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Cyclones in a Changing Climate: The Case of Bangladesh

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Abstract

This paper integrates 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 rise by 2050. The approach identifies polders, coastal populations, settlements, infrastructure, and economic activity at risk of inundation, and estimates the damage from storm surge inundation versus the cost of several adaptation measures. A 27-centimeter sea-level rise and 10 percent intensification of wind speed resulting from global warming suggests that the vulnerable zone increases in size by 69 percent given a +3-meter inundation depth, and by 14 percent given a +1-meter inundation depth. Estimates indicate investments including strengthening polders, foreshore afforestation, additional multi-purpose cyclone shelters, cyclone-resistant private housing, and further strengthening of the early warning and evacuation system would cost more than \$2.4 billion, with an annual recurrent cost of more than \$50 million. These estimates can serve as a prototype in climate negotiations of the adaptation costs of extreme weather events.

Keyword: *Bangladesh, Climate Change, Storm Surges, Geographic Overlays, Damage, Adaptation Cost*

1. Introduction

Bangladesh is a global hotspot for tropical cyclones.⁸ Between 1877 and 1995, Bangladesh was hit by 154 cyclones, including 43 severe cyclonic storms, 43 cyclonic storms, and 68 tropical depressions.⁹ Since 1995, 5 severe cyclones have hit the country's coast. On average, a severe cyclone strikes the country every three years (GOB 2009). The country's topography is extremely low and flat with two-thirds of its land area less than 5 m above sea level. As a result, lives and property in low-lying coastal districts along the Bay of Bengal are highly vulnerable to inundation from cyclone-induced storm surges¹⁰. Cyclone Sidr (November 2007) and Cyclone Aila (May 2009) provide recent examples of devastating storm-surge in Bangladesh.¹¹

The scientific evidence indicates that increased sea surface temperature with climate change will intensify cyclone activity and heighten storm surges (IWTC 2006; IPCC 2007; see also Woodworth and Blackman 2004; Pielke et al. 2005; Woth, Weisse, and von Storch 2006; and Emanuel et al. 2008).¹² Surges will be further elevated by a rising sea level as thermal expansion continues to occur and ice cap(s) continue to melt (Nicholls et al. 2007; Dasgupta et al. 2011).¹³ Hence, increase in sea surface temperature and sea-level rise in a changing climate, may exacerbate Bangladesh's vulnerability to cyclones. Larger storm surges will then threaten greater future destruction, because surges will increase the depth of inundation and will move

⁸ The United Nations Development Programme (UNDP) has ranked Bangladesh as the world's most vulnerable country to tropical cyclones (UNDP 2004) See also Nicholls 2006.

⁹ 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).

¹⁰ *Storm surge* refers to the temporary increase in the height of the sea-level due to extreme meteorological conditions: low atmospheric pressure and/or strong winds (IPCC AR4 2007).

¹¹ In 2007, Cyclone Sidr, a 10-year return period cyclone with an average wind speed of 223 km per hour resulted in 4,234 casualties and 55,282 injuries (EMDAT –CRED). Livelihoods of 8.9 million people were affected and damages and losses from Cyclone Sidr totaled US\$1.67 billion (GoB 2008).¹¹ In 2009, Cyclone Aila, a 1.2 year return period cyclone with an average wind speed of 95 km per hour caused 190 deaths, 7,103 injuries and affected 3.9 million people. The estimated damage of assets from Aila is US\$270 million (EMDAT -CRED).

¹² A sea-surface temperature of 28° C is considered an important threshold for the development of major hurricanes of categories 3, 4 and 5 (Michaels, Knappenberger, and Davis 2005; Knutson and Tuleya 2004).

¹³ The most recent evidence suggests that sea-level rise could reach 1 meter or more during this century (Rahmstorf 2007; Dasgupta and Meisner 2009), although the likelihood of that magnitude of increase remains uncertain.

further inland - threatening larger areas than in the past. The destructive impact of storm surges will generally be greater when the surges are accompanied by strong winds and large onshore waves. This scientific evidence points to the need for greater disaster preparedness in Bangladesh.

Given the pervasive impacts of climate-related risks on cyclones over time, the government of Bangladesh has highlighted severe cyclones as a significant hazard and ensuring adequate flood protection infrastructure as a “pillar” of the Climate Change Strategy and Action Plan (GoB, 2009).¹⁴ Currently, systematic studies of the cost of climate proofing coastal protective infrastructure are scarce in Bangladesh. To date, most analytical work has been confined to case studies, with relatively limited sets of locations, impacts, and adaptation measures to date (Khalil 1992; Hoque 1992; Ali 1999; Quadir and Iqbal 2008). This paper aims to fill that knowledge gap by providing itemized estimates of potential damage and the incremental costs of adapting to intensified cyclones and related storm surges out to the year 2050. The itemized cost and damage estimates for future cyclones developed in this paper could help spur the Government of the People’s Republic of Bangladesh to develop adaptation plans now in order to avoid future losses from cyclone-induced flood amplification. For the international community, these estimates could serve as a prototype of the adaptation costs to extreme weather events in climate negotiations.

In this paper, information on climate change, hydrodynamic models, and geographic overlays are combined to assess the vulnerability of coastal areas in Bangladesh to larger storm surges and sea-level rise by 2050. The approach identifies polders (diked areas), coastal populations, settlements, infrastructure, and economic activity at risk of inundation from storm surges, and estimates the expected cost of damage versus the cost of several adaptation measures. A conservative 27-centimeter sea-level rise and 10 percent intensification of wind speed have been considered to approximate climate change from global warming by 2050.¹⁵

¹⁴ The government recognizes climate change is an environmental as well as a developmental issue; and is committed to protect the country from its adverse impact and maintain a stable growth path of the country.

¹⁵ This paper is based on the analytical work on extreme weather events in a changing climate commissioned in Bangladesh by the World Bank for the Economics of Adaptation to Climate Change study. Three consultations in Dhaka took place in May 2009, November 2009 and May 2010 for review of the technical details by local experts. A

At the outset, we acknowledge several limitations in our analysis. This analysis has not addressed the likely damages from wind, rain, salinity intrusion during cyclones nor has it addressed out-migration from the coastal zone that may be induced by sea level rise and more intense cyclones. Land subsidence of the coastal region is not included in the modeling because of inherent uncertainties. This analysis is based on conservative projections of the future. Resource constraints refrained us from running alternative scenarios; and therefore the reported estimates should be treated as conservative initial estimates. We also have not attempted to estimate location-specific probability of 10-year return period cyclones.

