WPS8251

Policy Research Working Paper 8251

Mangroves as Protection from Storm Surges in Bangladesh

Susmita Dasgupta
Md. Saiful Islam
Mainul Huq
Zahirul Huque Khan
Md. Raqubul Hasib

WORLD BANK GROUP
Development Research Group
Environment and Energy Team
November 2017

Abstract

Mangrove forests can reduce the vulnerability of adjacent coastal lands from storm surges by slowing the flow of water. Although the potential utility of mangroves in disaster risk reduction is increasingly recognized by coastal managers, efficient use of this ecosystem-based protection is often hindered by the scarcity of location-specific information on the protective capacity of mangroves. This paper evaluates that capacity in seven coastal locations of Bangladesh, where surge heights can range from 1.5 to 9 meters. Estimates confirm varying levels of protection from different species, width, and density of mangrove forests. The findings highlight that mangroves must be used along with built infrastructure such as embankments. However, mangroves in the foreshore of embankments will contribute to savings in maintenance costs by protecting the built infrastructure from breaching and other damages.

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Mangroves as Protection from Storm Surges in Bangladesh

Susmita Dasgupta*
Lead Environmental Economist, Development Research Group, World Bank, United States

Md. Saiful Islam
Specialist, Coast, Port and Estuary Management Division, Institute of Water Modeling, Bangladesh

Mainul Huq
Consultant, World Bank, Bangladesh

Zahirul Huque Khan
Director, Coast, Port and Estuary Management Division, Institute of Water Modeling, Bangladesh

Md. Raqubul Hasib
Specialist, Coast, Port and Estuary Management Division, Institute of Water Modeling, Bangladesh

October, 2017

This research was conducted under the South Asia Water Initiative - Sundarbans Landscape

* Corresponding Author: Susmita Dasgupta. Email: sdasgupta@worldbank.org;
Tele phone: 1-202-473-2679; Fax: 1-202-522-2714

JEL Classification: Q54; Q57

We are thankful to Polly Means for her help with the graphics. We would also like to extend our special thanks to Md. Istiak Sobhan for his guidance on selection of mangrove species and Sharifuzzaman Choudhury for his help with the literature review. We are also grateful to Sunando Bandyopadhyay, Brian Blankespoor, Abedalrazq F. Khalil and Glenn Marie Lange for their useful comments and suggestions.

1. Introduction

In recent years, considerable attention has been given to the protective role of mangroves[1] and other coastal forests either alone or alongside built infrastructure against coastal hazards.[2] The evidence that mangroves may shelter coastal communities and assets from coastal erosion, wind and swell waves, cyclones, etc. is well known in tropical coastal ecology and the potential utility of mangroves as a tool in disaster risk reduction is increasingly recognized by coastal managers (Chapman, 1976; UNEP-WCMC, 2006; Doney et al. 2012; McIvor et al 2012a; McIvor et al. 2012b; Waite et al. 2014). Numerous modeling and mathematical studies have shown that mangrove forests can attenuate the height of waves as well as water flow velocity (Brinkman et al., 1997, Mazda et al. 1997, 2006; Massel et al., 1999; Quartel et al., 2007, Barbier et al. 2008, Gedan et al. 2011; Zhang et al. 2012; McIvor et al. 2013; Liu et al. 2013; Pinsky et al. 2013). These studies also indicate that the extent of protection from mangroves strongly depends on a number of characteristics of the forest: density, diameter of trunks and roots, floor shape, bathymetry, as well as spectral characteristics of the waves, and the tidal stage at which waves enter the forest. In order to maximize the potential of mangrove forests to act as bioshields to protect

[1] Mangroves are salt-tolerant evergreen forests found along sheltered coastlines, shallow-water lagoons, estuaries, rivers or deltas in 124 tropical and subtropical countries and areas (Tomlinson 1986; Ellison and Stoddart 1991). A "mangrove" has been defined as a "tree, shrub, palm or ground fern, generally exceeding more than half a meter in height, and which normally grows above mean sea level in the intertidal zones or marine coastal environments, or estuarine margins" (Duke 1992). The term 'mangrove' describes both the ecosystem and the plant families that have developed specialized adaptations to live in this tidal environment. The mangrove ecosystem represents an interface between terrestrial and marine communities, which receive a daily input of water from the ocean (tides) and freshwater, sediments, nutrients and silt deposits from upland rivers. Mangroves may grow as trees or shrubs according to the climate, salinity of water, topography and edaphic features of the area in which they exist.

