050, nearly half of the country's 123 coastal polders will be overtopped, and inadequate mangrove forests will mean higher-velocity storm surges. Moreover, the capacity of life-saving cyclone shelters and early warning and evacuation systems will be exceeded.

By 2050, the adaptation cost of coping with cyclonic storm surges in a changing climate will total about US\$2.4 billion, with an annual recurrent cost of more than \$50 million. The costing of adaptation refers to the increased inundation area and depth for a 10-year return cyclone in a changing climate (Table 2).

multipurpose cyclone shelters needed to protect the additional coastal residents exposed to inundation risk. More than one-third of the total cost is for enhancing the height of polders-33 sea-facing and 26 interior polders-while the remainder is dedicated to constructing cyclone-resistant private housing, increasing coastal afforestation to protect sea-facing polders, and strengthening the early warning system.

It should be noted that this analysis for cyclonic storm-surge protection does not address the likely problem of salinity intrusion or the out-migration from the coastal zone that may be induced by a rise in sea level and intensified storm surges.

Toward adaptation and investment planning

By 2050, the total adaptation cost to offset the added inundation from climate change is estimated at US\$5.7 billion^{**}: \$3.3 billion to protect infrastructure from inland monsoon

Table 2 Total adaptation cost for cyclones and associated storm surges by 2050 (at 2009 prices)

Measure	Baseline scenario	Additional cost with climate change	
	Investment (million US\$)	Investment (million US\$)	Annual recurrent cost (million US\$)
Polders	2,462	892	18
Foreshore afforestation		75	
Multipurpose cyclone shelters		1,200	24
Cyclone-resistant private housing		200	
Strengthening early warning system		39	8 +
Total	2,462	2,407	50 +

About half of this adaptation cost-US\$1.2 billion-is for constructing an extra 5,700

floods and \$2.4 billion for storm-surge protection. The comparison of even a

[§] Deficits in dealing with current climate-related risks.

^{**} This represent about 5.7% of GDP (at 2009 current price)

conservative damage estimate from a single 10-year-return-period cyclone (Appendix), with the storm-surge protection cost, indicates the incremental cost of adapting to climate change by 2050 is small compared to the potential damage, strengthening the case for rapid adaptation.

Given the large uncertainties about the magnitude and timing of added risks from climate change, however, sequencing of adaptation actions is a necessity, particularly in a fiscally constrained environment. The itemized adaptation cost estimates presented in this report can serve as a tool to enable decision makers in Bangladesh to prioritize and sequence adaptation actions and investments, as resources permit. Recognizing the uncertainties in the timing and magnitude of impacts of climate change, a prudent strategy would begin by addressing existing risks that current residents face. Existing investments, which have reduced the impacts of floods and cyclones, provide a solid foundation for undertaking additional measures to reduce potential damages now and

in the future.

It should be noted that the evaluation presented in this report has assumed that the infrastructure investments will be made within a framework of appropriate development policies and efficient institutional arrangements.

Taken alone, these "hard" adaptation investments cannot yield the expected benefits. Sound public policies, prudent planning, and institutions with highly skilled human resources are required to ensure that such capital-intensive measures are wisely implemented. In the longer horizon, physical measures may not reduce losses and human suffering as much as expected. They must be complemented by education, job training, and other "soft" investments designed to reduce reliance on resources and assets whose value may be eroded by climate change. Finally, adaptation planning should not attempt to resist the impact of climate change. Rather, it should offer a sustainable path that accommodates its effects in the least disruptive way without placing a disproportionate burden on the poor and vulnerable.

Chapter

Monsoon Floods and Cyclones

Bangladesh is widely recognized as one of the world's most climate vulnerable countries. Situated in the delta of the Ganges, Brahmaputra, and Meghna (GBM) rivers, the country is exposed to a range of climate variability, from seasonal droughts to severe monsoon floods, tropical cyclones and related storm surges. Natural disasters regularly strike, often resulting in loss of life and severe damage to infrastructure and economic assets. The crops and livelihoods of the rural poor, including those living along densely-populated coastlines, are especially sensitive to climate hazards. The country faces numerous climate change-related challenges linked to the greater watershed beyond its borders. This chapter briefly reviews Bangladesh's recent history of inland monsoon floods and cyclones and the risk of climate change to recent gains in adaptation.

Exposure to monsoon floods

Bangladesh ranks as the sixth most flood-prone country in the world (UNDP 2004). In an average year, nearly one quarter of Bangladesh is inundated, with more than three-fifths of land area at risk of floods of varying intensity (Ahmed and Mirza 2000). Every four or five years, a

severe flood occurs during the monsoon season, submerging more than three-fifths of the land (GOB 2009). Since 1954, the country has experienced 21 above-normal floods, 4 of which were exceptional and 2 catastrophic (Box 2.1).¹

The most recent exceptional flood, which occurred in 2007, inundated 62,300 km² or 42 percent of total land area, causing 1,110 deaths and affecting 14 million people; 2.1 million ha of standing crop land were submerged, 85,000 houses completely destroyed, and 31,533 km of roads damaged. Estimated asset losses from this one event totaled US\$1.1 billion (BWDB 2007).

Flooding in Bangladesh results from a complex set of factors, key among which are extremely low and flat topography, uncertain transboundary flow,² heavy monsoon rainfall, and high vulnerability to tidal waves and congested drainage channels. Two-thirds of Bangladesh's land area is less than 5 m above sea level. Each year, an average flow of 1,350 billion m³ of water from the GBM basin drains through the country. During the summer monsoon season, when the country receives about four-fifths of its annual rainfall, the three rivers have a combined peak flow of 180,000 m³ per second.³

¹ A flood whose inundation area exceeds 21 percent of Bangladesh's total land area has been *classified* as *above normal*; above-normal floods have been further divided into four subcategories: moderate (21-26 percent inundation area), severe (26-34 percent inundation area), *exceptional* (34-38.5 percent inundation area), and *catastrophic* (more than 38.5 percent inundation area) (Mirza 2002).

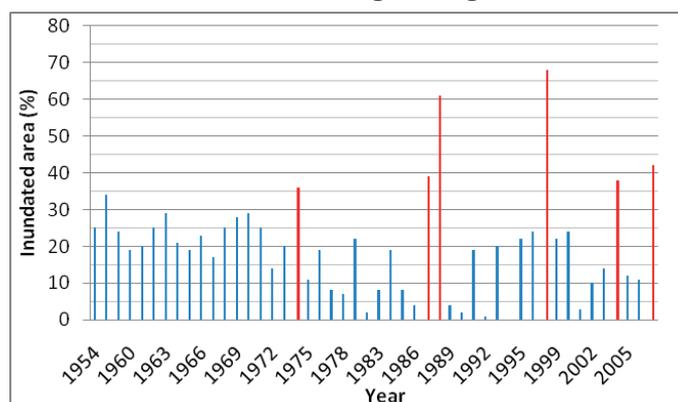
² Fifty-seven international rivers flow into Bangladesh.

³ Surpassed only by that of the Amazon.

Box I.1 History of Inland Monsoon Floods

The historical record of floods in Bangladesh indicates that a significant number of above-normal floods occurred between 1890 and 2007. Time-series analysis indicates that this above-normal flooding has not followed any regular pattern historically. From 1892 to 1922, there was frequent flooding, while the subsequent 50 years had few above-normal floods. Since 1950, however, the frequency of above-normal flood events has increased (Hofer and Messerli 2006).

Extent of above-normal flooding in Bangladesh, 1950-2009



Source: CEGIS (2010).

Statistics on recent floods show that the extent of inundation from severe floods may exceed two-thirds of total land area.

Recent exceptional or catastrophic floods in Bangladesh						
Impact	1974	1987	1988	1998	2004	2007
Area affected (thousand km ²)	53	57	90	100	56	62
% total land area inundated	37	40	63	69	39	42
Millions of people affected	30	30	47	31	33	14
Fatalities (no.)	28,700	1,657	2,379	918	285	1,110
Houses damaged (thousands)	na	989	2,880	2,647	895	1,000
Roads damaged (km)	na	na	13,000	15,927	27,970	31,523
Crops damaged (millions of 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 (million US\$)	12,459	23,969	26,034	44,092	55,900	68,400
Asset losses (% of GDP)	7.5	4.9	5.5	4.8	3.3	1.6
Return period (years)	9	13	55	90	12	14

Sources: Islam and Mechler (2007); BWDB (2007).

The exceptional flood of 1998, the most severe on record in terms of both depth of inundation and duration, affected 69 percent of total land area. Nearly 100,000 km², including 6,000 km² of standing crop lands, were flooded; about 1 million households suffered property damage, and 16,000 km of roads and 6,000 km of embankments were affected. About half of the country was under water for up to 67 days, with inundation depth reaching up to 3 m. All but 11 of the country's 64 districts experienced flooding of varying magnitude.

Major factors contributing to such extreme devastation included lingering intensive rain in July and August 1998; simultaneous above-danger flow levels of the Ganges, Brahmaputra, and Meghna rivers; backwater effects resulting from synchronization of peak flow of the three rivers and high tides; and the La Niña effect at that time (World Bank 2010).

Exposure to cyclones

Bangladesh is also a global hotspot for tropical cyclones.⁴ Nearly every year, cyclones hit the country's coastal regions in the early summer (April-May) or late rainy season (October-November). Between 1877 and 1995, Bangladesh was hit by 154 cyclones, including 43 severe cyclonic storms, 43 cyclonic storms, and 68 tropical depressions.⁵ On average, a severe cyclone (26-34 percent inundation area) strikes the country every three years (GOB 2009) (Box 1.2).

In 2007, Cyclone Sidr, a 10-year return cyclone, struck the southwest coast of Bangladesh⁶ with an average wind speed of 223 km per hour, causing 3,406 casualties, 55,282 injuries and affecting 8.9 million people. It damaged 0.6 million ha of standing crop land, completely destroyed 537,775 houses, and submerged 8,075 km of roads. Estimated damages and losses from Cyclone Sidr totaled US\$1.67 billion (GOB 2008).

Records indicate that the greatest damage during cyclones has resulted from the inundation caused by cyclone-induced storm surges.⁷ Though time-series records of storm-surge height are scarce in Bangladesh, existing

literature indicates a 1.5-9 m height range during various severe cyclones. Surges that make landfall during high tide are even more devastating. In general, it has been observed that the frequency of a 10-m high wave (surge plus tide) along the Bangladesh coast is about once every 20 years, while a wave with a 7-m height occurs about once in 5 years. In addition, wind-induced waves of up to 3.0 m in height may also occur under unfavorable conditions (MCSP 1993).

Bangladesh is on the receiving end of about two-fifths of the world's total impact from storm surges (Murty and El-Sabh 1992). The reasons for this disproportionately large impact include the recurvature of tropical cyclones in the Bay of Bengal; the wide, shallow continental shelf, especially in the eastern part of the country;⁸ the high tidal range;⁹ the triangular shape at the head of the Bay of Bengal, which helps to funnel sea water pushed by the wind toward the coast, causing further surge amplification; the nearly sea-level geography of the coastal land; and the high-density population and coastal protection system (Ali 1999).¹⁰

4 The United Nations Development Programme (UNDP) has ranked Bangladesh as the world's most vulnerable country to tropical cyclones (UNDP 2004).

5 Based on the observed maximum sustained surface wind measured at a height of 10 m averaged over 3 minutes, tropical storms are classified as super cyclonic (wind speed over 220 km per hour), very severe cyclonic (119-220 km per hour), severe cyclonic (90-119 km per hour), cyclonic (60-90 km per hour), deep depression (51-59 km per hour), and depression (32-50 km per hour) (IMD 2010).

6 The four worst affected districts were Bagerhat, Barguna, Patuakhali and Piroipur. The seven moderately affected districts were Barishal, Bhola, Gopalganj, Jhalkathi, Khulna, Madaripur and Shariatpur.

7 Storm surge refers to the temporary increase in sea height in a particular locality due to extreme meteorological conditions (i.e., low atmospheric pressure and/or strong winds) (IPCC 2007).

8 This wide shelf amplifies the storm surges as the tangential sea-level wind-stress field associated with the tropical cyclone pushes the sea water from the deep water side onto the shelf; being pushed from the south by wind stress, the water has no place to go but upwards, which creates the storm surge.