The remainder of the paper is organized as follows. Section 2 presents the case of storm surges in Bangladesh. Section 3 describes the modeling and simulation to determine the impact of climate change on magnitude of cyclone-induced inundation. Potential damage from a 10-year return period cyclone in Bangladesh by 2050 is presented in Section 4. Section 5 summarizes the cost of adaptation, and Section 6 concludes the paper.

2. Cyclone-induced Storm Surges in Bangladesh

Cyclones pose a threat to lives and property in low-lying coastal regions in Bangladesh. Records indicate that the greatest damage during cyclones has resulted from the inundation caused by cyclone-induced storm surges.¹⁶ Though time-series records of storm-surge height are scarce, existing literature indicates a 1.5m to 9 m height range during various severe cyclones.¹⁷

In Bangladesh, 32.1 human casualties have been recorded per 100,000 people exposed to cyclones (UNDP 2004). The reasons for this disproportionately large impact of cyclones include the recurvature of tropical cyclones in the Bay of Bengal; the wide, shallow continental shelf,

more technical version of the paper was peer reviewed and can be downloaded from http://climatechange.worldbank.org/sites/default/files/documents/EACC_Bangladesh.pdf

¹⁶ 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 (2010).

¹⁷ Storm-surge heights of 10m or more have not been uncommon; for example, the 1876 Bakerganj cyclone had a reported surge height of 13.6m (SMRC 2000).

especially in the eastern part of the country;¹⁸ the high tidal range;¹⁹ 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). Most surge amplifications occur in the Meghna estuarine region.

Surges that make landfall during high tide are even more devastating. In general, it has been observed that the frequency of a 10m high wave (surge plus tide) along Bangladesh coast is about once every 20 years, while a wave with a 7m height occurs about once in 5 years.²⁰

The IPCC AR4 indicates that future storm surges and related 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 indicate 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). Tropical cyclone simulations with four general circulation models for the A1B emission scenario conducted by Emanuel (2005) 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 General Circulation Model (World Bank and United Nations 2010).²¹ Hence, from a practical perspective vulnerability of Bangladesh to cyclones and storm surges may increase even more as a result of climate change.

3. Charting a New Course: Methodology and Vulnerable Area and Population

¹⁸ 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.

¹⁹ Records indicate 7–8 m high tide in the Sandwip Channel.

²⁰ In addition, wind-induced waves of up to 3m in height may also occur under unfavorable conditions (MCSP 1993).

²¹ The four General Circulation models considered are CNRM, ECHAM, GFDL and MIROC. For CNRM, ECHAM and GFDL, simulation results indicate reduction in intensity.

Given the large uncertainties about the magnitude and timing of the added risks from climate change in Bangladesh, it is essential to identify the potential damage and costs of adapting the country’s critical infrastructure to intensified storm-surge patterns in a changing climate. This research approach integrates information on climate change, assets at risk, growth projections to estimate damage and adaptation cost estimates in a five-step process. First, an *Economic Development baseline* for future Bangladesh was developed. Second, the potential inundation zone and projected depth of inundation caused by cyclonic storm surges were demarcated for a *Baseline Risk Scenario without climate change* and for a *Scenario with Climate Change* for the same economic development baseline. Third, the critical population and infrastructure exposed to the added risk of inundation in a changing climate—the critical impact elements—were identified. Fourth, expected additional damage and loss from a single 10-year return period cyclone²² induced storm surges in a changing climate (out to 2050) was computed. Fifth, the cost of adapting these critical impact elements in order to avoid damage from the added inundation caused by climate change was quantified.

Economic Development baseline: To start with, a development baseline that builds on recent economic trends and extends them to 2050 based on normal economic development patterns was defined to approximate future (2050) Bangladesh. Table 1 summarizes the assumption of key changes in the Bangladesh economy between now and 2050, which includes 53 percent more people, more than twenty-fold increase in GDP, and decreased dependence on agriculture. The people of Bangladesh are expected to be ten times richer, consuming twenty times more electricity per person, living in *pucka* houses, and enrolling all primary-aged children in schools.

Table 1: Economic indicators Bangladesh: Current and 2050

| Indicator | Current Indicators | | | Indicators in 2050 | |
|-----------------------------|--------------------|------|--------------------------------------|--------------------|-----------------|
| | Value | Year | Source/ comments | Value | Source/comments |
| Population (million) | 130 | 2001 | Bangladesh Bureau of Statistics(BBS) | 228 | BBS |

²² A 10-year return period cyclone was selected as it is conservative yet sufficiently frequent to warrant changes in the planning and budget allocation of the Government of Bangladesh.

| | | | | | |
|--|---------|---------|--------------------------|---------|--|
| Population average annual growth rate | 1.58 | 1991-01 | State of the Coast, 2006 | 1.15% | BBS & State of the Coast, 2006 (replacement fertility in 2021) |
| Coastal population (million) | 35 | 2003 | State of the Coast, 2006 | 58 | BBS & State of the Coast, 2006 |
| Coastal population average annual growth rate | 1.36% | 1991-01 | State of the Coast, 2006 | 1.05% | BBS & State of the Coast, 2006 |
| GDP (billions of constant 2009 USD) | \$75 | 2007 | WDI 2009 | \$1,614 | Projected with growth rates in the following row. |
| GDP avg. annual growth rate | 5.9% | 2001-09 | Ministry of Finance | 7.5% | Various government announcements |
| Per capita GDP (constant 2009 USD) | \$470 | 2007 | WDI 2009 | \$6,395 | Implied |
| Road length (km) | 272,487 | 2007 | BBS | 340,609 | Assumed 25% expansion |
| Share of paved roads | 30% | 2007 | BBS | 100% | Assumed |
| Primary school net enrollment rate | 91% | 2007 | Ministry of Education | 100% | WDI 2009, average level in comparator countries * |
| Secondary school gross enrollment rate | 43% | 2007 | Ministry of Education | 70% | WDI 2009, average level in comparator countries * |
| Per capita electricity consumption (KWh) | 150 | 2007 | BBS | 3000 | WDI 2009, average level in comparator countries * |
| Share of pucca houses in rural areas | 2.23% | 2001 | BBS | 98% | current housing characteristics in Bangladesh by income level |
| Rice production (million metric tons) | 27 | 2006 | BBS | 75 | Yu et al, 2010, existing climate variability scenario |

Notes: Current per capita GDP in comparator countries: Brazil(\$5,860), Malaysia(\$6,420), Lebanon(\$5,800), and Uruguay(\$6,390). Source : World Development Indicators, World Bank

This economic development baseline provided the basis for comparing the damage and costs under climate change against the counterfactual baseline scenario that does not include climate change,²³ as defined below.