[2] Mangroves as a natural infrastructure has received increased attention in the aftermath of the 2004 Indian Ocean tsunami.

people and other assets from coastal hazards, additional location-specific research is necessary to design and manage these coastal forests. This paper is a step forward in that direction.

This paper evaluates the effect of different species of mangroves, density of trees and width of mangrove forests on cyclone-induced surge height and water flow velocity in coastal Bangladesh.[3] First, location-specific analysis was undertaken to short-list suitable mangrove species for three coastal segments prone to cyclones. Second, the hydrodynamic model for the Bay of Bengal, based on the MIKE21FM modeling system, was run multiple times to simulate the devastating cyclone Sidr that made landfall in Bangladesh in 2007 at the Barisal coast. Third, estimates of surge height and water flow velocity were recorded for different widths of mangroves under different density of planting using specific information on local topography, bathymetry, and root and trunk systems of mangrove species. The analysis is based on estimation of resistance of water flow from mangroves based on field measurements of root and trunk systems.

Bangladesh provides an exemplary backdrop for investigation of coastal protection from mangroves during cyclones, as Bangladesh is the world's most vulnerable country to tropical cyclones (UNDP 2004). Bangladesh was hit by 48 severe cyclonic storms and 49 cyclonic storms between 1877 and 2016, 20 of which recorded hurricane wind speeds during the more recent period of 1966-2016.[4] On average, a severe cyclone strikes the country every three years (GoB 2009) and records indicate that the greatest damage during cyclones resulted from the inundation caused by cyclone-induced storm surges.[5] Though time-series records of storm-surge

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[3] Some researchers who are skeptical about the ability of mangroves to protect against tsunamis have noted that mangroves might be more capable of protecting against tropical storm surges (Kerr and Baird 2007; Chatenoux and Peduzzi, 2007).

[4] Tropical storms are classified as severe cyclonic storms with hurricane wind speed (wind speed over 118 km per hour), severe cyclonic (89–117 km per hour), cyclonic (62–88 km per hour), deep depression (52–61 km per hour), and depression (40–51 km per hour) based on the observed maximum sustained surface wind speed measured at a height of 10 m averaged over 3 minutes, (IWM 2009).

[5] 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).

height are scarce, existing literature indicates a 1.5m to 9m height range along the shoreline of Bangladesh during various severe cyclones.[6] The country's topography being extremely low and flat, with two-thirds of its land area less than 5m above sea level, lives and assets in low-lying coastal districts along the Bay of Bengal are highly vulnerable to inundation from cyclone-induced waves and storm surges.[7]