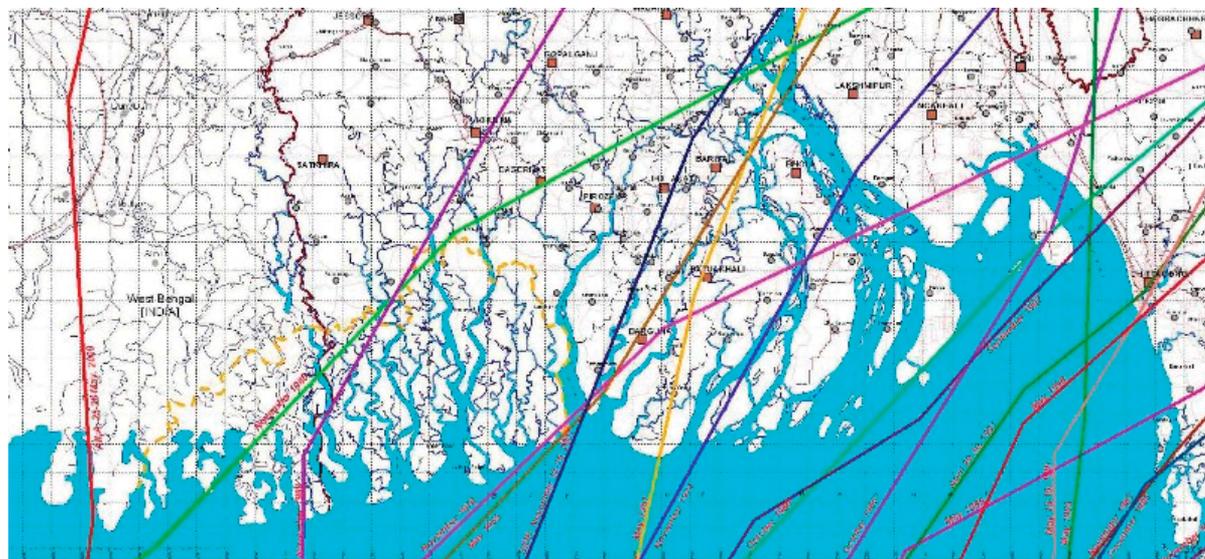
9 Records indicate 7-8 m high tide in the Sandwip Channel.

10 Most surge amplifications occur in the Meghna estuarine region.

Box 1.2 History of Cyclones and Related Storm Surges

Cyclones pose a threat to lives and property in low-lying coastal regions of Bangladesh. From 1960 to 2009, 19 major cyclones made landfall in the country; since 1995, its coast has been hit by five severe cyclones.*

Risk from major cyclones in 1960-2009 spanned Bangladesh's entire coastline



Source: IWM

The greatest damage during cyclones has resulted from the inundation caused by cyclone-induced storm surges. Existing literature indicates a 1.5-9 m height range during various severe cyclones. Storm-surge heights of 10 m or more have not been uncommon; for example, the 1876 Bakerganj cyclone had a reported surge height of 13.6 m (SMRC 2000).

Typical storm-surge features of cyclones in Bangladesh		
Wind velocity (km/hr)	Surge height (m)	Limit to coastal inundation (km)
85	1.5	1.0
115	2.5	1.0
135	3.0	1.5
165	3.5	2.0
195	4.8	4.0
225	6.0	4.5
235	6.5	5.0
260	7.8	5.5

At present, there is a 10-percent chance each year that Bangladesh will be hit by a super cyclonic storm. The extent of storm-surge inundation from Cyclone Sidr, a 10-year-return-period cyclone that hit in 2007, was 8.7 percent more than the historical average for similar storms.

Probability of higher-intensity cyclones in Bangladesh		
Cyclonic storm surge	Wind speed (km/hr)	Annual minimum probability (%)
Super	> 220	10
Very severe	119-220	20
Severe	90-119	30

* For details on major cyclones that crossed Bangladesh from 1960 to 2009, see Dasgupta et al., *Vulnerability of Bangladesh to Cyclones in a Changing Climate: Potential Damages and Adaptation Cost*, Appendices 2 and 3. World Bank, Washington, DC (2010b).

Building resilience over the years

The Government of Bangladesh is fully committed to improving the country's resilience to climate risks and has invested heavily in adaptation measures and policies. A significant investment has been made in river embankments, emergency shelters, and disaster relief operations; and the country has established infrastructure design standards and building codes.¹¹ Bangladesh now has a world-class, community-based early warning system, and has built cyclone shelters on stilts to allow storm surges to flow underneath.

Rural residents in flood-prone areas have also adapted by building their houses on raised mounds above the normal flood level. Rural roads, schools, and medical centers have been raised above normal flood level, where feasible. Farmers have adjusted their cropping patterns to take advantage of the flood water; switching from traditional low-yielding, deepwater (aman) rice to high-yielding, irrigated (boro) rice.

In general, the relative severity of the impacts from natural hazards in Bangladesh has decreased substantially since 1970s as a result of

improved macroeconomic management, increased resilience of the poor and efficient disaster management and flood protection infrastructure (World Bank, 2010). Damages from the 1974 flood, a 1-in 9-years event, totaled 7.5 percent of GDP; by contrast, the exceptional flood of 1998, which had double the inundation area, produced significantly less damage, at 4.8 percent of GDP. The increased resilience of Bangladesh to natural disasters 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 since 1990.¹² In fact, positive growth rates were sustained even after the devastating 1998 flood. Changes in cropping patterns, adequate reserves of food grains and increased rice imports by both the public and private sectors have also contributed to offset the negative effects of major flood events. Community-based early warning system and emergency cyclone shelters have significantly reduced deaths and injuries during natural disasters over time.

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

¹² Despite several major disasters, Bangladesh remains among the few countries that have avoided a single year of negative growth since the 1990s.

Added risk of climate change

These gains may be at risk if the severity of natural disasters increases with climate change. The effects of climate change are projected to exacerbate Bangladesh's vulnerability to severe monsoon floods and cyclonic storm surges (GOB 2009). Across the 16 General Circulation Models (GCMs) and three emission scenarios considered by the Intergovernmental Panel on Climate Change (IPCC), the consensus is on predicted 1-3°C temperature rise for the GBM basin by 2050 (IPCC 2007). Though estimates on precipitation changes vary widely across the GCMs, most indicate up to 20 percent more rainfall during the monsoon season (July-September). Heavier, more erratic rainfall in the GBM system during the monsoon season is expected to aggravate the extent of inland flooding in Bangladesh. Increase in ocean surface temperature and rising sea levels are likely to intensify cyclonic storm surges and further increase the depth and extent of storm surge-induced coastal inundation (IPCC 2007; World Bank 2010).

More intense inland and coastal floods may overtop and breach embankments, causing greater erosion of river banks, resulting in loss of homes and agricultural land, and more sedimentation of riverbeds, leading to drainage congestion and water logging. Damages and losses will likely be geographically concentrated in areas that also have the highest concentrations of the poor and most vulnerable populations, whose livelihoods, including agriculture and fisheries, are extremely weather-sensitive.

Moving forward

Keenly aware of the potentially disastrous environmental and socioeconomic consequences of future climate extremes, the Government of Bangladesh is fully committed to global climate-change advocacy and action, having already

invested heavily in adaptation measures and adoption of policies to address the effects of more frequent and destructive water-related weather events. The Bangladesh Climate Change Strategy and Action Plan (BCCSAP), adopted prior to the Copenhagen Summit in 2009, identified inland monsoon flooding and tropical cyclones and related storm surges as two of the three major climate hazards facing the country; ensuring adequate flood protection infrastructure is one of six pillars identified in the BCCSAP (GOB 2009).

The government has already committed about US\$200 million from its own resources to establish a climate change fund, called the *Bangladesh Climate Change Trust Fund*, to address the priority adaptation needs of the most vulnerable sectors. It recognizes that water-related climate hazards require a rapid, strategic response to maintain the country's stable growth path and thus avoid enormous adverse effects on livelihoods and the long-term health of the Bangladesh people, including the poorest and most vulnerable families.

Study objective and scope

Given the large uncertainties about the magnitude and timing of the added risks from climate change in Bangladesh, it is essential to identify the costs of adapting the country's critical infrastructure to intensified monsoon flooding and storm-surge patterns. To date, however, few if any systematic studies have been developed on the costs of climate-proofing Bangladesh's infrastructure. Previously, most analytical work has been confined to case studies, with relatively limited sets of locations, impacts, and adaptation measures (Khalil 1992; Hoque 1992; Ali 1999). The present study seeks to fill in the knowledge gap by providing estimates of vulnerable area, population at risk, and itemized incremental costs of adapting critical infrastructure to intensified monsoon floods and

cyclones and related storm surges out to the year 2050.

To itemize the estimates of adaptation cost to climate change, this study integrates information on climate change, hydrodynamic models, and geographic overlays to assess the vulnerability of Bangladesh to larger monsoon floods and larger storm surges and sea-level rise by 2050. In each case, the study first demarcated the potential inundation zone and projected depth of inundation for both a baseline scenario without climate change and one with climate change out to the year 2050. It then identified the critical impact elements and populations and infrastructure exposed to the added risk of inundation in a changing climate. Finally, it quantified the cost of adapting infrastructure to avoid further damage due to climate change.¹³ At the outset, it should be noted that in the absence of detailed location-specific data on the

functional status of existing infrastructure and the current risk of overtopping and breakdowns during a disaster, the focus of the study was to avoid further damage from additional inundation due to climate change.

The remainder of the report is organized as follows. Chapter 2 details the potential inundation zones and depths and identifies the population at added risk from monsoon floods in a changing climate; Chapter 3 then quantifies the cost of climate-proofing infrastructure for inland monsoon floods out to the year 2050. Similarly, Chapter 4 details the potential inundation zones and depths and populations at added risk from cyclonic storm surges in a changing climate; while Chapter 5 identifies critical infrastructure at added risk and provides the total and itemized adaptation cost estimates. Finally, Chapter 6 concludes and suggests broad policy recommendations.

¹³ This study is part of a larger World Bank-supported study, entitled the Economics of Adaptation to Climate Change (EACC). The EACC study was developed in four discrete areas with varying degrees of analytical depth and quantification: (i) inland monsoon floods, (ii) tropical cyclones and related storm surges, (iii) impacts on agriculture and food security, and (iv) local perspectives on adaptation (World Bank 2010).

Chapter 2

Added Inundation from Inland Monsoon Floods in a Changing Climate

Bangladesh has extensive infrastructure—including embankments, shelters, and early warning and evacuation systems—to protect its population and assets in the floodplains. Such protective measures have significantly reduced the loss of life and livelihoods and property damage resulting from extreme weather events over time. Yet the warmer, wetter future projected for the GBM basin suggests that future inundation from above-normal flood events will exceed the country's current level of disaster preparedness.

This chapter briefly reviews the forecast of monsoon floods in a changing climate, details the potential inundation zones and depths, and identifies populations at added risk from this climate hazard.

Added risk of climate change

Bangladesh is located at the mouth of the GBM basin. The entire GBM basin (an average of 1,350 billion m³ of water flow per year) drains through Bangladesh. Hence, the timing, location, and extent of flooding depend not only on the 7 percent of precipitation that occurs within Bangladesh's borders but on that of the entire GBM basin.

Most climate-related research points to a warmer, wetter GBM basin in the coming decades. Increased rainfall in the upper GBM basin is expected to result in higher river flows from Nepal, India, China, and Bhutan into Bangladesh (IPCC 2007). Mirza and Dixit (1997) estimated that a 2^o C warming, combined with a 10-percent increase in precipitation, would increase runoff by 19 percent for the Ganges, 13 percent for the Brahmaputra, and 11 percent for the Meghna. In Bangladesh, depth of flooding would be pronounced in the lowlands of southwest Dhaka, Rajshahi, and Sylhet, and the districts of Faridpur, Pabna, Comilla, and Mymensingh. In a more recent study, Mirza et al. (1998) reported a 5-percent increase in precipitation for the GBM basin, combined with 1^o C temperature rise, could result in up to a 20-percent increase in flooded area. Severity of extreme floods, such as the 20-year flood event, is estimated to increase marginally. Another study conducted in 1998 concluded that a 1-20 percent increase in monsoon rainfall will increase surface runoff by 20-45 percent in Bangladesh (Ahmed and Alam 1998).¹ In addition, for Bangladesh alone, the median predictions of the 16 GCMs for three emission scenarios considered by the IPCC point to a warming of

¹ An earlier study indicated that a 10-percent increase in monsoon precipitation in Bangladesh could increase runoff depth by 18-22 percent, resulting in a sevenfold increase in the probability of an extremely wet year (Qureshi and Hobbie 1994).

1.55⁰ C and a 4-percent increase in precipitation by 2050 (Yu et al. 2010).² Hence, forecasts by most of the climate-related research indicate vulnerability of Bangladesh to severe monsoon floods will increase further with climate change (World Bank 2010).

Changes in potential inundation zones and depths due to climate change

To assess the impact of climate change on inundation from monsoon, this study first demarcated the potential inundation zone and projected depth of inundation for both a baseline scenario without climate change and one with climate change. The 1998 exceptional flood, with a 90-year return period, was taken as the baseline scenario. This was the counterfactual against which future climate change risk was measured. For the scenario with climate change, the Model for Interdisciplinary Research on Climate (MIROC) 3.2 GCM, under the A2 emissions scenario of the IPCC, was used to predict changes in monthly precipitation and temperature between 1998 and 2050. It should be noted that among the 16 GCMs, the MIROC 3.2 results in the largest increase in runoff for Bangladesh. To approximate the monthly precipitation and

temperature over the entire GBM basin in 2050, precipitation and temperature projections for each 50 km x 50 km grid covering the basin were applied to the historical monthly averages for 1998.