²³ The estimates of damage and adaptation costs are conditional on this economic development baseline.

Baseline (without climate change) Risk Scenario: For defining the baseline risk (without climate change) scenario, tracks of the 19 major cyclones that made landfall in Bangladesh from 1960 to 2009 were used, along with their corresponding observed wind and pressure fields (Figure 1).²⁴ 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).²⁵ The resulting inundation map is based on the maximum level of inundation at all grid points of the model.

Core Climate Change Scenario: Storm-surge related risk is expected to increase from historical levels due to climate change. To approximate cyclones and related storm surges in a changing climate, this analysis considered a sea-level rise (SLR) of 27 cm (UK DEFRA 2007), increased wind speed of 10 percent (Nicholls et al. 2007; World Bank 2010), and landfall during high tide to approximate cyclones in a changing climate by 2050.²⁶

**Figure 1: Risk from major cyclones in 1960–2009
spanned Bangladesh’s entire coastline**

[Insert Figure 1]

Source: Authors’ calculations. Institute of Water Modeling (IWM), Bangladesh

Since future storm tracks cannot be predicted with any degree of precision, cyclone-related risks under the climate change scenario were developed simulating a set of five storms that

²⁴ Ibid., Appendix 3.

²⁵The 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. See Dasgupta et al., Appendix 1. World Bank, Washington, DC (2010).

²⁶ Scientific evidence to date suggests that the frequency of intense cyclones in the Bay of Bengal will increase; thus, the probability of a potential landfall during high tide will also rise.

span the entire Bangladesh coastline.²⁷ Simulations of the 1974, 1988, 1991 and 2007 cyclones indicated that cyclone tracks from those years covered the Sunderban coast, southwestern coast (Sunderban to Patuakhali), Bhola and Noakhali coast in the Meghna Estuary, and the eastern coast (Shitakunda to Bashkhali). In addition, a 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 2).

Figure 2: Five cyclone tracks span Bangladesh’s coastline under the climate change scenario

[Insert Figure 2]

Source: Authors’ calculations. IWM, Bangladesh

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, maps depicting the extent and depth of inundation for 2050 were generated once again applying the Bay of Bengal model.

It should be noted that land subsidence in the coastal region of Bangladesh is not included in the core analysis because of inherent uncertainties about future changes.

²⁷ The tracks of the same 19 historical cyclones and the affected coastal regions to simulate potential tracks out to 2050.

Inundation area estimates, in this analysis, are computed from the envelopes of the inundation zones of the individual cyclone tracks.²⁸ Comparison of inundation area estimates indicated that the vulnerable area in coastal Bangladesh with more than 3 m of inundation depth is likely to increase by 69 percent and that with a 1m-3m inundation depth is likely to increase by 14 percent due to climate change (Figure 3).

Figure 3: High risk area by 2050 in a changing climate

[Insert Figure 3]

Source: Authors' calculations. IWM, Bangladesh

| 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 |

Complexity of predictions in deltas in a changing climate: Coastal Bangladesh is a part of the Ganges delta. Future projections in deltas are inherently complex as deltas are not static, but are under a continuously changing process of sedimentation and erosion. The undertaking has been made further complicated due to uncertainties in spatial and temporal distribution of climate change impacts. We explored the implications of this uncertainty for our estimates with a sensitivity analysis over the existing mid-range of sea-level rise: 27cm- 32cm²⁹ by 2050 and

²⁸ This approach is in line with the other initiatives of cyclone hazard mapping for Bangladesh, for example see link <http://www.uwec.edu/jolhm/eh2/molnar/map.htm>

²⁹ Although there is widespread agreement among scientists that sea levels will rise due to climate change, regional estimates of sea-level rise (SLR) are scarce. In the absence of scientific SLR estimates corresponding to various emission scenarios for the Bay of Bengal, upon consultation with the experts on cyclone modeling in Bangladesh, “medium sea level rise” by 2050, derived from Rahmstorf (2007) estimate was adopted. See Neumann (2007) for details.

2mm/year – 5mm/year land subsidence³⁰ of Bengal delta in Bangladesh. Percentage change in the vulnerable area estimates for these alternative scenarios over the baseline are summarized below. These estimates are derived from the Digital elevation Model (DEM) of Bangladesh and illustrate the conservative nature of the core climate change estimates reported in this paper.

| depth (m) | 27cm SLR & 2mm/year subsidence | 27cm SLR & 5mm/year subsidence | 32cm SLR & 2mm/year subsidence | 32cm SLR & 2mm/year subsidence |
|----------------------|---|---|---|---|
| | Change (%) | Change (%) | Change (%) | Change (%) |
| >1 | + 20 | + 28 | + 23 | + 30 |
| >5 | + 81 | + 99 | + 92 | + 107 |

GIS software was used to estimate the infrastructure assets and population exposed to inundation risk from cyclones and associated storm surges by 2050 under the baseline and the core climate change scenarios.

Bangladesh has extensive existing infrastructure—including polders, cyclone shelters, early warning and evacuation systems—to protect low-lying coastal areas. To identify the infrastructure exposed to added inundation risk, GIS software was used to overlay the best available, spatially-disaggregated data on current assets and activities in the country’s coastal zone, with projected inundation zones for 2050 under the baseline and climate change scenarios.³¹ For each exposure indicator, estimates were calculated by overlaying the inundation zone with the appropriate exposure-surface data set.