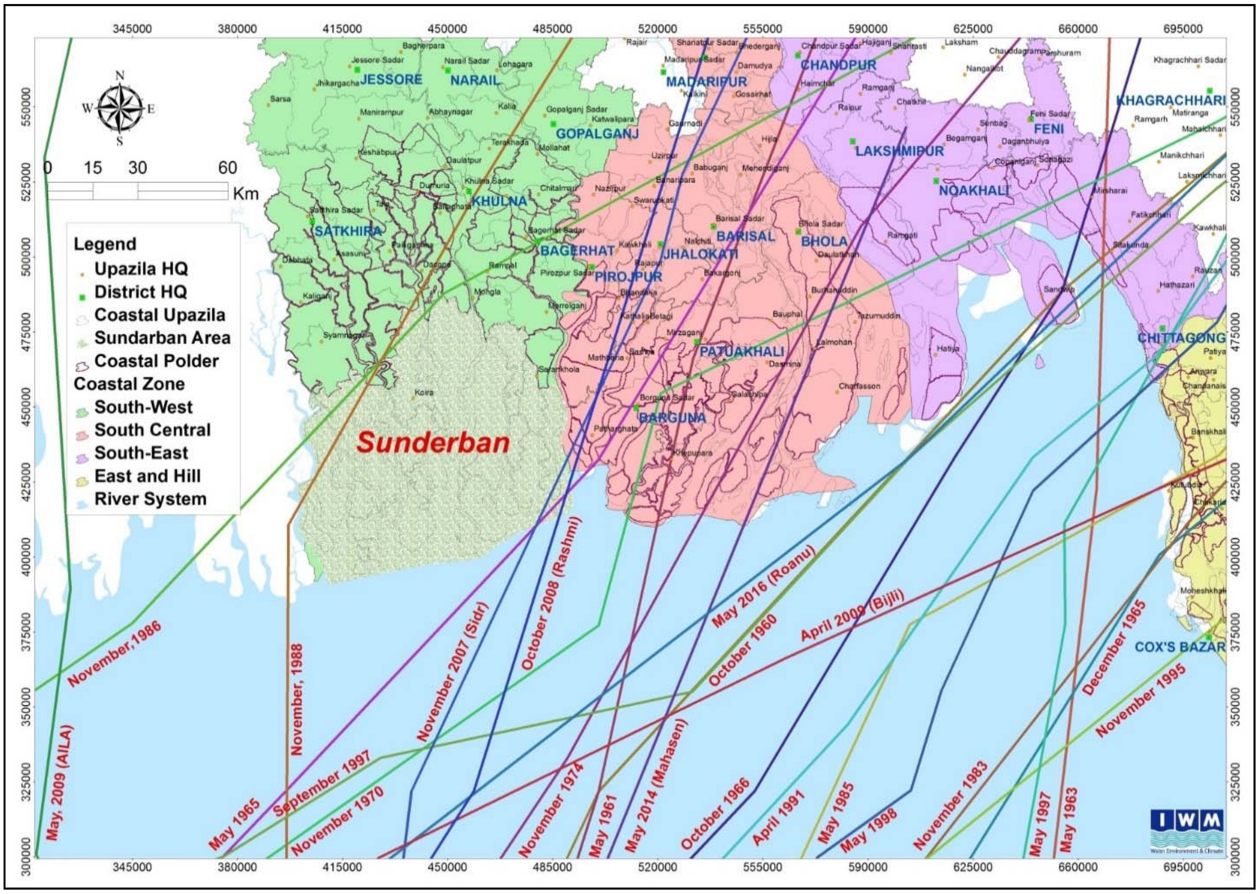


Figure1: Tracks of severe cyclones and cyclones striking the coast of Bangladesh during 1960-2016

[6] 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).

[7] *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).

In the early 1960s and 1970s, and in recent years, 139 polders, of which 49 were sea facing, were constructed in Bangladesh to protect low-lying coastal areas against tidal flood and salinity intrusion, and to some extent from storm surges during cyclones. In recent years, potential impacts of sea-level rise have become a major concern for the Government of Bangladesh in light of climate change. The government in collaboration with the World Bank has initiated a Coastal Embankment Improvement project for enhancing the height of 17 selected polders in the southwest coastal region where polder heights were low and cyclone strikes were relatively infrequent in the past but where it has increased in recent years. This study was undertaken to develop a basis for the necessary engineering judgement in designing this forest cover for various segments of the foreshore of polders, with the expectation that mangroves will attenuate surge, wave and water velocity during cyclones, and complement the height of embankments as part of the coastal protection infrastructure.

The findings emphasize that the presence of mangroves does attenuate surge heights and water flow velocity, but the level of attenuation is location specific, depending on the mangrove species, width of the mangrove strip as well as on the density of mangroves. Estimates further indicate, although likely surge height reduction is from 4 cm to 16.5 cm from a 50m to 2km wide mangrove strip, the water flow velocity is likely to reduce by 29% to 92% from 50m or 100m wide mangrove forests of *Sonneratia apetala* and *Avicennia officinalis*. At the outset, it should be noted that we have not estimated the extent of attenuation of wind waves from mangroves during cyclones in this paper; modeling of wind waves should be addressed in future research. Estimates of resistance to water flow from different species of mangroves at different densities of planting are major contributions of this paper to the literature on disaster risk management.