To identify the inundation risk exposure out to 2050 under both the baseline and climate-change scenarios, a four-step process was used. First, transboundary flows and estimated runoffs from the GBM river basins were simulated using the GBM model in the MIKE Basin platform.³

Second, to generate flood levels, the extent of inundation, and the duration of extreme flood events for each 300 m x 300 m grid during the monsoon period, the National Flood Model of Bangladesh, developed by Bangladesh's Flood Forecasting and Warning Centre, was used.⁴

Third, the results of daily inundation depth were synthesized to determine the highest depth for each grid point during the monsoon period and to identify which areas would be vulnerable to floods of a minimum, 24-hour duration.⁵

Finally, the grid points were grouped into five risk exposure zones (Figure 2.1).

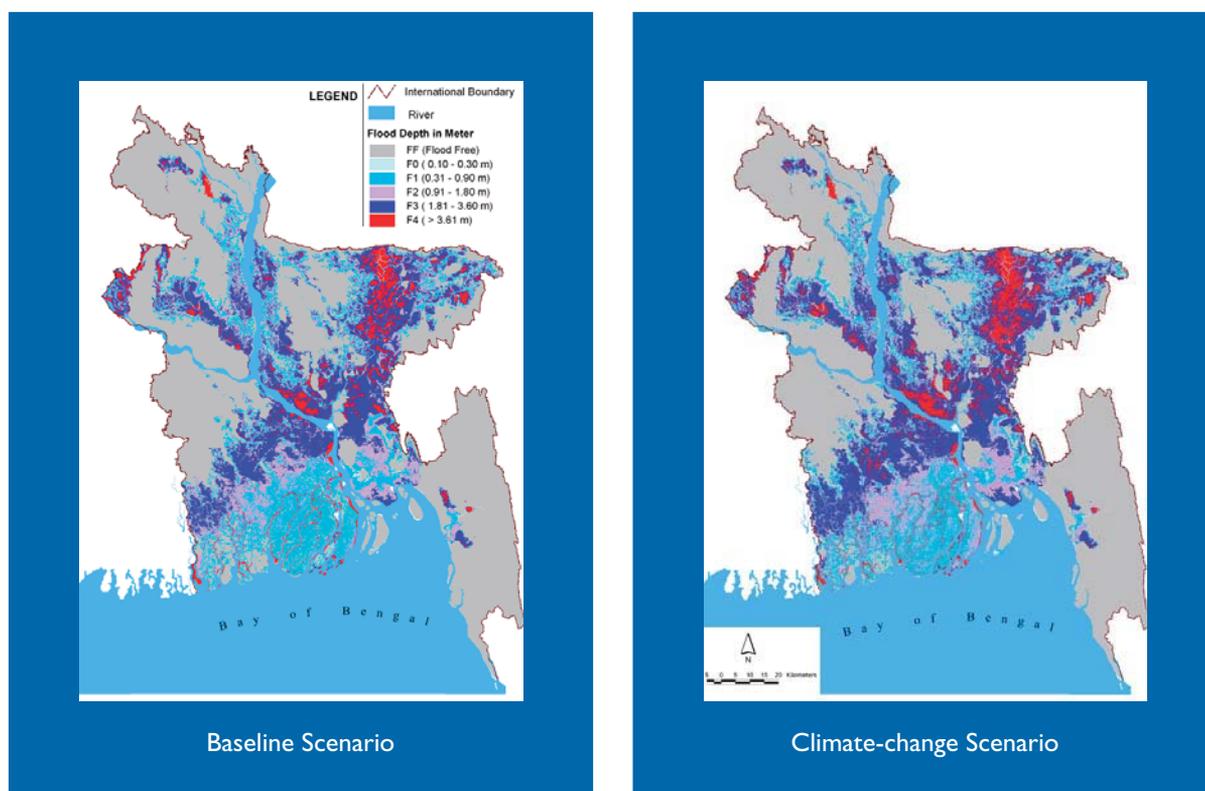
2 The resolution of the models varies with about five grid boxes typically covering Bangladesh. The national values are weighted averages, with the weights equal to the percentage of each grid that is within Bangladesh.

3 This model was developed in 2006 at the BWDB's Flood Forecasting and Warning Centre. For this research, the Institute of Water Modeling updated the model to include river alignments of the GBM basins, using available physical maps of India, Nepal, and Tibet. Basin subcatchments were re-delineated using the Digital Elevation Model, based on the SRTM-version 3. The model was first calibrated using the 2005 year-round hydrological feature and validated for 2006 and 2007; further updating used hydrological data from 2009 (the most recent year).

4 The hydrodynamic model, based on the current national Digital Elevation Model, included all of Bangladesh's important rivers and canals (khals) (10,235 km), floodplain routing channels (1,147 km), and link channels; simulations included all of the country's existing flood control and drainage infrastructure and flood protection measures. Bathymetries of the rivers were updated, incorporating the latest available cross-sections; bathymetries of floodplain routing channels were taken from the national land terrain model of the Flood Action Plan. Flood forecasting included data from more than 200 rainfall stations and some 30 evapotranspiration stations.

5 The choice of 24 hours was based on the potentially severe damage to roads, embankments, and rural houses that typify floods of this duration. Models to reliably determine duration beyond a few days are currently unavailable. This analysis does not account for urban or flash floods.

Figure 2.1 Comparison of risk-exposure zones for 24-hour duration floods



Source: IWM

Estimates indicate that under the baseline scenario, 45 percent of land would be under at least 0.3 m of water. Under the climate-change scenario,⁶ the total flooded area would increase by 4 percent; more importantly, the inundation depth in most flooded areas would rise (Table 2.1).⁷

Table 2.1 Inundation-area estimates out to 2050

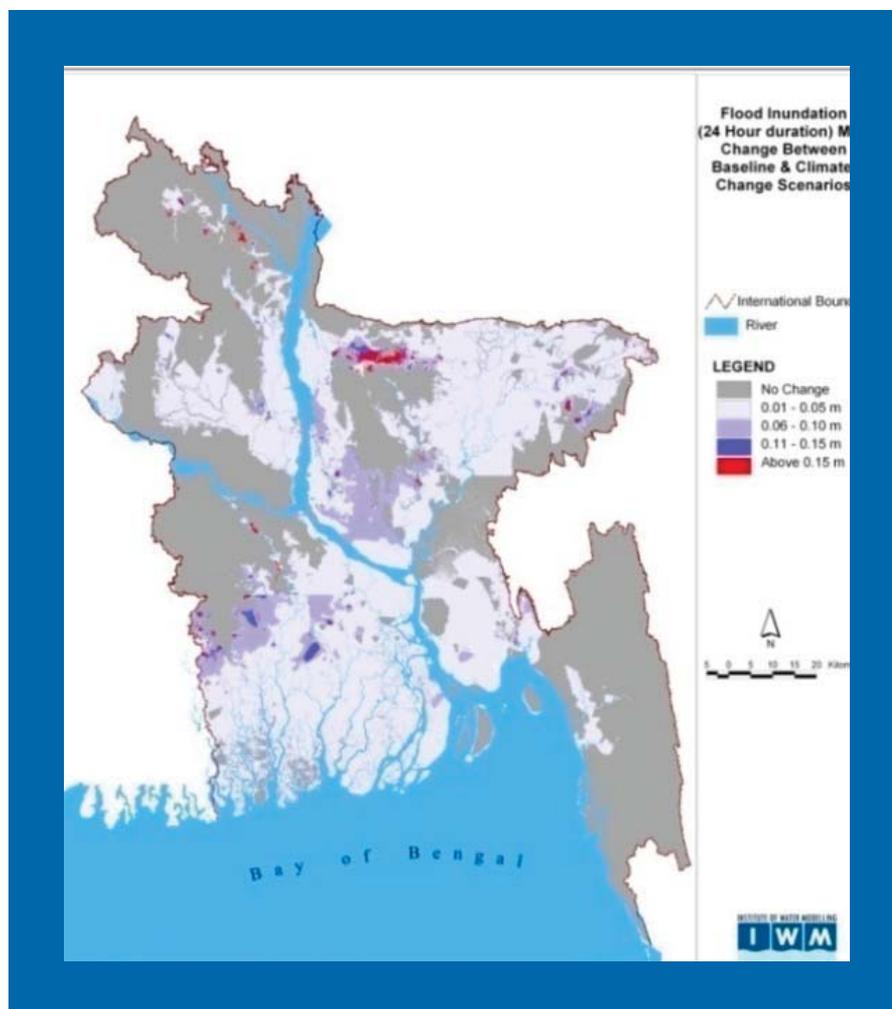
Inundation (m)	Baseline scenario		Climate-change scenario		Change due to climate	
	km ²	% total area	km ²	% total area	km ²	% total area
Flood free	69,439	52	64,550	49	(4,889)	(3)
F0 (0.1-0.3)	2,950	2	2,251	2	(699)	
F1 (0.3-0.9)	14,123	11	11,975	9	2,148	(2)
F2 (0.9-1.8)	19,118	14	20,723	15	1,605	1
F3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

⁶ MIROC 3.2 GCM and A2 emissions scenario

⁷ Areas inundated to depths greater than 0.9 m increase from 34 percent of total area under the baseline scenario to 40 percent under the climate-change scenario. At the peak period, land distribution is about the same as for the 24-hour duration flood.

Areas with large expected changes in inundation depth are spread out across the country (Figure 2.2).

Figure 2.2 Change in inundation depths across Bangladesh



Source: IWM

Further scrutiny of estimates indicates that, although climate change is likely to increase inundation depth in about half of Bangladesh, depths greater than 15 cm are expected to occur in only 544 km², or less than 0.5 percent of the country (Table 2.2).

Table 2.2 Additional inundation depths with climate change

Added inundation depth (cm)	Area (km ²)	Share of total area (%)
No change	70,249	52.6
1-5	56,102	42.0
5-10	5,841	4.4
10-15	786	0.6
> 15	544	0.4
Total change	133,522	100.0

Population at risk

To determine the number of people exposed to inland monsoon floods under the two scenarios at various depths of inundation, the flood risk exposure map was overlaid on the 2001 population map, using GIS software. In 2001, about 23 million people lived in rural areas with estimated inundation depths greater than 0.3 m.⁸ Under the baseline scenario, that number would fall to 19.2 million by 2050, owing to urban migration. However, in a changing climate, 1.9 million more people would be affected in the newly inundated areas, implying that 21.1 million rural people would be at risk of inundation depths greater than 0.3 m. This is 9 percent more than under the baseline scenario but about 9 percent less than the current figure (Table 2.3).

Table 2.3 Vulnerable population estimates for inland monsoon floods

Inundation level (m)	Population exposed under baseline scenario*	Population exposed in 2050 under baseline scenario	Projected population exposed in 2050 under climate-change scenario	Change (%) between baseline and climate-change scenarios in 2050
F0 (0.1-0.3)	1,009,898	843,729	681,031	-19
F1 (0.3-0.9)	6,721,555	5,615,588	4,566,517	-19
F2 (0.9-1.8)	8,490,523	7,093,488	8,108,952	14
F3 (1.8-3.6)	7,105,158	5,936,072	7,543,397	27
F4 (> 3.6)	669,027	558,945	899,066	61
Total exposed population	22,986,263	19,204,093	21,117,932	9

* According to the 2001 population census (BBS 2007).

Most people living in inundated areas, however, would be vulnerable to higher inundation depths. For example, 16.6 million people would be exposed to inundation depths greater than 0.9 m, 22 percent more than under the baseline scenario. This figure would be offset by a 19-percent decline in the population living in areas with inundation depths less than 0.9 m.

It should be noted that the estimated population exposed in 2050 presented above is based on an expected annual growth rate of 1.15 percent for rural and urban populations. This projection does not account for autonomous adaptation by rural households in response to changing flood-risk conditions or recently initiated government land-use and coastal-zone management policies now being implemented.

⁸ The exposed population count, estimated at the district (Thana) level, uses the population density and total area that fall into each risk zone. The total exposed population is the sum of the exposed population across all thanas.

Chapter 3

Adaptation Cost: Inland Monsoon Floods

The estimates of area and population at added risk from inland monsoon floods in a changing climate, presented in the previous chapter, point to Bangladesh's need for greater flood preparedness. Based on these inundation area estimates, the study quantified the cost of climate-proofing infrastructure for inland monsoon floods out to the year 2050. This chapter reviews how critical infrastructure at risk were identified and then provides the total and itemized cost estimates of climate-proofing them.