³⁰ Subsidence of land, if significant, will amplify surge-induced inundation. Available estimates of land subsidence of lower Bengal delta vary widely from a fraction of a millimeter to a few centimeters per year (Huq, 2012).

³¹ Exposure surface data were collected from various public sources, such as Bangladesh Railways, Bangladesh Water Development Board, Local Government Engineering Department (LGED), Public Works Department, Roads and Highways Department, Water Resources Planning Organization, Center for Environmental and Geographic Information services (CEGIS) and the World Bank. .

Estimates indicate currently 8.06 million people in coastal Bangladesh are vulnerable to inundation depths greater than 3m resulting from cyclonic storm surges. With population growth, that number is projected to increase 68 percent by 2050 under the baseline scenario. Without further adaptation measures, the figure would rise by another 67 percent, and 22.64 million people in coastal Bangladesh will be exposed to inundation depths greater than 3m by 2050 in a changing climate (Table 2).

Table 2: 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 |

4. Expected Damage and loss from a single 10- year return period cyclone and storm surges in a Changing Climate by 2010

This section estimates the expected impact of a single average 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 damages resulting from Sidr, the cyclone which made a landfall in Bangladesh in 2007. At the outset, we acknowledge that reliance on this single storm may bias the damage estimates in unobservable ways.

Based on major cyclone events experienced by Bangladesh from 1876 to 2009, it is estimated that a cyclone like Sidr has a 10-year return period. However, the areal extent of cyclone Sidr (with wind speed of 223 km per hour) was 8.7 percent higher than the average historical cyclone with a 10-year return period. Hence, it is understood that the damages and losses from an average 10-year return period cyclone will be less than Sidr if such cyclone were to strike Bangladesh coast today. Therefore, in calculating damages from an average 10-year return period cyclone under “no climate change”, this research scaled down the damages from Sidr by 8.7 percent. Currently an average 10-year return period cyclone covers 26 percent of the vulnerable (total surge-induced inundation) area. It is estimated that in a changing climate, a future 10-year return period storm is likely to be more intense and will cover 43 percent of the vulnerable area. So, in computation of expected damages from a 10-year return period storm in future climate, this additional area coverage of 17 percent was taken into account. Finally, all estimates were adjusted for 2009 price levels, in accordance with the 18-percent increase in the GDP deflator in 2007 and 2009.

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 increased costs of continuing essential services. **The total additional potential damage from a 10-year return period cyclone in a changing climate is estimated at US\$2.437 billion, with US\$2.123 billion in added potential losses (Table 3).**

Table 3. Additional potential damage and loss from an average cyclone-induced inundation in a changing climate by 2050

| 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 |

The sub-sections below estimate the potential human casualties and injuries from such a cyclone, 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.³²

Assuming that Bangladesh attains a replacement fertility rate by 2021 and 1-percent average annual growth in coastal population between 2001 and 2050, the total number of people exposed to the risk of storm surge inundation from a 10-year return period cyclone by 2050 is 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 of 4,637 additional human casualties and 75,268 more injuries by 2050..³³

³² 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.

³³ 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.

However, it should be noted that these are upper bound estimates under the assumption that there are no changes in the human casualty and injury rates over time. Casualty and injury rates are expected to decline as cyclone-resilient *pucka* houses become affordable for an increasing proportion of coastal residents and if “user-friendly” shelter designs encourage higher usage rates.

Housing

In 2007, the housing sector was hardest hit by Cyclone Sidr. The types of houses damaged were predominantly *semi-pucka*, *kacha*, and *jhupris*.³⁴ 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 square feet, with 2,000 square feet of brick wall surface and US\$2,143 (Tk. 150,000) of household assets. Assuming that half of all walls and household assets are damaged, replastering of houses would cost US\$229 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

³⁴ *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).

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 *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 4).

Table 4. 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 |

Historical records show that Bangladesh is about twice more likely to be hit by a tropical 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, 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.³⁵ 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.

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

³⁵ Between 2007 and 2050, Bangladesh's GDP is expected to increase 21.48 times.

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.

Cautionary note:

The present study computed and reported expected damage and loss estimates from a conservative core scenario of climate change; and for one economic development scenario of Bangladesh in 2050, presented in Table 1. Future is uncertain. Ideally, an array of estimates of potential damage and loss should be computed taking into account alternative economic development scenarios of Bangladesh. Changes in each economic indicator is likely to affect sectoral damages. As an illustration, nine damage and loss estimates are presented below with high and low estimates of SLR, land subsidence and a lower annual GDP growth rate of 5% per annum.

| | Alternative scenarios | Damage estimate (million US\$) | Loss estimate (million US\$) |
|----------|---|-----------------------------------|---------------------------------|
| 1 | Core Case: 5.9% annual GDP growth rate , 27 cm SLR, no subsidence | 2,436.60 | 2,122.90 |
| 2 | 5.9% annual GDP growth rate , 27cm SLR, 2 mm/year subsidence | 3,402.93 | 2,964.82 |
| 3 | 5.9% annual GDP growth rate, 27cm SLR, 5 mm/year subsidence | 3,684.46 | 3,210.11 |
| 4 | 5.9% annual GDP growth rate, 32cm SLR, 2 mm/year subsidence | 3,548.34 | 3,091.51 |
| 5 | 5.9% annual GDP growth rate, 32cm SLR, 5 mm/year subsidence | 3,789.92 | 3,301.99 |

| | | | |
|-----------|--|----------|----------|
| 6 | 5% annual GDP growth rate, 27cm SLR, no subsidence | 2,058.90 | 1,321.64 |
| 7 | 5% annual GDP growth rate, 27cm SLR, 2 mm/year subsidence | 2,875.44 | 1,845.79 |
| 8 | 5% annual GDP growth rate, 27cm SLR, 5 mm/year subsidence | 3,113.33 | 1,998.49 |
| 9 | 5% annual GDP growth rate, 32cm SLR, 2 mm/year subsidence | 2,998.31 | 1,924.66 |
| 10 | 5% annual GDP growth rate, 32 cm SLR, 5 mm/year subsidence | 3,202.44 | 2,055.69 |

Estimates presented above suggest the development scenario considered in this paper generated a relatively conservative damage estimate. Underlying sectoral estimates indicate housing, agriculture and non-agricultural productivity are significantly impacted by a potential lower GDP growth. Resource and time constraints refrained us from computing the full array of damage and loss estimates corresponding to alternative development scenarios. It should be subject of future analysis.