The remainder of the paper is structured as follows: section 2 presents the study area; section 3 describes the methodology including selection of suitable mangrove species and hydraulic modeling and simulation; section 4 presents the estimates of attenuation of storm surge and water velocity with a brief discussion; and section 5 presents the conclusions of this study.

2. Study Area

Upon consultation with experts from Bangladesh, three areas were selected for analysis: (i) the foreshore of polder 35/1 (ii) land area adjacent to Polder 40/2, and (iii) a location at the southern foreshore of the Polder 40/1 in the Sundarbans and the Central coast of Bangladesh.[8] These study areas were selected considering their vulnerability to storm surge and tidal characteristics, such as mud flat accretion/erosion and availability of adequate mangrove afforestation area in the foreshore of the coastal polders. The study areas are in Bagerhat and Borguna districts where the incidence of poverty is high and natural disasters, especially recurrent cyclones in recent years, have been cited as a major reason behind the poverty.[9] As cyclones can make landfall anywhere and it is not possible to predict a future cyclone track with certainty, our analysis covered severe cyclone SIDR (2007) and seven sites selected in the three aforementioned study areas. Table 1 presents a few key characteristics of the study areas and Figure 2 displays the study sites.

[8] Sundarbans coast and central coast of Bangladesh were struck by 10 severe cyclones and cyclones during 1960-2016. Records indicate an increase in the frequency of severe cyclones striking the region over time. Cyclone Sidr in 2007, cyclone Rashmi in 2008 and cyclone Aila in 2009 are examples of recent devastating cyclones.

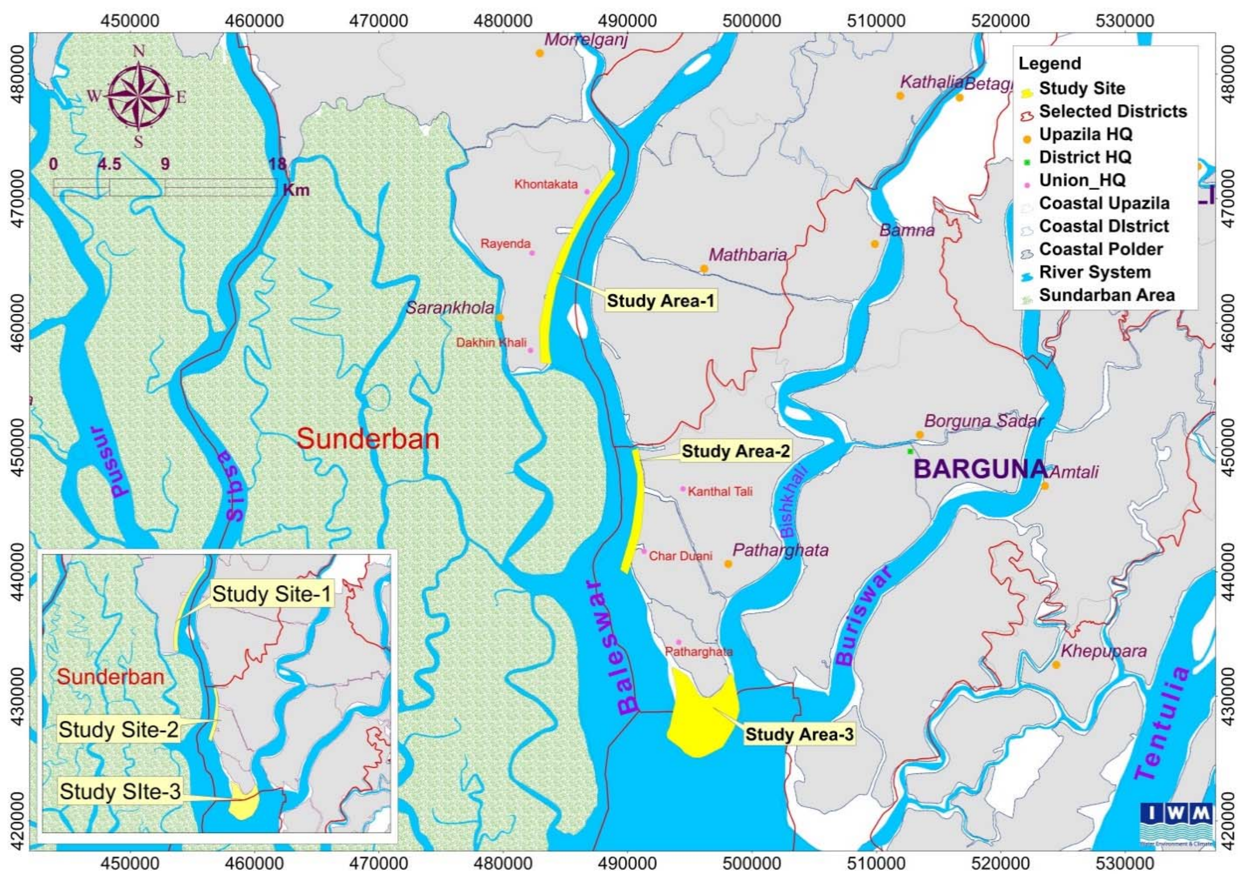
[9] The poverty maps developed by the Bangladesh Bureau of statistics, World Food Program and the World Bank estimates total poverty population with food expenditures are at or below the food poverty line established by the Bangladesh Bureau of Statistics for Bagerhat and Barguna districts are 619,480 and 168,098 respectively in 2011. These numbers include extremely poor households who do not meet the basic needs of food expenditure World Bank (2014a, b).