Infrastructure at added risk of monsoon flood inundation due to climate change

To estimate the cost of climate-proofing infrastructure, the added risk of inundation due to climate change was determined, taking the difference between the baseline and climate-change inundation depths for each 300 m x 300 m grid. The infrastructure analyzed included roads, railways, river embankments, and drainage infrastructure. Current spatial distribution of infrastructure was taken as the starting point for identifying which assets in a changing climate would be most vulnerable to the added risk of inundation by 2050.¹ The stock of infrastructure in 2050 was then projected by uniformly applying expected changes in the economy-including population and income growth and structural

shifts away from agriculture toward industry and services-across the country. The zones with added risk exposure from inundation due to climate change were overlaid on the infrastructure map, using GIS software. For infrastructure with a large spatial extent (e.g., roads, railways, and river embankments), the exposure estimate was measured by the asset's spatial extent in kilometers. For drainage structures (e.g., culverts), the stock exposed in each inundation risk zone was a count of the number of assets located in that zone.

The next sections present itemized estimates of adaptation costs for roads, cross-drainage road facilities, railways, river embankments, drainage within coastal polders, and scour protection out to the year 2050. All estimates are indicated in 2009 prices.

Roads

National and regional roads of Bangladesh were designed to withstand floods with a 50-year return period, while feeder roads were designed to be built above normal flood levels (Siddiqui and Hossain 2006). Yet recent major floods have proven the insufficiency of these standards to prevent large infrastructure losses. Road damage from the exceptional flood of 1998 alone

¹ The best available spatially-disaggregated maps and data for these assets were acquired from various public sources, including Bangladesh Railways, Bangladesh Water Development Board, Local Government Engineering Department, Center for Environmental and Geographic Information Services, Public Works Department, Roads and Highways Department, Water Resources Planning Organization, and the World Bank.

accounted for 15 percent of total damages or about 0.7 percent of GDP (Islam and Mechler 2007). Hence, the concern is that inundation risks of roads will be aggravated with climate change.

In the absence of long-term planning for additional new roads, this study assumed that, by 2050, total road length in Bangladesh will increase over existing stock by another 25 percent; the assumed 25-percent expansion of the road network was applied uniformly across

the existing network.² The road length (in kilometers) exposed to added inundation risk from climate change was estimated for various road types using GIS overlays of added risk-zone maps over existing road network maps (Table 3.1). In 2050, about 2 percent of roads will be subject to added inundation greater than 1 m; while 87 percent will be exposed to 0.5 m of additional inundation due to climate change.

Table 3.1 Length of road (km) at added risk of inundation from climate change by 2050

Added inundation depth	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	7	1	0	0	8	16	-
All exposed	7,019	4,809	1,204	683	12,683	26,400	100%
Share of all exposed	27%	18%	5%	3%	48%	100%	

The estimated adaptation cost for elevating the entire road³ network to offset the added risk of inundation due to climate change is Tk. 190 billion (US\$2.72 billion). National and regional roads account for about 12 percent of this total, while rural and feeder roads comprise the remaining 88 percent (Table 3.2).

2 Bangladesh already has one of the densest road networks in the world; however, road quality is poor. Most new investments in road infrastructure are likely to be for upgrading roads to higher standards (e.g., by paving unpaved roads), rather than expansion. [It has been further assumed that all the rural roads will be paved by 2050.](#)

3 The cost of raising roads to avoid further inundation has been calculated based on the following unit costs: wearing course 50 mm thick of Tk 8,350 /m³; base course 50 mm thick Tk 7,899 /m³; aggregate base (type I) 100 mm Tk 2,819 /m³; aggregate base (type II) 100 mm Tk 2,232 /m³; road excavation Tk 184/m³ and earth fill from borrow pit Tk 124 /m³. Calculations have been made for each division (Barisal, Chittagong, Dhaka, Khulna, Rajshahia and Sylhet).

Table 3.2 Adaptation cost by road type (million US\$)

Added inundation depth	Feeder road (type A)	Feeder road (type B)	National	Regional	Rural	Total	Share of total
0-0.5	770	449	184	94	854	2,351	87%
0.5-1.0	95	57	37	14	106	310	11%
1.0-1.5	10	8	2	1	16	37	1%
1.5-2.0	3	2	0	<1	8	14	1%
2.0-2.5	1	1	0	0	2	3	0%
2.5-3.0	1	0	0	0	1	2	0%
All exposed	818	517	224	110	968	2,718	100%
Share of all exposed	32%	19%	8%	4%	36%	100%	

Cross-drainage road facilities

Bangladesh's roads currently lack sufficient facilities to permit cross-drainage of flood water. With the increased flood-water volume expected in a changing climate, more culverts and regulators will be needed, and some culverts will need to be raised to permit the free flow of water. Deeply inundated areas (more than 0.9 m) are expected to increase another 7,735 km², and each 1.5 m × 1.8 m drainage structure can drain about 10 km², at a cost of Tk. 15 million. Thus, 775 new drainage structures will be needed to drain the added, deeply inundated areas due to climate change, at a total cost of Tk. 11,625 million (US\$ 166.07 million). Furthermore, 315 additional culverts will need to be raised, at a cost of 1 million each, for a total

Railways

Bangladesh Railways has no plans to expand its network in the foreseeable future, with the exception of doubling the track between Dhaka and Chittagong over the next few years. Thus, this study assumed that the country's rail network in 2050, including the Dhaka-Chittagong expansion, would remain the same. The rail length (in kilometers) exposed to added inundation risk from climate change was estimated for various track types using GIS overlays of added risk-zone maps on existing railway maps (Table 3.3). In 2050, less than 2 percent of tracks will be subject to added inundation greater than 1 m; yet 85 percent will be exposed to 0.5 m of additional inundation due to climate change.

Table 3.3 Railway tracks at risk of inundation by 2050 with climate change

Track gauge type (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	173.3	10.8	2.4	1.7	-	-	-	188.1
Broad	205.8	35.0	7.0	-	-	0.4	0.3	248.5
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	0.9	0.3	708.1

Thus, most rail tracks—broad-, meter-, and double-gauge—will need to be raised more than 0.5 m, which increases the cost of earthwork.⁴ For tracks raised 0.5–1 m, the cost of earthwork per kilometer of rail track is US\$20,539 for broad- and double-gauge and US\$16,821 for meter-gauge. The total cost of raising railway tracks to offset the added risk from climate change is US\$27 million (\$11 million for double-gauge, \$10 million for broad-gauge, and \$6 million for meter-gauge tracks).

River embankments

The Bangladesh Water Development Board (BWDB) currently maintains 9,943 km of river embankments, 5,111 km of drainage canals, and 13,949 flood control/regulating structures. Embankments protect agricultural land, major

percent (5,088 km) will be subject to inundation depths of up to 0.5 m and less than 1 percent (29 km) to depths of more than 1 m. The bulk of the cost of raising embankments to various inundation depths to offset the added risk of climate change is for required earthwork (Tk. 125 per m³); other costs include compaction (Tk. 60 per m³) and turfing (Tk. 25 per m²) (Table 3.4). The total cost for raising embankments is Tk. 6,727 million (US\$96 million).

Coastal polder drainage

Higher precipitation during the monsoon season and rising sea level in a changing climate are expected to increase drainage congestion in Bangladesh's 123 existing coastal polders (areas with a dyke).⁵ In this study analysis, trial simulations were conducted for four coastal

Table 3.4 Itemized cost of raising river embankments (million US\$)

Task	Additional inundation depth (m)			Total
	0-0.5	0.5-1.0	1.0-1.5	
Earthwork	55.9	1	65	
Compaction	26	4	1	31
Turfing	0	-	0	0
Total cost	81	13	2	96

cities, and small towns from 10-, 15-, and 50-year return floods. Presently, the BWDB does not anticipate expanding embankment length through 2050 (BWDB 2003). By overlaying GIS maps of added inundation risk zones on maps of existing embankments, this study found that, of the 5,421 km of embankments exposed to the added inundation from climate change, 94

polders to determine the average number of additional vents needed to drain water inside the polder owing to the added congestion from climate change. In each simulation, the length of opening under the climate-change scenario was adjusted to reduce the water depth inside each polder to the level under the baseline scenario.

4 The process of raising rail tracks involves removing and replacing the ballast, rail, and other heavy iron works; dismantling and replacing the tracks; procuring earthwork with sand and ballast; spreading; and four-stage mechanical tamping. See Dasgupta et al., *Climate Proofing Infrastructure in Bangladesh: The Incremental Cost of Limiting Future Inland Monsoon Flood Damage*, Table 8; World Bank, Washington, DC (2010a).

5 The cost of rehabilitating inoperative water regulators in coastal polders or adding new ones to meet the drainage needs under the baseline scenario are not part of the adaptation cost due to climate change.

Thus, the adaptation measure is the added length of the opening needed to ensure the same drainage conditions for both scenarios. The number of additional vents required for the four trials (7, 17, 24, 51) was computed by dividing the length of opening by the width of each vent (1.52 m). Under the climate-change scenario, 1,475 additional vents, at a cost of Tk. 20 million each, will be required to drain the additional volume of monsoon flood water from the identified polders.⁶ The total cost of additional drainage regulators in coastal areas is Tk. 29,500 million (US\$421.4 million).

Scour protection

Erosion of Bangladesh's unprotected river banks is expected to increase in a changing climate, as confirmed by previous experience (CEGIS 2010). The BWDB estimates that the maximum discharge of the Ganges, Brahmaputra, and Meghna rivers will increase by 17, 20, and 8 percent, respectively, with increased scour depths of 1.87, 0.96, and 1.13 m (BWDB 2003). Increased scour depth, in turn, is expected to raise the annual operation and maintenance costs of existing river bank protection works by 6.8 percent, due to the added requirement of launching apron.

Over the past two years, the BWDB required Tk. 1,045 million (US\$14.9 million), on average, to protect against scouring. In a changing climate, the annual protection cost is expected to rise by US\$1 million to Tk. 1,116 million (US\$15.9 million).⁷

Though expensive, infrastructure investments are long-lived and yield large benefits when designed appropriately. Hence, it is essential to develop appropriate standards commensurate with the likely climate risks over expected asset lives and update them over time, as new research results 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 provide a more reliable all-weather network with lower maintenance costs. As new research results increase the certainty of an area's flooding risk, design standards for roads in that area should be raised accordingly. Similarly, embankments should be strengthened beyond their current protective capacity as the added risk from floods becomes more certain.

Cost of added inundation from inland monsoon floods

Recent major floods have proven that Bangladesh's standards for national and regional roads are insufficient to prevent large losses of road infrastructure. In addition, the inadequacy of drainage facilities for these roads is likely to worsen in a changing climate. Furthermore, climate change will subject most of the country's rail network and river embankments to 0.5 m of added inundation and increase drainage congestion in coastal polders and scour depths of unprotected river banks.

6 As per discussions with the local experts, it has been assumed that installation of additional vents is not necessary when inundation depth is less than 0.9 m as water drains relatively quickly.

7 Erosion of unprotected river banks could not be estimated for lack of relevant data.

By 2050, an estimated US\$3.3 billion will be required to protect roads, railways, river embankments, and drainage infrastructure against the added inundation from inland monsoon floods due to climate change. For the climate change scenario considered, the itemized

estimates for this infrastructure provide a lower bound on the actual costs of adaptation, as they do not include the additional adaptation required in urban areas and for currently unprotected river banks (Table 3.5).

Table 3.5 Total adaptation cost for inland monsoon floods

Cost component	Investment (million US\$)
Road height enhancement	2,718
Road cross-drainage	5
Railway height enhancement	27
River embankment enhancement	96
Cross-drainage of coastal polders	421
Total cost	3,267

More than 83 percent of the total adaptation cost is for raising the height of the road network. Additional drainage structures in coastal areas account for another 13 percent of costs, while the remaining measures account for less than 4 percent of the total adaptation cost.

Chapter 4

Added Inundation from Cyclones in a Changing Climate

Cyclones pose a threat to lives and properties of low-lying coastal regions in Bangladesh. Nearly every year, cyclones hit the country's coastal region and a severe cyclone strikes the country every three years, on average. In a changing climate, increase in ocean surface temperature and rising sea levels are likely to intensify cyclonic storm surges and further increase the depth and extent of storm surge-induced coastal inundation in Bangladesh.

This study integrated information on climate change, hydrodynamic models, and geographic overlays to assess the vulnerability of coastal areas in Bangladesh to larger storm surges and sea-level by 2050. The focus of this study was on cyclones with 10 percent or greater probability of occurring each year.¹ This chapter briefly reviews scientific evidence to date on cyclone forecasts, and then details the potential inundation zones and depths and populations at added risk from storm surges in a changing climate.