5. Costing of Adaptation

Bangladesh has an extensive infrastructure such as polders, cyclone shelters, early warning and evacuation system to protect coastal regions. This exercise of costing of adaptation is focusing on climate proofing existing protection infrastructure. In particular, adaptation costs are estimated for five protection measures-polders (upgrade only), afforestation (expansion only), cyclone shelters (expansion only), cyclone-resistant housing (expansion only), and early warning systems (upgrade and expansion).³⁶

It should be noted that despite the extensive infrastructure Bangladesh has in place to protect coastal residents from cyclonic storm surges and tidal waves, currently 44 of the country's 123

³⁶ These adaptation measures aim to reduce the area, assets, and activities exposed to inundation risk, and hence diminish the need for additional asset-specific resilience enhancing investments, such as raising the height of roads further inland. However, it should be noted that such resilience enhancing investments are essential to protect assets in areas that are currently not protected by polders (e.g. many small islands). Polders were not constructed in these areas primarily because of the low density of assets and activities in these areas. The cost of increasing the resilience of specific assets in these areas should be relatively small; no attempt has been made in this research to estimate this cost.

coastal polders run the risk of overtopping if a severe cyclone hits. As a result, Bangladesh has a current adaptation deficit totals US\$2.462 billion (World Bank, 2010).³⁷ In a changing climate, the greater expanse and depth of the areas inundated will put many more existing structures at risk. By 2050, another 59 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 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). The costing of adaptation refers to the increased inundation area and depth for a 10-year return cyclone in a changing climate. The subsections that follow itemize the estimated adaptation costs for enhancing the height of coastal polders, increasing afforestation measures to protect sea-facing polders, constructing multipurpose cyclone shelters and cyclone-resistant private housing, and strengthening the early warning and evacuation system.

Table 5: Total adaptation cost for cyclones and associated storm surges by 2050

| Measure | Baseline scenario | Additional cost with climate change | |
|--------------------------------|---------------------------|-------------------------------------|--------------------------------------|
| | Investment (billion US\$) | Investment (million US\$) | Annual recurrent cost (million US\$) |
| Polders | 2.462 | 892 | 18 |
| Foreshore afforestation | | 75 | |
| Multipurpose | | 1,200 | 24 |

³⁷ The government of Bangladesh has an active program to construct cyclone shelters. While reliable estimates of the number of shelters under construction or being planned are not available because of the magnitude of government agencies and NGOs undertaking this effort, they are likely to be in the thousands eventually. The consensus among experts in these institutions and the relevant government agencies is that an additional 2,000-2,500 shelters need to be built to accommodate vulnerable population in current climate. Discussion with the officials of the LGED indicated the current deficit in cyclone shelters will likely be eliminated with the extensive shelter construction efforts that are planned or already under way.

| cyclone shelters | | | |
|---------------------------------------|-------|-------|------|
| Cyclone-resistant private housing | | 200 | |
| Strengthening of early warning system | | 39 | 8 + |
| Total | 2.462 | 2,407 | 50 + |

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.³⁸ This research used GIS software to overlay the best available, spatially-disaggregated data on polders in the country’s vulnerable coastal zone. To identify which polders will likely be overtopped by intensified storm surges in a changing climate and the extent of that overtopping, the research 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, 26 interior polders and 33 sea-facing coastal polders will be overtopped (Figure 4).

Figure 4: In a changing climate, 33 sea-facing and 26 interior polders will likely be overtopped by 2050.

[Insert Figure 4]

Source: Authors’ calculations. IWM, Bangladesh

The study computed the cost of enhancing the height of the polders identified as likely to be overtopped in a changing climate. The amount of needed earthwork was determined from engineering designs, and the current local prices for earthwork, compaction, and turfing were

³⁸ The Bangladesh Water Development Board maintains an extensive database on coastal polders, including data on their length, location, construction year, and cost.

provided by the Bangladesh Water Development Board.³⁹ 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 of the height-enhanced polders in interior or marginal areas was also estimated. Maintenance cost was assumed to represent 2 percent of capital investment. In a changing climate, the adaptation cost (33 sea-facing and 26 interior polders) totals US\$892 million (Table 6).⁴⁰

Table 6: Estimated cost of enhancing height of coastal embankments (million US\$)

| Polder type | Baseline scenario | Additional cost with climate change |
|--------------------|--------------------------|--|
| Interior | 317 | 389 |
| Sea-facing | 2,145 | 503 |

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.⁴¹ 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 Institute of Water Modeling recommend a minimum of 500-m width mangrove forest to protect sea-facing polders.

This study analysis estimated the current length of coastal afforestation between the coastline and polders, using Google Earth and GIS methodology, to compute the gap between the recommended 500-m width mangroves and existing area-specific ones. The results indicate

³⁹ See Dasgupta et al., *Vulnerability of Bangladesh to Cyclones in a Changing Climate: Potential Damages and Adaptation Cost*, Appendix 4. World Bank, Washington, DC (2010).

⁴⁰ Ibid., Appendix 5.

⁴¹ 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).

that 897 km length of existing sea 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 x 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. Yet many existing cyclone shelters are in dilapidated condition and fail to provide for the special needs of women, people with disabilities, and provision of 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.

In 2001, more than 8 million people in coastal Bangladesh were exposed to storm surge–induced inundation depths of more than 3 m. By 2050, that number is expected to rise to more than 13.5 million under the baseline scenario. In a changing climate, another 9.1 million inhabitants will be exposed to similar inundation risk. Accommodating these additional people will require adding 5,702 multipurpose cyclone shelters, at an estimated cost of US\$1.2 billion.⁴²

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

⁴² 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.

2008). In coastal regions, houses can be made cyclone-resistant by following suitable designs and building codes. This study analysis, which consulted 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 subsidized⁴³ construction material and housing credit would require setting up a revolving fund in the amount of US\$200 million.