Table 1: Key characteristics of the Study Areas

Study Area	River/Sea-facing	Mud flat/tidal characteristics	Maximum Salinity (PPT)	Setback Distance of the Polder (foreshore)*
Area 1: adjacent to polder 35/1(Union: Kontakata, rayenda and Dakhin Khali, sub-Upazila: Sharankhola, District: Bagerhat)	**River facing** along the right bank of Baleswar river	Mud flat erosion	8.25	50-70m
Area 2: adjacent to Polder 40/2 (Union: Knathaltali and Char Duani, Upazila: Patharghata, District: Barguna)	**River facing** along the left bank of the Baleswar river	Mud flat accretion	10.80	100-150m
Area 3: adjacent to Polder 40/1 (Union: Patharghata, Upazila: Patharghata, District: Barguna)	**Sea facing** and exposed to the estuary of Baleswar and Bishkhali River	Mud flat accretion	20.30	2 km

*Source- Field Measurement

Figure 2: Study sites



3. Hydrodynamic model set up, selection of mangrove species and estimation of resistance to water flow

To understand the protective role of mangroves, a hydrodynamic model was set up and updated with location-specific data to represent the coastal as well as estuarine features of the study areas. Cyclonic wind field and pressure field information generated from historic cyclone data were added to the hydrodynamic model for developing the Storm Surge Model. Upon consultation with the local experts and after conducting focus group discussions with local inhabitants, various species of mangroves were short-listed for each study area considering their economic value and survivability in the study sites in the location-specific tidal characteristics and water salinity. Manning's Numbers (M)[10] were computed for short-listed mangrove species taking into account the physical characteristics of the mangrove trees. These Manning's Numbers served as estimates of resistance to the flow of water from the mangrove trees while passing through the forest. Further details on the process are described below.