Added risk of climate change

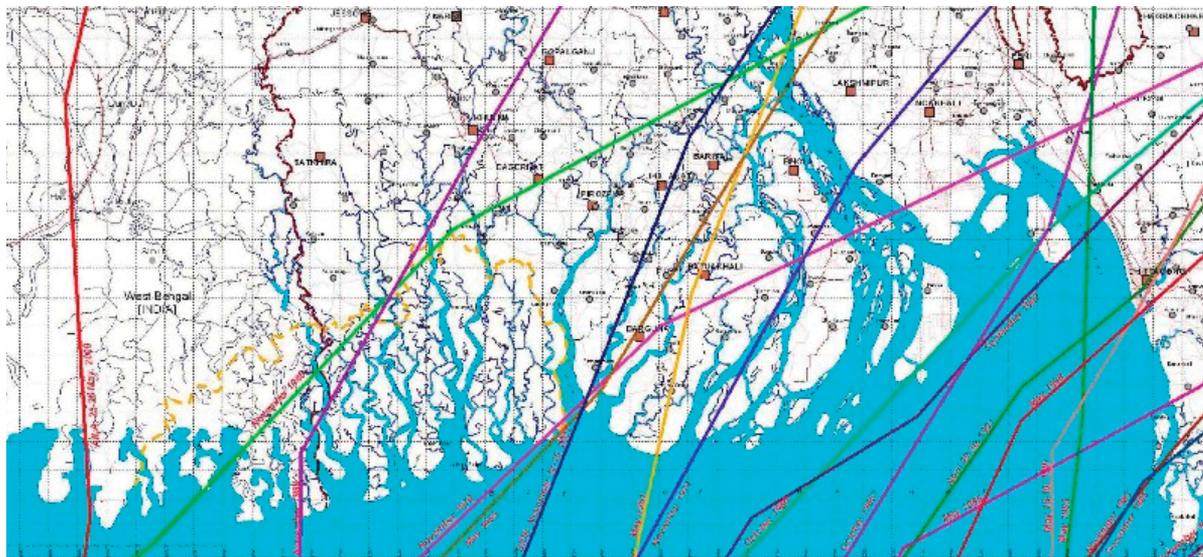
The available scientific evidence indicates that increased sea-surface temperature with climate change will intensify cyclone activity in the tropics and heighten storm surges (IWTC 2006; IPCC

2007; Hansen and Sato 2011). The IPCC further indicates that future cyclonic storm surges and related coastal floods in Bangladesh will likely become more severe as future tropical cyclones increase in intensity (IPCC 2007). A study using dynamic, Regional Climate Model (RCM)-driven simulations of current and future climates indicates a significant increase in the frequency of highest storm surges for the Bay of Bengal, despite no substantial change in the frequency of cyclones (Unnikrishnan et al. 2006). Emanuel projects increased intensity of tropical storms by 2100 for the North Indian Ocean, as measured by the percent change in landfall power using the MIROC (United Nations and World Bank 2010). Surges will be further elevated by a rising sea level as thermal expansion and ice cap(s) continue to melt (Nicholls et al. 2007; Dasgupta et al. 2010b).

Larger storm surges threaten greater future destruction, because they will increase the depth of inundation and will move further inland, threatening larger areas than in the past. The destructive impact of storm surges will generally be greater when surges are accompanied by strong winds and large onshore waves. This scientific evidence points to the need for greater disaster preparedness in coastal Bangladesh.

¹ The study analysis did not address the likely problem of salinity intrusion that a rise in sea level and intensified cyclonic storm surges might induce.

Figure 4.1 Tracks of major cyclones in 1960-2009 spanned Bangladesh's entire coastline.



Source: IWM

Changes in potential storm-surge zones and depths due to climate change

To assess the impact of climate change on cyclone-induced storm surges, this study first demarcated the potential inundation zone and projected depth of inundation for both a baseline scenario without climate change and one with climate change. Under the baseline scenario, tracks of the 19 major cyclones that made landfall from 1960 to 2009 were used, along with their corresponding observed wind and pressure fields (Figure 4.1).² These historic cyclones formed the basis against which future climate change risk was measured.

The inundation effect of storm surges was assessed using the two-dimensional Bay of Bengal Model, recently upgraded and updated under the Comprehensive Disaster Management Program of Bangladesh (UK DEFRA 2007). The model is based on the MIKE 21 hydrodynamic modeling system, and its domain covers the coastal region of Bangladesh up to Chandpur and the Bay of

Bengal up to 16° latitude.³ The resulting inundation map is based on the maximum level of inundation at all grid points of the model.

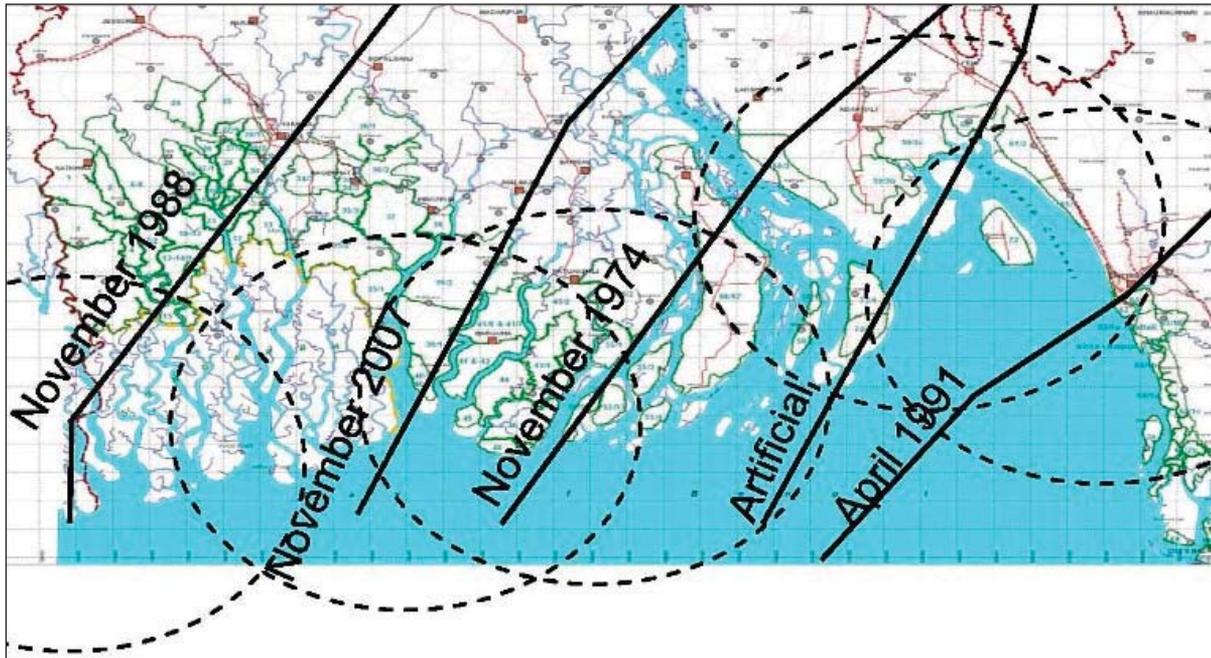
To approximate cyclones in a changing climate by 2050, this analysis considered a sea-level rise of 27 cm (UK DEFRA 2007), increased wind speed of 10 percent (World Bank 2010), and landfall during high tide.⁴ The scenario with climate change used the tracks of the same 19 historical cyclones and the affected coastal regions to simulate potential tracks out to 2050. The overlapping tracks of the 1974, 1988, 1991, and 2007 cyclone tracks covered the Sundarban coast, southwestern coast (Sundarban to Patuakhali), Bhola and Noakhali coast in the Meghna Estuary, and eastern coast (Sitakunda to Banskhali); an artificial track was generated to cover the Sandwip coast and parts of the Noakhali and Chittagong coasts in the central part of the Meghna Estuary. Together, these five tracks were used to determine the inundation zones due to climate change-induced storm surges (Figure 4.2).

² See Dasgupta et al., *Vulnerability of Bangladesh to Cyclones in a Changing Climate: Potential Damages and Adaptation Cost*, Appendix 3. World Bank, Washington, DC (2010b).

³ *Ibid.*, Appendix 1.

⁴ Scientific evidence to date suggests that the intensity of cyclones in the Bay of Bengal will increase in frequency; thus, the probability of potential landfall during high tide will also rise.

Figure 4.2 Five cyclone tracks span Bangladesh's entire coastline under the climate-change scenario.

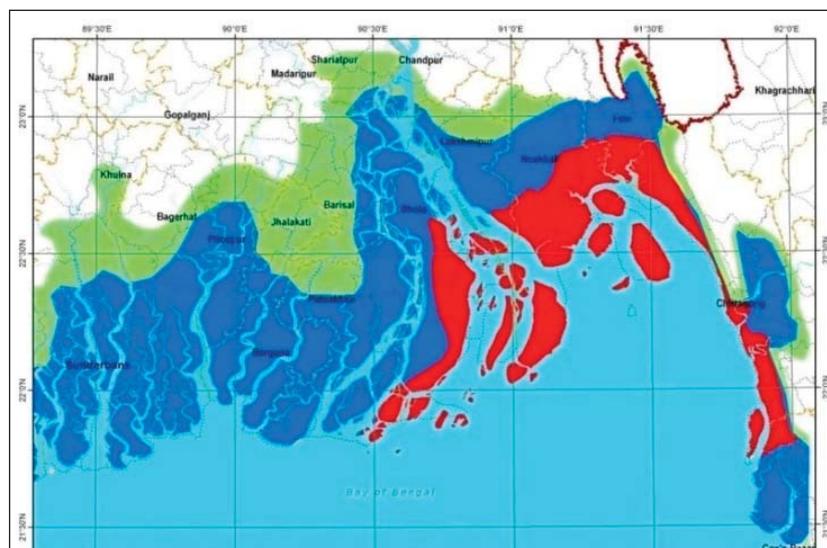


Note: The meteorological parameters of Cyclone Sidr were used to demarcate the artificial track

To determine potential future inundation zones by 2050 under the climate-change scenario, the storm-surge model was run for the five cyclone tracks (covering the entire coastal area), incorporating a 27-cm rise in sea level, a 10-percent increase in wind speed, and landfall of cyclones during high tide. Based on the simulation results, which accounted for potential

intensification of cyclone-induced inundation, inundation maps for 2050 were generated, again applying the Bay of Bengal model. Results showed that, under the climate-change scenario, the areas vulnerable to inundation depths of more than 1 m and 3 m, respectively, would be 14 and 69 percent higher than under the baseline scenario (Figure 4.3).

Figure 4.3 High risk area by 2050 in a changing climate (Source: IWM)



Inundation depth (m)	Baseline scenario (km ²)	Climate-change scenario (km ²)	Change (%)
> 1	20,876	23,764	+14
3	10,163	17,193	+69

In addition, it is estimated that a 10-year-return-period cyclone in a changing (2050) climate will be more intense and cover 43 percent of the vulnerable area, 17 percent more than the current coverage.⁵

Coastal population at risk

GIS software was used to estimate the population exposed to inundation risk from cyclones and associated storm surges by 2050 under the two scenarios.⁶

Currently, 8.06 million people in coastal Bangladesh are vulnerable to inundation depths greater than 3 m resulting from cyclonic storm surges. With population growth, that number is projected to increase to 13.5 million by 2050 under the baseline scenario. Without further adaptation measures, another 9.1 million coastal inhabitants will be exposed to similar inundation risk by 2050 under the climate-change scenario. The population exposed to 1-3m inundation depth is expected to increase by 7.06 million due to climate change (Table 4.1).

Table 4.1 Vulnerable population estimates for cyclonic storm surges

Inundation depth (m)	Current	2050 under baseline scenario	Change (%) between current and baseline scenario	2050 under climate-change scenario	Change (%) between baseline and climate-change scenarios in 2050
> 1	16.83	28.27	+ 68	35.33	+ 25
> 3	8.06	13.54	+ 68	22.64	+ 67

As a cautionary note, it should be noted that this analysis did not address the out-migration from coastal zones that a rise in sea level and intensified cyclonic storm surges might induce.

⁵ The study did not attempt to estimate the location-specific probability of 10-year-return-period cyclones.

⁶ Since the values of the pixels in population surfaces represented numbers of people, the exposure was calculated by multiplying the exposure surface by the inundation zone and then summing by multiplying grid count and value. The computation used population density at the thana level.

Chapter 5

Adaptation Cost: Cyclones

Bangladesh is highly prone to cyclones. Since the 1960s, the government has invested \$10 billion on polders, cyclone shelters, and emergency warning and awareness-raising systems to protect low-lying coastal areas. These protective measures have significantly reduced cyclone-related loss of life and property damage over time. However, in a changing climate, the greater expanse and depth of cyclone-induced storm surges may exceed the capacity of the country's protective coastal infrastructure and current level of disaster preparedness.