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.⁴⁴

The estimated costs of the surveys and mathematical modeling required to improve projections for location-specific inundation, as recommended by the Institute of Water Modelling, total US\$8 million. Modernization of the Bangladesh Meteorological Department (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 per year, while the awareness-raising promotion program recommended by the Red Crescent Society totals US\$3 million annually.

6. Conclusion

⁴³ Subsidy systems should always be designed with caution so that misuse of subsidies can be avoided.

⁴⁴ The study team conducted focus group interviews with experts at the Institute of Water Modelling, Bangladesh Meteorological Department, Red Crescent Society, and residents of recent cyclone-affected areas on their recommendations for strengthening the early warning and evacuation system.

Bangladesh is a cyclone-prone country. Cyclones hit the coastal areas of Bangladesh every year, and on average a severe cyclone, with wind speed ranging 90 – 119 km per hour, strikes Bangladesh every three years. Cyclone risk spans the entire coastline of Bangladesh, and the historical evidence highlights the danger associated with cyclone-induced storm surges. The vulnerability of Bangladesh may increase even more as current scientific evidence points towards a probable increase in the frequency of intense tropical cyclones in the Bay of Bengal.

At present, systematic studies of storm surge patterns for the future, location-specific potential damage scenarios and adaptation alternatives are scarce in Bangladesh; this paper is an attempt to narrow that knowledge gap. This analysis integrates information on climate change, hydrodynamic models, and geographic overlays to assess the vulnerability of coastal Bangladesh to larger storm surges and sea-level rise by 2050; and the study method adopted a five-step process. First, an economic development baseline for future (2050) Bangladesh was developed. Second, the potential inundation zone and projected depth of inundation caused by cyclonic storm surges were demarcated for a baseline scenario without climate change and one with climate change with hydrodynamic models. Third, the critical populations and infrastructure exposed to the added risk of inundation in a changing climate — the critical impact elements—were identified with GIS overlays. Fourth, potential additional damage and loss from a single 10-year return period cyclone in a changing (out to 2050) climate was computed. Fifth, the cost of protecting these critical impact elements in order to avoid damage from the added inundation caused by climate change was quantified.

Conservative estimates of climate change indicate that a 27-centimeter sea-level rise and 10 percent intensification of wind speed from global warming is likely to increase the storm surge-induced inundation area (vulnerable coastal zone) in size by 69 percent given a +3m inundation depth and by 14 percent given a +1m inundation depth by 2050. At present, a 10-year return period cyclone with an average wind speed of 223 km per hour, as recorded during the Cyclone Sidr, 2007, covers 26% of the vulnerable zone; estimates of this research indicate that a similar cyclone will be more intense with global warming and is likely to cover 43% of the vulnerable zone by 2050 - exposing an additional 9.1 million inhabitants to risk of inundation. The projection of damage reported in this paper suggests a 10-year return period cyclone out to

2050 will result in an additional financial damage and loss of \$4.560 billion⁴⁵ in a changing climate. In addition, a conservative estimate of monetized loss from additional deaths and injuries is \$1.03 billion.

At present, Bangladesh has 123 polders, an early warning & evacuation system and more than 2,400 emergency shelters to protect coastal inhabitants from tidal waves and storm surges. Yet, estimates point out that currently Bangladesh has an adaptation deficit of \$2.462 billion. It has been further estimated that in a changing climate by 2050, 59 polders will be overtopped during storm surges and another 5,500 cyclone shelters (each with the capacity of 1,600 people) will be needed. Estimates also indicate investments including strengthening polders, foreshore afforestation, additional multi-purpose cyclone shelters, cyclone-resistant private housing, and further strengthening of the early warning and evacuation system would cost more than \$2.4 billion with an annual recurrent cost of more than \$50 million to cope with climate change.⁴⁶

Future is uncertain. Ideally, any projection of the kind presented in this paper should consider alternative climate change scenarios and alternative development scenarios of Bangladesh. The scenario presented in this paper is based on conservative point estimates and therefore be treated as conservative initial estimates.

The climate is expected to change gradually; the required investments for adaptation can be made incrementally.⁴⁷ The conservative itemized adaptation cost estimates provided in this paper can serve as a tool to spur the Government of the People's Republic of Bangladesh to develop location-specific coastal adaptation plans at this time to avoid future losses. Ratios of

⁴⁵ of which damage is \$2.437 billion and loss is \$2.123 billion. The most recent 10-year return period cyclone, Cyclone Sidr caused a financial damage and loss of \$1.67 billion in 2007.

⁴⁶ This analysis assumes a framework of appropriate development policies and institutional arrangements within which to make the assessed infrastructure investments. Indeed, sound policies, planning, and institutions are essential to ensure that capital-intensive measures are used in the right circumstances to yield the expected benefits. Height enhancement of polders, for example, must be carefully considered since construction is usually followed by the accumulation of physical capital behind the barrier, which is considered "safe."

⁴⁷ Embankments must be strengthened beyond their current protective capacity as the added risk of inundation becomes more certain. Similarly, it is 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.

location-specific potential damage⁴⁸ and adaptation cost can be used to prioritize and sequence investments as resources permit. Recognizing the uncertainties in the timing and magnitude of impacts of climate change, a prudent strategy may begin by addressing the adaptation deficit and existing risks that current residents face. Existing investments, which have reduced the impacts of cyclones, provide a solid foundation on which to undertake additional measures to reduce potential damages now and in the future.

For the international community, this paper presents a detailed bottom-up methodology to estimate potential damage, adaptation deficit and adaptation cost to intensified storm surges in a changing climate. The approach integrates information on climate change, assets and activities at risk, growth projections, likely damage and cost estimates. Conservative estimates presented in this paper can also serve as a prototype of the adaptation costs to extreme weather events in climate negotiations.

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⁴⁸ Computation of location-specific damage estimates is subject of future research.