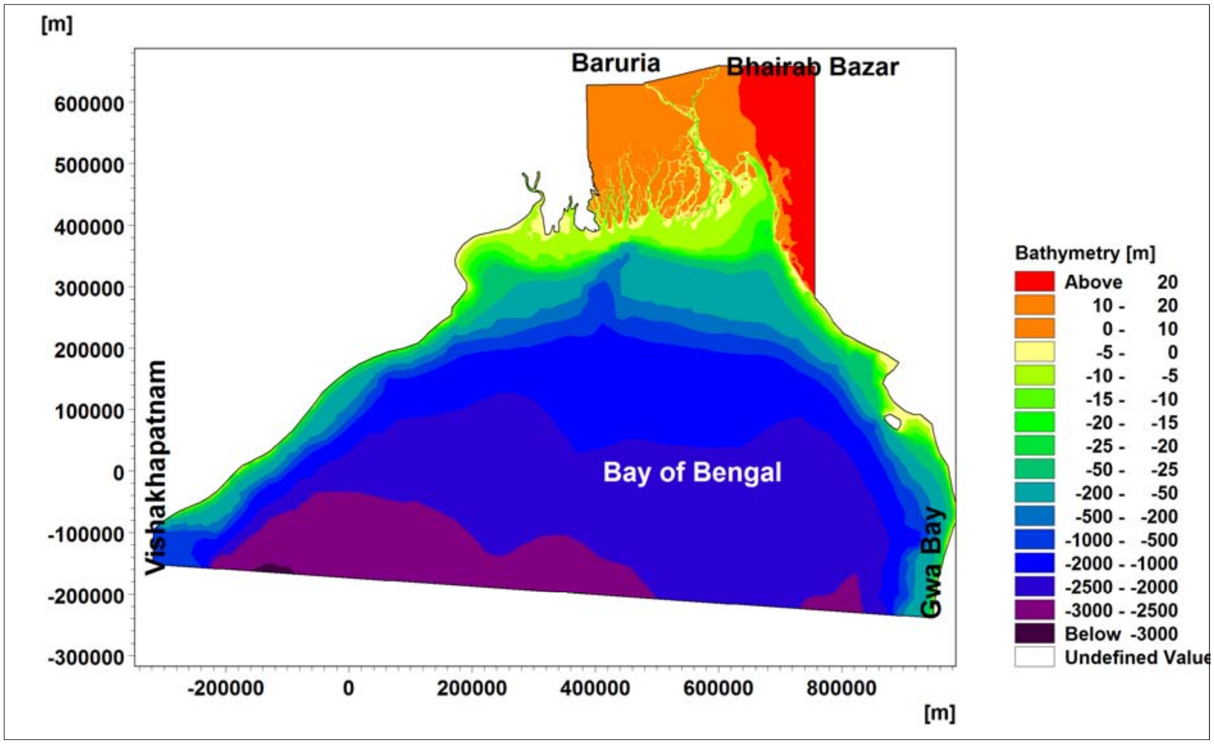
Setup of the hydrodynamic water flow model and development of the cyclone model

The hydrodynamic model for Bay of Bengal was upgraded with conversion of structured computational grid (MIKE 21Classic) to a flexible mesh system (MIKE 21FM) to enhance the resolution of the grids around islands, along coastline and other areas of interest.[11] See Figure 3 for the updated Bay of Bengal model. The area covered by the model starts from Baruria on the Padma River down to 16^0 north latitudes in the Bay of Bengal. Three open boundaries were defined in the model, two in the north defined by the daily discharge time series of river water: one in the Padma River at Baruria, and another one in the Upper Meghna River at Bhairab; and

[10] Inverse of Manning's roughness coefficient, n.
[11] For example, quadrangular/rectangular mashes were generated in the straight stretch of a channel and triangular mashes were generated where reaches were meandering. Both quadrangular and triangular mashes were generated to assess the effect of inter tidal area.

one in the south in the Southern Bay of Bengal from Vishakhapatnam in India to Gwa Bay of Myanmar generated by the MIKE ZERO Tool Box of the Global Tide Model.[12]