Based on the inundation area and vulnerable population estimates presented in the previous chapter, this study assessed gaps in protective coastal infrastructure and quantified the adaptation cost to more intensified 10-year-return-period cyclones out to the year 2050. To itemize the adaptation-cost estimates, the study started with the identification of the critical infrastructure exposed to the added risk of storm-surge inundation in a changing climate. This chapter first presents how critical infrastructure at added risk of storm surge-induced inundation were identified and then provides the total and itemized adaptation cost estimates.

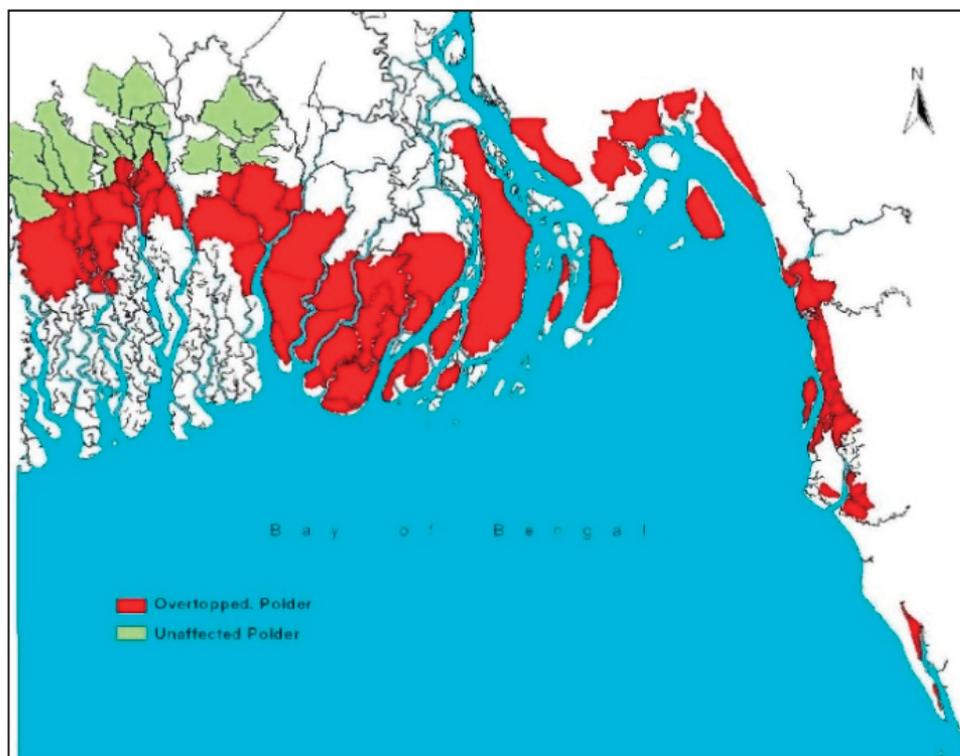
Infrastructure at added risk of storm-surge inundation due to climate change

To identify the infrastructure exposed to added inundation risk, GIS software was used to overlay the best available, spatially-disaggregated data on polders, cyclone shelters, and other infrastructure in the country's coastal zone, with projected inundation zones and inundation depths for 2050 under the baseline and climate-change scenarios.¹ For each exposure indicator, estimates were calculated by overlaying the inundation zone with the appropriate exposure-surface data set. For the exposure grid surfaces, three GIS models were built to calculate the exposed value. The exposure indicators, including land surface, agriculture extent, road infrastructure, and railways, were measured in square kilometers or kilometers. The exposure estimates of other impact elements (e.g., cyclone shelters) were counts.

The next sections present itemized estimates of adaptation measures, including height enhancement of coastal polders, afforestation to protect sea-facing polders, multipurpose cyclone shelters, cyclone-resistant private housing, and strengthening of the early warning and evacuation system. All estimates are indicated in 2009 prices.

¹ Exposure surface data were collected from the public sources noted in footnote 1 (chapter 3).

Figure 5.1 In a changing climate, 33 sea-facing and 26 interior polders will likely be overtopped by 2050.



Source: IWM

Height enhancement of coastal polders

In the 1960s and 1970s, 123 polders, 49 of which are sea-facing, were constructed to protect Bangladesh's low-lying coastal areas against tidal floods and salinity intrusion.² To identify which polders will likely be overtopped by intensified storm surges and the extent of that overtopping, the study computed differences between the crest level of embankment for each polder and the inundation depths projected for 2050 under the baseline and climate-change scenarios.

The results indicate that by 2050, under the baseline scenario, 14 interior polders and 30 sea-facing polders will be overtopped; under the climate-change scenario, an additional 26 interior

polders and 33 sea-facing coastal polders will be overtopped (Figure 5.1).

The study computed the cost of enhancing the height of the polders identified as likely to be overtopped. The amount of needed earthwork was determined from engineering designs, and the current local prices for earthwork, compaction, and turbing were provided by the BWDB.³ The cost of required hard protection of some polder sections was computed using the rate for the highest ranked, locally available technology (i.e., cement concrete blocks with sand filters and geo-textile). The cost of compensating private landowners for the additional land needed to strengthen the bases

² The BWDB maintains an extensive database on coastal polders, including data on their length, location, construction year, and cost.

³ See Dasgupta et al., *Vulnerability of Bangladesh to Cyclones in a Changing Climate: Potential Damages and Adaptation Cost*, Appendix 4. World Bank, Washington, DC (2010b).

Table 5.1 Estimated cost of enhancing height of coastal embankments (million US\$)

Polder type	Baseline scenario	Climate change scenario	Additional cost due to climate change
Interior	317	706	389
Sea-facing	2,145	2,648	503
Total	2,462	3,354	892

of the height-enhanced polders in interior or marginal areas was also estimated. Maintenance cost was assumed to represent 2 percent of capital investment. Under the baseline scenario, the adaptation costs total \$2.46 billion. In a changing climate, the additional adaptation cost totals US\$892 million (Table 5.1).⁴

Afforestation protection of sea-facing polders

In the past, foreshore afforestation schemes have proven cost effective in dissipating wave energy and reducing hydraulic load on embankments during storm surges.⁵ Currently, however, Bangladesh has insufficient foreshore forests. Of the 957-km total length of embankment of 49 sea-facing polders, there are only 60 km of forest belts, much of which is degraded. The Department of Forests and IWM recommend a minimum of 500-m width mangrove forest to protect sea-facing polders.

To compute the gap between the recommended 500-m width mangroves and existing area-specific ones, this study estimated the current length of coastal afforestation between the coastline and polders using Google Earth and GIS methodology. The results indicate that 897 km length of existing sea facing polders would require mangrove forests for protection. For the recommended 500-m

width protective forest belt, a foreshore area of 448.5 km² (897 km × 0.5 km) would require afforestation. At the current cost of US\$168,000 per km², the projected cost would total US\$75 million.

Multipurpose cyclone shelters

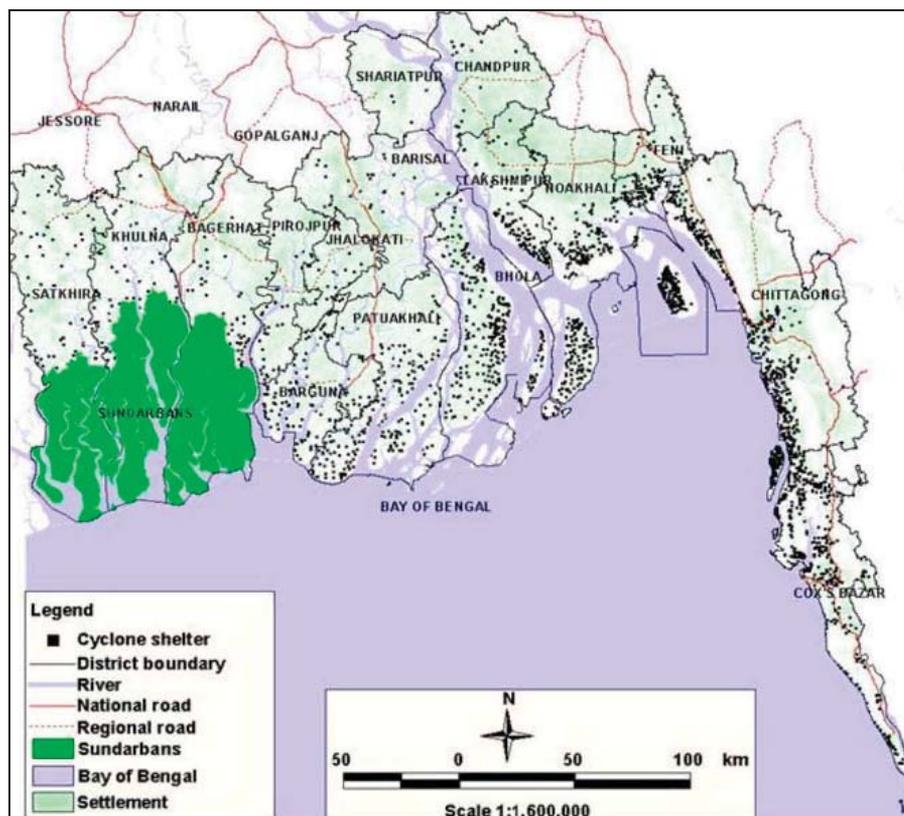
In Bangladesh, cyclone shelters are critical for protecting human lives and livestock. During Cyclone Sidr in 2007, for example, 15 percent of the affected population took refuge in cyclone shelters, which were estimated to have saved thousands of lives (Figure 5.2). Yet many existing cyclone shelters are in dilapidated condition and fail to provide for the special needs of women, people with disabilities, and provision for livestock.

Though the need for cyclone shelters is expected to decline if polders are raised sufficiently and properly maintained, shelters will still be needed to protect inhabitants of smaller islands, where polder protection may not be cost effective; people living in areas with projected inundation depths greater than 3 m; and residents living in one-story houses. Current consensus favors multipurpose cyclone shelters with elevated space for livestock and overhead water storage that can also serve as a primary school or office space in non-emergency times.

⁴ Ibid., Appendix 5.

⁵ Such benefits were evident in Cyclone Sidr (2007) and Cyclone Aila (2009). An in-depth study of the damages and losses from Cyclone Sidr noted that even scattered, unplanned forestation along the foreshore of the embankments substantially reduced the velocity of storm surges (GOB 2008).

Figure 5.2 Spatial locations of existing cyclone shelters in coastal areas



Source: CEGIS

Vulnerable-population estimates presented in the previous chapter indicate that 9.1 million inhabitants will be exposed to storm surge-induced inundation depths of more than 3 m due to climate change by 2050. Accommodating these additional people will require adding about 5,700 multipurpose cyclone shelters, at an estimated cost of US\$1.2 billion.⁶

Cyclone-resistant private housing

In the past, the housing sector has accounted for a significant portion of cyclone damage. For example, in 2007, it accounted for half of the economic damage caused by Cyclone Sidr (GOB

2008). In coastal regions, houses can be made cyclone-resistant by following suitable designs and building codes. This study analysis, which included consultations with local architects and civil engineers, recommends encouraging the construction of brick-built houses with concrete roofs (on stilts, if needed), in accordance with appropriate building codes. These houses could serve as single or multi-family cyclone shelters during storm surges. The subsidized construction material and housing credit would require setting up a revolving fund in the amount of US\$200 million.⁷

⁶ To estimate the costing of multipurpose cyclone shelters, current cyclone-shelter costs and capacity were collected from World Bank-funded projects. The current cost of a shelter to accommodate 1,600 people is US\$214,000.

⁷ Subsidies must be designed with caution to avoid misuse.

Strengthened early warning and evacuation system

Bangladesh's early cyclone warning and evacuation system is vital to saving lives. The overall quality of cyclone and storm-surge forecasting has improved in recent years; however, the general consensus is that further improvements are needed. These include the need for greater precision in forecasting, especially with regard to landfall location and location-specific inundation depth; broadcasting of warnings in local dialects; and raising awareness to promote timely and appropriate evacuation.⁸

The estimated costs of the surveys and mathematical modeling required to improve projections for location-specific inundation, as recommended by the IWM, total US\$8 million. Modernization of the Bangladesh Meteorological Department (BMD) (setting up additional observatories and upgrading existing ones, establishing radiosonde stations, modernizing workshop and laboratory, and developing training institute facilities) totals US\$30 million. Operation and maintenance costs of existing and additional observatories are estimated at US\$5 million annually, while the awareness-raising promotion program recommended by the Red Crescent Society totals US\$3 million per year.

On further infrastructure investment

The strong structural-protection measures considered in this analysis (i.e., polders) reduced the need to raise the resilience of such infrastructure as roads and bridges to storm surges, except in regions or islands without current or anticipated polder protection.