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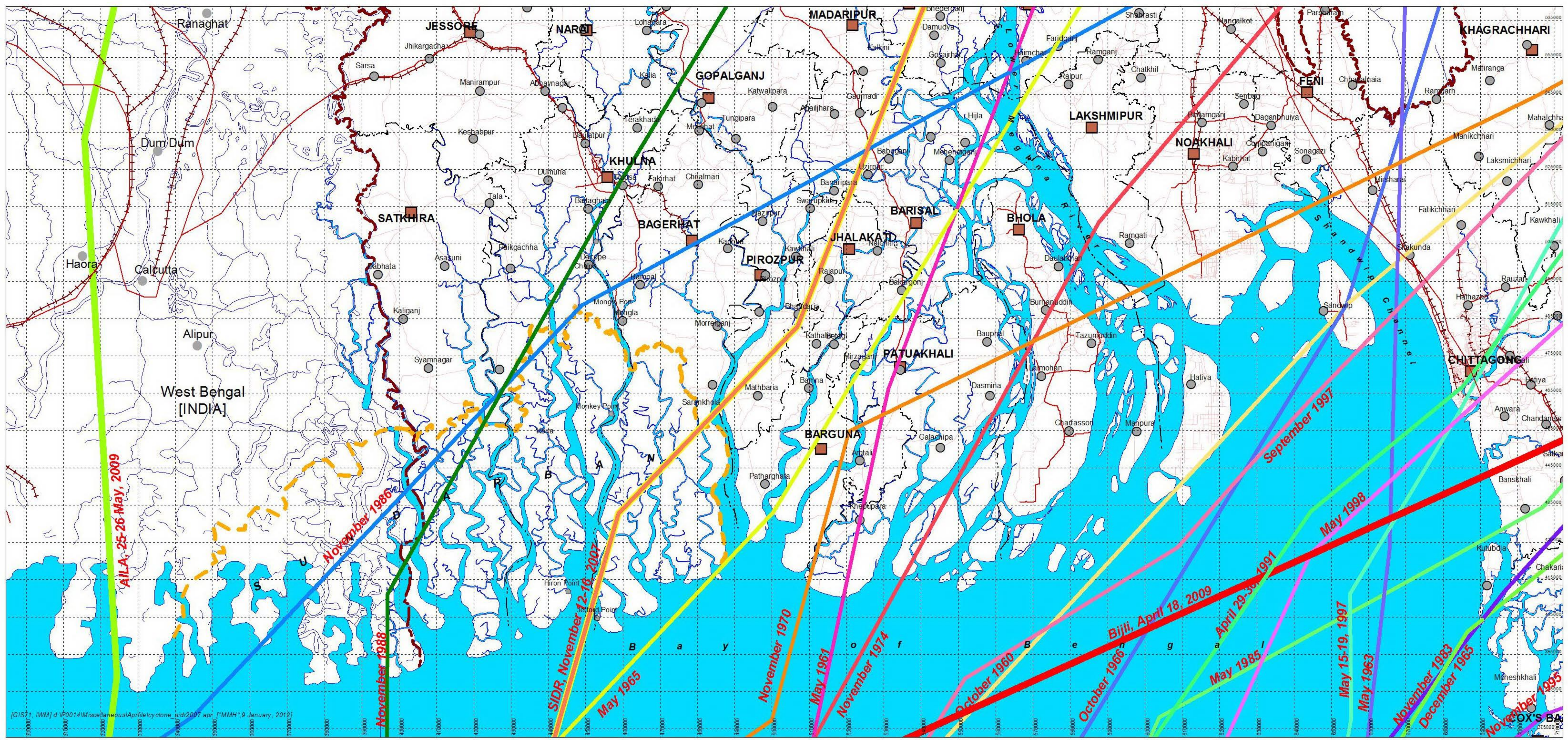
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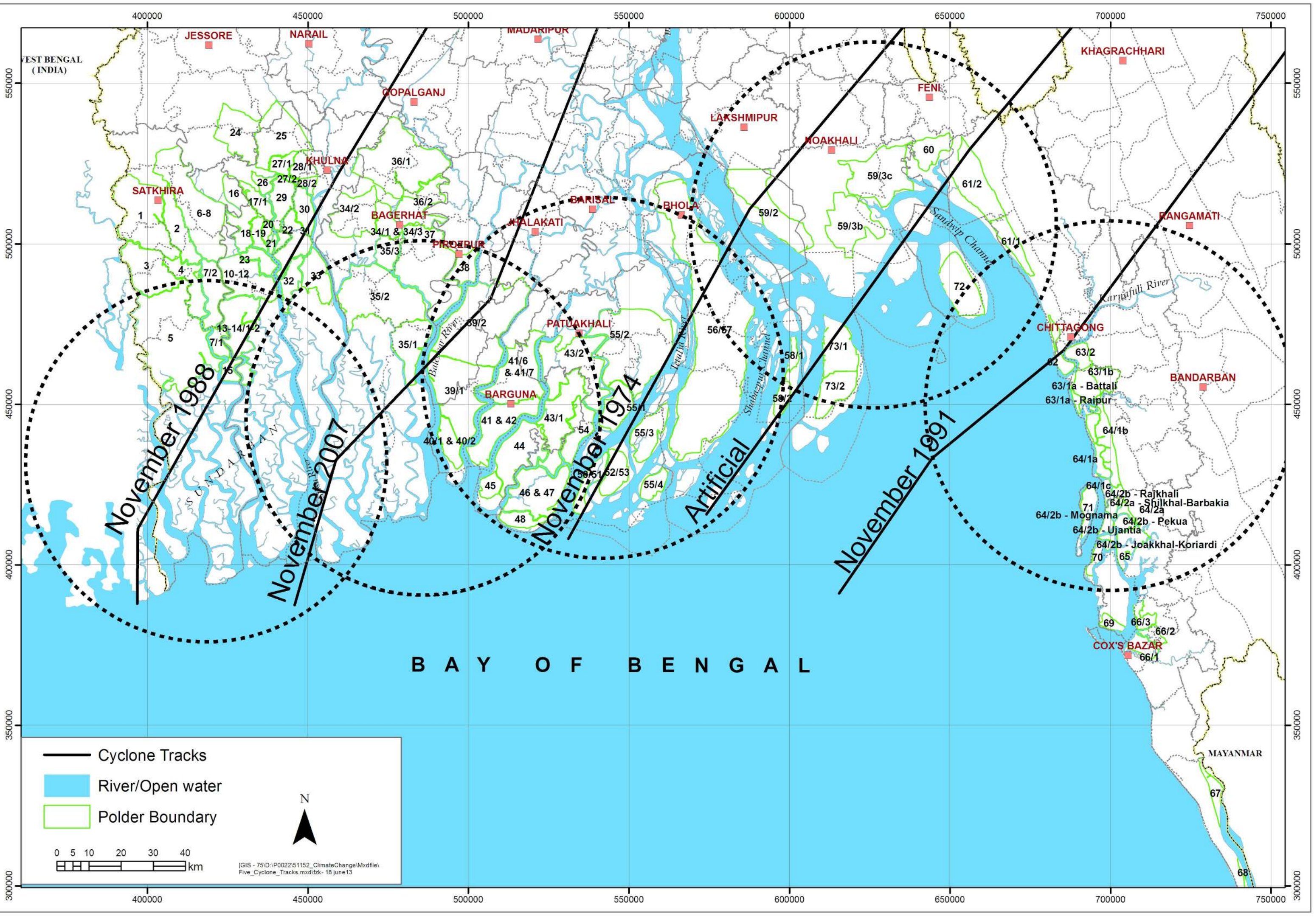
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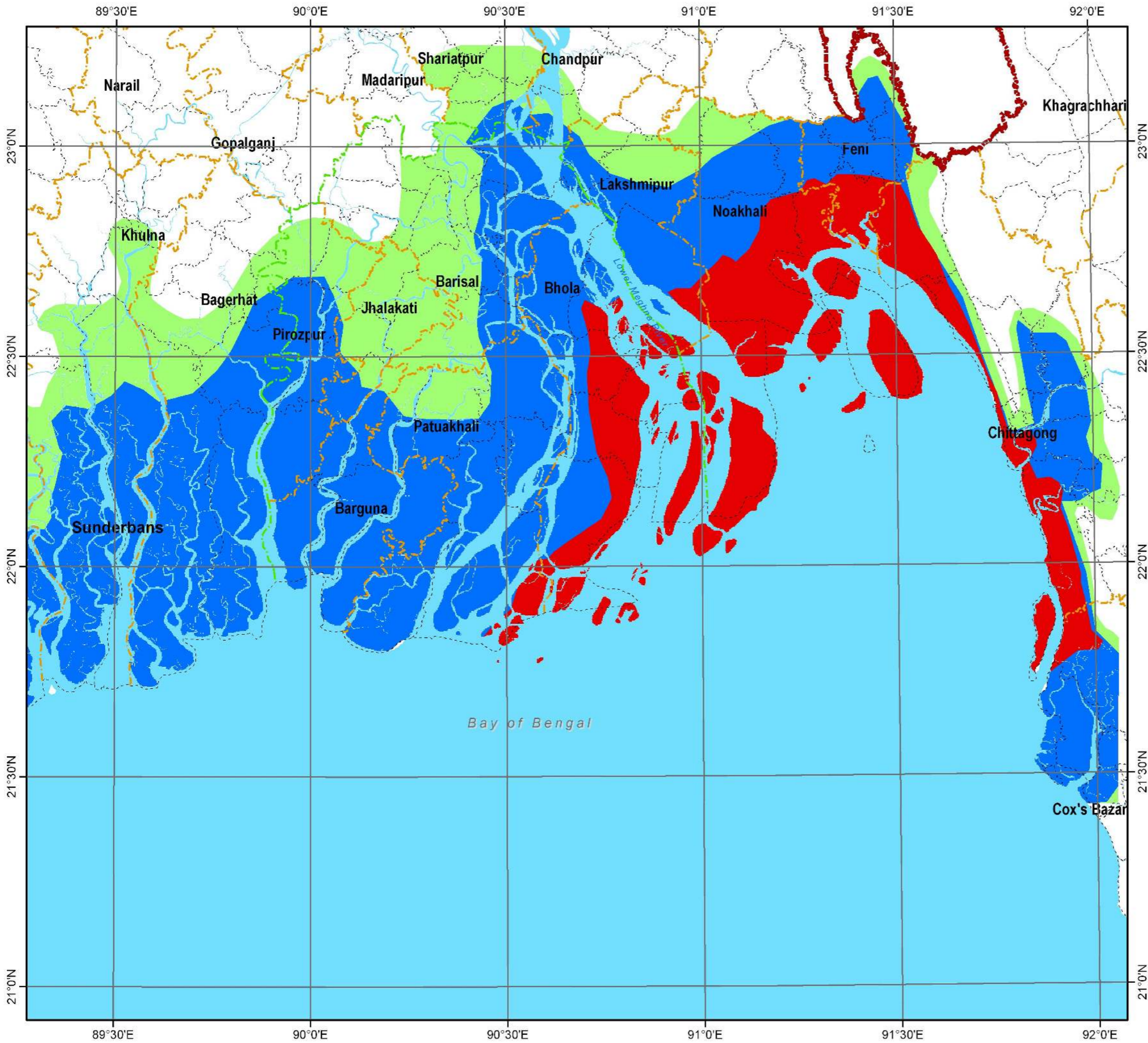
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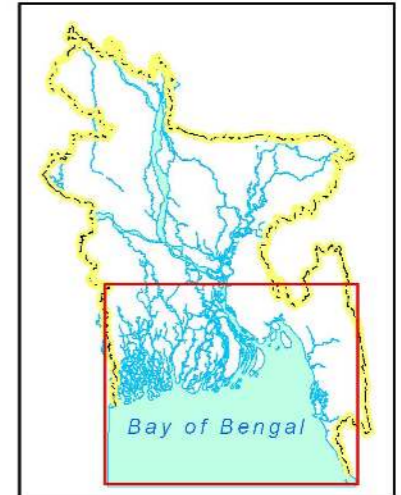
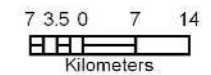
Inundation Risk Map - 2050

Legend

- International Boundary
- Division Boundary
- District Boundary
- Thana Boundary
- River

Inundation Riskzone

- > 1 Meter
- > 3 Meter
- > 6 Meter



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