Figure 3: Geographical extent of the Bay of Bengal Model used in this analysis



[12] The global tide model data represents the major diurnal and semidiurnal tidal constituents with a spatial resolution of 0.25° × 0.25° based on TOPEX/POSEIDON altimetry data (Ole Baltazar Andersen, 1995). It has 258 tidal constituents in each location. Line series parameter was used to generate water level boundary conditions for flow models in MIKE21. The developed bathymetry file was used to detect the open boundaries and to update the number of lines and geographical position.
Major diurnal and semidiurnal tidal constituents of the origin Visakhapatnam and end location of the south boundary Gwa Bay were collected from the Admiralty Tide Table of 1995 and cross-checked with the Admirality Tide Table of 2017, and are described below:

Tidal Constitutents	M2		S2		K1		O1		f4	
	Amp	Phase	Amp	Phase	Amp	Phase	Amp	Phase	Amp	Phase
Gwa Bay	0.75	266	0.32	304	0.14	330	0.05	338	0.193	180
Vishakhapatnam	0.48	239	0.21	274	0.11	336	0.04	320	-	-

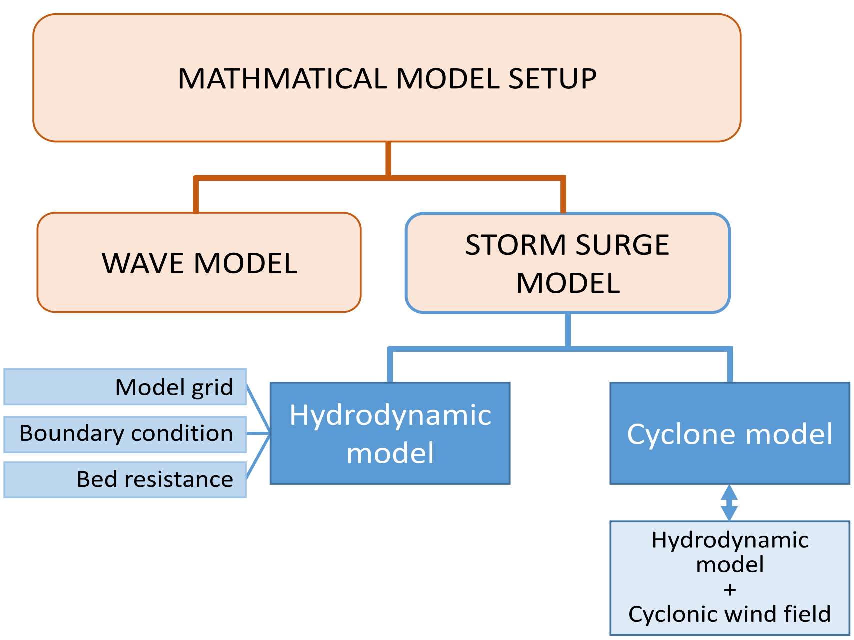
(Source: Admiralty Tide Table, 1995)

Islands and shorelines were delineated using recent Google Images. The bathymetry of the hydrodynamic model was updated using secondary data from different sources, including the surveyed river bathymetry data from the IWM, Ocean bathymetry data (C-Map from the IWM). Setback distances of the polders in the study regions were measured; and the shorelines of different segments of the study area were developed based on the foreshore areas.

To generate the storm surge model, cyclonic wind and pressure field were added to the hydrodynamic model as inputs of meteorological parameters. Historic cyclone data on (i) radius of maximum wind, (ii) maximum wind speed, (iii) cyclone track forward speed and direction, (iv) central pressure and (v) natural pressure from the Bangladesh Meteorological Department were used to estimate the cyclonic wind field and pressure. Holland Single Vortex theory was applied to generate the cyclonic wind field (Holland 1980). The generated cyclonic wind and pressure fields for the cyclone track were then used in the hydrodynamic model to simulate the cyclonic storm surges.

Figure 4 describes the setup of the mathematical model and describes how storm surge heights were estimated for this analysis.