Cost of added inundation from cyclones and related storm surges

Despite the extensive infrastructure Bangladesh has in place to protect coastal residents from cyclonic storm surges and tidal waves, geographic overlays of inundation depth under the baseline (without climate-change scenario) reveal that currently 44 of the country's 123 coastal polders run the risk of overtopping if a severe cyclone hits. As a result, the country has an outstanding adaptation deficit of US\$2.46 billion, making it more difficult to fully climate-proof infrastructure.

In a changing climate, the greater expanse and depth of the areas inundated will put many more existing structures at risk. Geographic overlays of inundation depth under the climate-change scenario indicated another 59 coastal polders will be overtopped by 2050, and inadequate mangrove forests will mean higher-velocity storm surges. Moreover, the capacity of life-saving cyclone shelters and early warning and evacuation systems will be exceeded.

⁸ The study team conducted focus group interviews with experts at the IWM, BMD, Red Crescent Society, and residents of recent cyclone-affected areas on their recommendations for strengthening the early warning and evacuation system.

Table 5.2 Total adaptation cost for cyclones and associated storm surges by 2050

Measure	Baseline scenario	Additional cost with climate change	
	Investment (million US\$)	Investment (million US\$)	Annual recurrent cost (million US\$)
Polders	2,462	892	18
Foreshore afforestation		75	
Multipurpose cyclone shelters		1,200	24
Cyclone-resistant private housing		200	
Strengthening of early warning system		39	8 +
Total	2,462	2,407	50 +

By 2050, the total additional investment needed to cope with a changing climate will total about US\$2.4 billion, with an annual recurrent cost of more than US\$50 million (Table 5.2). The costing of adaptation refers to the increased inundation area and depth for a 10-year return cyclone in a changing climate.

Chapter 6

Toward Adaptation and Investment Planning

As indicated in the previous chapters, in the coming decades, Bangladesh is likely to experience heavier, more erratic monsoon flooding of greater inundation depth, extent, and duration, as well as higher-intensity cyclonic storm surges with potentials to ravage further inland. The area vulnerable to inland monsoon inundation will rise by 4 percent, and the entire area at risk (nearly half of the country) is expected to encounter higher inundation depths due to climate change. The coastal area vulnerable to storm surge-induced inundation with a depth of more than 3 m will rise by about 69 percent by 2050, suggesting that a single cyclone with a 10-year return period will cause significantly more damage (Appendix).

In a changing climate, the greater expanse and depth of the areas affected by inland monsoon floods and tropical cyclones will put the population, assets, and economic activities at further risk. **This study's itemized cost assessments indicate that, at 2009 prices, the total cost of adaptation to offset the added inundation from climate change is estimated at US\$3.3 billion for inland monsoon flood protection infrastructure and US\$2.4 billion for storm-surge protection by 2050.**¹ These cost

assessments for the two climate hazards analyzed, totaling US\$5.7 billion, are conservative, and do not include the added adaptation required for urban areas, unprotected river banks, and salinity intrusion. As mentioned previously, the country currently has a significant climate-adaptation deficit,² making it more difficult to determine the full cost of climate-proofing infrastructure.

Given the large uncertainties about the magnitude and timing of added risks from climate change, sequencing of adaptation actions is a necessity, particularly in a fiscally constrained environment. The itemized adaptation-cost estimates presented in this report can serve as a tool to enable decision makers in Bangladesh to prioritize and sequence adaptation actions and investments, as resources permit. Recognizing the uncertainties in the timing and magnitude of the impacts of climate change, a prudent strategy would begin by addressing existing risks that current residents face. Existing investments, which have reduced the impacts of floods and cyclones, provide a solid foundation upon which additional measures to reduce potential damages now and in the future may be undertaken to minimize the climate risks.

¹ The estimated damage from a single 10-year-return-period cyclone, compared to the cost of storm-surge protection, indicates that the incremental cost of adapting to climate change by 2050 is small compared to the potential damage, which strengthens the case for rapid adaptation (Appendix); this comparison is conservative, given that the damage from more frequent, but less intense, cyclones has not been considered.

² Hence, there exist substantial risks from severe flooding, even in the current climate.

The evaluation of infrastructure investments conducted in this study has been done within a framework of appropriate development policies and efficient institutional arrangements. Taken alone, these "hard" adaptation investments cannot yield the expected benefits. Indeed, sound public policies, planning, and institutions are the foundation for ensuring that more capital-intensive measures are wisely implemented. Design of flood embankments, for example, must be carefully considered since their construction is usually followed by the accumulation of physical capital behind the barriers, which are considered "safe." Flood embankments must be strengthened beyond their current protective capacity as the added risk of inundation becomes more certain. It is also critical to develop appropriate design standards commensurate with likely climate risks over the expected lives of assets and update them as new research becomes available.

It should also be taken into account that physical measures may not reduce human suffering and asset damages and losses as much as expected in the long run. These "hard" investments must be complemented by education, job training, and other "soft" investments designed to reduce reliance on resources and assets whose value may be eroded by climate change. In short, adaptation planning should not attempt to resist the impact of climate change. Rather, it should offer a sustainable path that accommodates its

effects in the least disruptive way without placing a disproportionate burden on the poor and vulnerable.

By 2050, the number of people living in urban areas is expected to triple, while the rural population will decline by nearly a third. Current government policies will determine where this urban population will settle and how well prepared it will be to adapt to a changed climate. Many households have already moved further inland and are adopting positive incentives to promote settlements and urban growth in low-risk areas. Sound policies that promote increased access to education and appropriate job training will better prepare future rural populations for productive urban lives and thus avoid perverse incentives to remain in high-risk coastal areas.

Coping with climate change over the longer term will also require strengthened cooperation among neighboring countries in the GBM basin. An effective strategy must include the development of institutions and mechanisms for transboundary negotiations on the sharing of water resources. This is not a new issue, but one whose importance may be amplified by climate change. As the stakes rise, taking steps now to promote and strengthen cooperative management of shared resources can not only offer all parties immediate benefits. It can also prevent the need for more expensive, disruptive solutions in the future.

References

- Ahmed, A. U., and M. Alam. 1998. "Development of Climate Change Scenarios with General Circulation Models." In *Vulnerability and Adaptation to Climate Change for Bangladesh*, eds. S. Huq, Z. Karim, M. Asaduzzaman, and F. Mahtab, 13-20. Dordrecht: Kluwer Academic Publishers.
- Ahmed, A. U., and M. M. Q. Mirza. 2000. "Review of Causes and Dimensions of Floods with Particular Reference to Flood '98: National Perspectives." In *Perspectives on Flood 1998*, eds. Q. K. Ahmad, A. K. A. Chowdhury, S. H. Imam, and M. Sarker, 67-84. Dhaka: University Press Limited.
- Ali, A. 1999. "Climate Change Impacts and Adaptation Assessment in Bangladesh." *Climate Research* 12: 109-116.
- BBS (Bangladesh Bureau of Statistics). 2007. *Population Census 2001*. National Series, Vol. I Analytical Report. Dhaka: BBS.
- BWDB (Bangladesh Water Development Board). 2003. "Technical Evaluation of Some Selected Flood Protection and River Erosion Control Works Already Implemented by BWDB." Dhaka: BWDB.
- . 2007. *Annual Flood Report 2007*. Flood Forecasting and Warning Centre Processing and Flood Forecasting Circle. Dhaka: BWDB.
- CEGIS (Center for Environmental and Geographic Information Services). 2010. *Mid-term Report on Field-based Research on the Impacts of Climate Change on Bangladesh Rivers*. Dhaka: Asian Development Bank.
- Cropper, M., and S. Sahin. 2009. *Valuing Mortality and Morbidity in the Context of Disaster Risks*. Policy Research Working Paper 4832. Washington, DC: World Bank.
- Dasgupta, Susmita, Mainul Huq, Zahirul Huq Khan, Md. Sohel Masud, Manjur Murshed Zahid Ahmed, Nandan Mukherjee, and Kiran Pandey. 2010a. *Climate Proofing Infrastructure in Bangladesh: The Incremental Cost of Limiting Future Inland Monsoon Flood Damage*. Policy Research Working Paper 5469. Washington, DC: World Bank.
- Dasgupta, Susmita, Mainul Huq, Zahirul Huq Khan, Manjur Murshed Zahid Ahmed, Nandan Mukherjee, Malik Fida Khan, and Kiran Pandey. 2010b. *Vulnerability of Bangladesh to Cyclones in a Changing Climate: Potential Damages and Adaptation Cost*. Policy Research Working Paper 5280. Washington, DC: World Bank.

- GOB (Government of the People's Republic of Bangladesh). 2008. *Cyclone Sidr in Bangladesh: Damage, Loss, and Needs Assessment for Disaster Recovery and Reconstruction*. Dhaka: GOB.
- . 2009. *Bangladesh Climate Change Strategy and Action Plan*. Dhaka: Ministry of Environment and Forests, GOB.
- Hansen, J. E., and M. Sato. 2011. "Paleoclimate Implications for Human-made Climate Change." NASA Goddard Institute for Space Studies and Columbia University Earth Institute. Mimeo.
- Hofer, T., and B. Messerli. 2006. *Floods in Bangladesh: History Dynamics, and Rethinking the Role of the Himalayas*. Tokyo: United Nations University Press.
- Hoque, M. Moazzammel. 1992. "Strategies and Measures To Reduce Cyclone Damage." In *Cyclone Disaster Management and Regional/Rural Development Planning: UNCRD-CIRDAP Seminar, Phase III, 27-29 January, 1992, Chittagong, Bangladesh*, 25-45. Nagoya, Japan: UNCRD.
- IMD (India Meteorological Department). 2010. Available at www.imd.gov.in/section/nhacl/dynamic/faq/FAQP.htm#q42. Accessed March 2011.
- IPCC (Intergovernmental Panel on Climate Change). 2007. *Climate Change 2007: The Physical Science Basis*. Fourth Assessment Report of the IPCC, Working Group I. Geneva: IPCC.
- Islam, K. M. N., and R. Mechler. 2007. *ORCHID: Piloting Climate Risk Screening in DFID Bangladesh: An Economic and Cost Benefit Analysis of Adaptation Options*. Sussex, UK: Institute of Development Studies.
- IWTC (International Workshop on Tropical Cyclones). 2006. "Statement on Tropical Cyclones and Climate Change." San José, Costa Rica, November 21-30. Available at www.gfdl.noaa.gov/~tk/glob_warm_hurr.html. Accessed January 2011.
- Khalil, G. 1992. "Cyclones and Storm Surges in Bangladesh: Some Mitigation Measures." *Natural Hazards* 6: 11-24.
- MCSP (Multi-purpose Cyclone Shelter Project). 1993. "Summary Report." Dhaka: Bangladesh University of Engineering and Technology and Bangladesh Institute of Development Studies.
- Mirza, M. M. Q. 2002. "Global Warming and Changes in the Probability of Occurrence of Floods in Bangladesh and Implications." *Global Environmental Change* 12: 127-38.
- Mirza, M. M. Q., and A. Dixit. 1997. "Climate Change and Water Resources in the GBM Basins." *Water Nepal* 5(1): 71-100.
- Mirza, M. Q., R. A. Warrick, N. J. Ericksen, and G. J. Kenny. 1998. "Trends and Persistence in Precipitation in the Ganges, Brahmaputra and Meghna Basins in South Asia." *Hydrological Sciences Journal* 43(6): 845-58.
- Murty, T.S., and M. I. El-Sabh. 1992. "Mitigating the Effects of Storm Surges Generated by Tropical Cyclones: A Proposal." *Natural Hazards* 6(3): 251-73.

- Nicholls, R. J., S. Hanson, C. Herweijer, N. Patmore, S. Hallegatte, J. Corfee-Morlot, J. Chateau, R. Muir-Wood. 2007. Ranking Port Cities with High Exposure and Vulnerability to Climate Extremes. OECD Environment Directorate, Environment Working Papers No. 1. Paris: Organisation for Economic Co-operation and Development.
- Qureshi, A., and D. Hobbie. 1994. *Climate Change in Asia*. Manila: Asian Development Bank.
- Siddiqui, K. U., and A. N. H. A. Hossain (eds.). 2006. *Options for Flood Risk and Damage Reduction in Bangladesh*. Dhaka: University Press Limited.
- SMRC (SAARC Meteorological Research Centre). 2000. *The Vulnerability Assessment of the SAARC Coastal Region Due to Sea Level Rise: Bangladesh Case*. Dhaka: SMRC.
- UK DEFRA (Department for Environment, Food and Rural Affairs). 2007. *Investigating the Impact of Relative Sea-level Rise on Coastal Communities and Their Livelihoods in Bangladesh*. London: UK DEFRA.
- UNDP (United Nations Development Programme). 2004. *A Global Report: Reducing Disaster Risk: A Challenge for Development*. New York: UNDP Bureau for Crisis Prevention and Recovery. Available at www.undp.org/bcpr.
- United Nations and World Bank. forthcoming. *UnNatural Disasters: The Economics of Reducing Death and Destruction*.
- Unnikrishnan, A. S., R. Kumar, S. E. Fernandez, G. S. Michael, and S. K. Patwardhan. 2006. "Sea Level Changes along the Indian Coast: Observations and Projections." *Current Science India* 90: 362-8.
- World Bank. 2009. *The Cost to Developing Countries of Adapting to Climate Change: New Methods and Estimates*. Environment Department. Washington, DC: World Bank.
- . 2010. *The Economics of Adaptation to Climate Change*. Environment Department. Washington, DC: World Bank.
- . 2010. Bangladesh Country assessment Strategy: 2011-2014.
<http://siteresources.worldbank.org/BANGLADESHEXTN/Resources/295759-1271081222839/6958908-1284576442742/BDCASFinal.pdf>. Accessed February 2011.
- Yu, Winston, Mozaharul Alam, Ahmadul Hassan, Abu Saleh Khan, Alex Ruane, Cynthia Rosenzweig, David Major, and James Thurlow. 2010. *Climate Change Risks and Food Security in Bangladesh*. London: Earthscan Publishers.

Appendix

Impact of a 10-year-return-period Cyclone in Bangladesh by 2050

This study also estimated the damage from a 10-year-return-period cyclone and associated storm surges by 2050. Exposure of critical impact elements using geographical overlays formed the basis for estimating the potential damages and losses for the baseline and climate-change scenarios. The assessment also drew on projected annual growth in Bangladesh's coastal population (1 percent) and GDP (6-8 percent) and the devastation (US\$1.67 billion damages and losses) experienced in 2007 resulting from Cyclone Sidr.

Based on major cyclone events from 1876 to 2009, it is estimated that a cyclone like Sidr (with wind speed of 223 km per hour) has a 10-year return period. In calculating damages, the study adjusted for the greater extent of storm-surge inundation (area with an inundation depth of 1 m or more) from Cyclone Sidr, which was 8.7 percent more than the historical average inundation area of a 10-year return cyclone in Bangladesh. It is estimated that future 10-year-return-period cyclones will cover 17 percent more vulnerable area than the current average. All estimates were adjusted for 2009 price levels, in accordance with the 18-percent increase in the GDP deflator in 2007 and 2009.

Population and infrastructure at added risk of storm-surge inundation due to climate change

In this analysis, damages refer to the potential complete or partial destruction inflicted on

assets, while losses refer to the potential flow of goods and services not provided and the increased costs of continuing essential services. The sections below estimate the potential human casualties and injuries from such a cyclone and their estimated economic damage, and the potential damage to sectors that experienced high monetary damage and losses from Cyclone Sidr in 2007 (housing, education, agriculture, non-agricultural productivity, roads, power, and protective coastal infrastructure).

Human casualties and injuries

In 2007, storm-surge inundation from Cyclone Sidr affected some 3.45 million residents in Bangladesh's coastal areas. Cyclone shelters saved thousands of lives, yet 3,406 people died and 55,282 more were injured, according to post-disaster assessments. Focus-group interviews with affected residents revealed that a large proportion of the population was reluctant to move to cyclone shelters, even during an emergency. The primary reasons cited for this reluctance were distance from the homestead, difficult access to shelters, unwillingness to leave unprotected livestock behind, scarcity of sanitation facilities, lack of user-friendly facilities for women, and overcrowding.

Assuming that Bangladesh attains a replacement fertility rate by 2021 and 1-percent average annual growth in coastal population between 2001 and 2050, the number of people exposed to the risk of storm-surge inundation

from a 10-year-return-period cyclone by 2050 would total 5.34 million under the baseline scenario and 10.04 million with climate change. Without improved infrastructure protection in a changing climate, extrapolation with the ratios of casualty (0.001) and injury (0.016) to exposure experienced in 2007 indicates a risk by 2050 of 4,637 additional human casualties and 75,268 more injuries.¹

It is enormously difficult to attach a monetary-equivalent value to these risks that can be combined with and compared to the risks of financial damage and loss. The most appropriate measure of the benefit from reduced risk of fatality is the Value of Statistical Life (VSL), which estimates the monetary equivalent of improved well-being for individuals from reduced risk of mortality. In reality, VSL should reflect the context of the risk; for example, the risk of sudden fatality from an accident would differ from that of reduced future life span from long-term pollutant exposure.

This analysis used a VSL estimate of Tk. 15.5 million (about US\$0.2 million) for Bangladesh.² Multiplying this figure by the expected value of the increased number of lives at risk from a 10-year-return-period cyclone in a changing climate results in US\$1.03 billion of additional economic damage from greater fatality risk.

To calculate the economic damages from increased risk of injury, this study adopted a crude lower-bound estimate, based on the World Health Organization figure for cost per outpatient visit at a secondary hospital in

Bangladesh (\$4.86) (Cropper and Sahin 2009). This yields a total economic damage from increased injury risk of US\$0.352 million; however, this estimate does not include any value of lost production and income from injury or the more subjective losses of well-being resulting from injury or incapacitation.

Housing

In 2007, the housing sector was hardest hit by Cyclone Sidr. The types of houses damaged were predominantly *semi-pucka*, *kacha*, and *jhupris*.³ Analysis of Bangladesh's 2001 census data indicates that only 2.23 percent of rural households with an annual income of US\$470 per capita (Tk. 2,750 per capita per month) or higher could afford a brick house with a concrete roof (i.e., *pucka* house). But it is expected that, by 2050, the vast majority (about 98 percent) of households will live in brick houses, suggesting a significant reduction in housing damage but a substantial rise in household asset damage from cyclones over time (BBS 2007).

In a changing climate, it is projected that an additional 1.45 million houses (assuming an average family size of 4.89) will be exposed to significant damage from storm surges by 2050. A 10-year-return-period cyclone, with a larger extent of inundated area, would be expected to damage another 1.6 million houses. The assumed size of a standard house is 400 ft², with 2,000 ft² of brick wall surface and US\$2,143 (Tk. 150,000) of household assets. Assuming that half of all walls and household assets were damaged, replastering of houses would cost US\$229

¹ In the baseline scenario, by 2050 a 10-year-return-period cyclone would cause an estimated 5,274 casualties and 85,609 injuries; under the climate-change scenario, those estimates would rise to 9,911 and 160,877, respectively.

² This estimate was computed by updating the central estimate of the VSL for the United States (US\$7.4 million in 2006 dollars) available from the US Environmental Protection Agency with a price adjustment between 2006 and 2008 and a GDP differential between the United States and Bangladesh.

³ *Semi-pucka* houses have foundations made of earthen plinth or brick and concrete, bamboo-mat walls, and roofs made of CI sheet with timber framing. *Kacha* houses have foundations made of earthen plinth, bamboo walls made of organic materials, and thatched roofs made of straw and split bamboo. *Jhupris* houses have ceilings made of various inexpensive materials (e.g., straw, bamboo, grass, leaves, polythene, gunny bags).

million (at Tk. 10 per square foot) and asset damages about US\$1.718 million.

Education infrastructure

Given that, by 2050, an additional 7.08 million coastal residents would be exposed to storm surges caused by climate change, 456,690 primary school students (2,283 primary schools) and 312,957 secondary school students (2,086 secondary schools) would be at risk. Accounting for the larger extent of inundation area from a 10-year-return-period cyclone, an additional 4,840 primary and secondary schools would be damaged. A standard school in Bangladesh is about 160 m² and its contents worth US\$2,857 (Tk. 200,000). Assuming that half of the school walls and contents would be damaged during inundation, the estimated damage would total US\$8.96 million, and the cost of making alternative arrangements during the repair of facilities would be US\$0.82 million.

Agriculture

The study analysis computed the potential damage and loss to crop production, livestock, and fisheries. Cereal production was limited to

cyclone in the post-monsoon season than in the pre-monsoon season (67 percent versus 33 percent). The resulting difference in risk exposure for the three major rice crops was accounted for in the damage estimations. Assuming a 2.4-percent annual growth rate for cereal production, observed during 2001-07, a 10-year-return-period cyclone would damage 50 percent of yield, resulting in US\$788.83 million of additional damage caused by climate change by 2050.

In 2007, Cyclone Sidr caused damages and losses of US\$19.3 million and US\$6.7 million to livestock and fisheries, respectively. Assuming annual growth rates of 3 and 6 percent, observed during 2001-07, the additional damage from a 10-year-return-period cyclone with climate change would total about US\$55.62 million and US\$66.36 million, respectively.

Non-agricultural productivity

In 2007, Cyclone Sidr inflicted US\$51.4 million in damages to Bangladesh's non-agricultural productive sectors, with storm-surge inundation covering 558,512 ha. That year, these sectors (including small- and medium-sized enterprises,

Table A-1 Cost (US\$) to enhance height of coastal embankments

Polder type	Baseline scenario	Added cost with climate change
Sea-facing	317 million	389 million
Interior	2.145 billion	503 million

aman (monsoon), *aus* (pre-monsoon), and *boro* (post-monsoon) rice. With the expanded area of storm-surge inundation expected with climate change, these crops are expected to incur significant damage (Table A-1).

Historical records show that Bangladesh is about twice as likely to be hit by a tropical

commerce, and tourism) accounted for more than four-fifths of the country's GDP (World Bank 2009); by 2050, their share of GDP is likely to grow by another 11 percent.⁴ In a changing climate, a 10-year-return-period cyclone is estimated to damage more than 1 million ha, representing an additional potential damage of US\$87.9 million.

⁴ Between 2007 and 2050, Bangladesh's GDP is expected to increase 21.48 times.

Road infrastructure

Past experience suggests that roads are partially damaged when the depth of surge inundation is less than 1 m and fully damaged above 1 m. Assuming a 25-percent growth in the country's road network from 2005 to 2050, the study analysis indicates that, under the baseline scenario, 3,998 km of roads would be exposed to an inundation depth of less than 1 m and 8,972 km exposed to a depth above 1 m by 2050. With climate change, those figures would rise to 10,466 and 10,553, respectively. Accounting for the larger extent of inundated area from a 10-year- return-period cyclone, an additional 3,461 km of roads would be partially damaged and 2,205 km fully damaged under the climate-change scenario. Based on the post-assessment damages from Cyclone Sidr in 2007, the additional damage to roads, bridges, culverts, and related infrastructure in a changing climate would total US\$239.5 million.

Power infrastructure

Damage from Cyclone Sidr in 2007 to Bangladesh's coastal power sector totaled US\$8.2 million. Given the coastal area's projected population growth between 2007 and 2050 and projected power consumption in countries with

a similar per capita income, Bangladesh's power infrastructure is expected to increase 5 times and its per capita power consumption 20 times by 2050. Based on the damages from Cyclone Sidr, combined with the projected growth in power infrastructure, potential damages under the baseline scenario would cost US\$239.1 million and US\$449.3 million under the climate-change scenario. The additional inundation damage from a 10-year-return-period cyclone would total US\$60.2 million in a changing climate.

Protective coastal infrastructure

Storm-surge overtopping of polder embankments, the key reason for polder damage, causes rapid and deep scours to form on the country-side slope of the embankment; the process rapidly weakens the structure, leading to its collapse. In 2007, Cyclone Sidr caused US\$70.3 million in damages to Bangladesh's coastal polders and related water regulators. A comparison of projected surge heights with heights of existing polder embankments indicates that, by 2050, an additional 15 polders will likely be overtopped by cyclonic storm surges in a changing climate, with an estimated additional US\$17.3 million in damages.

Cost of added inundation from a 10-year-return-period cyclone

Table A-2 Added potential damage and loss from an average cyclone-induced inundation in a changing climate by 2050 (\$2009 prices)

Infrastructure/ sector asset	Damage estimate (million US\$)	Loss estimate (million US\$)
Housing	1,947.3	0.8
Education	9.0	835.4
Agriculture	75.4	1,084.0
Non-agricultural productivity	87.9	52.7
Roads	239.5	150.0
Power	60.2	
Coastal protection	17.3	
Total	2,436.6	2,122.9

Damage refers to partial or complete destruction of assets

Loss refers to the loss in the flow of goods and services

The total additional potential damage from a 10-year-return-period cyclone in a changing climate is estimated at US\$2.44 billion, with US\$2.12 billion in added potential losses (Table A2).



THE WORLD BANK

HEADQUARTER

1818 H Street, N.W.
Washington, D.C.,
20433, USA
Tel: 1-202-473-1000
Fax: 1-202-477-6391
www.worldbank.org

DHAKA OFFICE

Plot: E-32, Agargaon,
Sher-e-Bangla Nagar,
Dhaka 1207, Bangladesh
Tel: 880-2-8159001-28
Fax: 880-2-8159029-30
www.worldbank.org.bd