Figure 4: Mathematical Model Setup



Selection of mangrove species

High-resolution maps of the distribution of mangrove species from the Department of Forests, Government of Bangladesh have identified 20 mangrove species in coastal Bangladesh.[13] However, tidal characteristics and salinity tolerance ranges of these mangrove species are widely different. Since survival of mangroves is critical for coastal protection, selection of mangrove species took into account the tidal characteristics as well as salinity tolerance of various mangrove species (Dasgupta, Sobhan and Wheeler 2017) and water salinity[14] in the study sites. Upon consultation with ecologists, seven mangrove species: *Avicennia officinalis, Bruguiera gymnorhiza, Ceriops decandra, Exoecaria agallocha, Heritiera fomes, Sonneratia apetala and Xylocarpus granatum* - which are likely to survive in the current water salinity - were short-listed. It was noted that *Avicennia officinalis* and *Sonneratia apetala* are likely to colonize only mudflats in newly-emergent areas where sedimentation is still ongoing, and *Ceriops decandra, Exoecaria agallocha, Heritiera fomes* are likely choices for the intertidal surfaces higher than newly-emergent areas. Subsequently, field visits were made to identify mangrove species common in the study areas. Finally, local inhabitants evaluated their familiarity with the various mangrove species, the direct use value of the mangrove species and their interest in preserving the species on a 1 to 5 scale. The final choice of location-specific mangrove species is provided below:

Study area 1: *Sonneratia apetala*, *Avicennia officinalis*

Study area 2: *Sonneratia apetala*, *Avicennia officinalis*

Study area 3: *Sonneratia apetala*, *Avicennia officinalis*, *Heritiera fomes*, *Exoecaria agallocha, Ceriops decandra*

[13] These include: *Acanthus ilicifolius, Acrostichum auereum, Aegialitis rotundifolia, Aegiceras corniculatum, Avicennia alba, Avicennia marina, Avicennia officinalis, Bruguiera gymnorhiza, Bruguiera sexangula,, Ceriops decandra, Ceriops tagal, Exoecaria agallocha, Exoecaria indica, Heritiera fomes, Kandelia candel, Rhizophora apiculate, Rhizophora mucronata, Sonneratia apetala, Sonneratia caseolari and Xylocarpus granatum*.

[14]See the River Salinity Information System at http://sdwebx.worldbank.org/climateportal/index.cfm?page=websalinity_dynamics&ThisRegion=Asia&ThisCcode=BGD Accessed April 2017.

Estimation of resistance to water flow from field measurements

Understanding the resistance of water flow over surfaces is critical for simulation of cyclone-induced surges as well as for estimation of water flow velocity. Friction between the fluid and a surface is generally represented by Manning's Number (M). Manning's Numbers for the Bay of Bengal Model domain for different depths of water are presented in Table 2.

Table 2: Manning Number distribution in the Bay of Bengal Model domain

Areas with depths	Manning's number, M ($m^{1/3}/s$)
Less than -20 m	32
-20 to -15 m	60
-15 to -10 m	65
-10 to -5 m	90
-5 to 0.46 m	100

Source: IWM, 2013

As expected, Table 2 indicates resistance to water flow increases with reduction in water depth.

Scientific literature to date emphasizes that mangroves can substantially reduce the vulnerability of adjacent coastal lands from storm surges, as the flow of water through the mangrove forest is obstructed by the matrix of roots/trunks and leaves of the mangrove trees. In order to estimate the resistance of water flow from various mangrove species, field visits were made to measure the diameter of the trunks, diameter of the roots and height of the roots from the ground level for each mangrove species short-listed for this analysis[15] (see Table 3). During field visits, the distance between mature plants was measured and local experts were consulted on feasible density of planting and spacing between trees.

[15] The impact of leaves has not been considered in this analysis.

Field measurement of the trunk system of *Sonneratia apetala* by the study team

Field measurement of roots of *Avicennia officinalis* by the study team

Table 3: Field data on characteristics of mangrove species

Mangrove species	Trunk diameter (m)	Root diameter (m)	Root height from existing ground level (m)
Sonneratia apetala	0.51	0.15	1.04
Avicennia officinalis	0.32	0.05	0.23
Heritiera fomes	0.5	0.05	0.28
Excoecaria agallocha	0.3	0.08	0.33
Ceriops decandra	0.3	0.05	0.3

The Manning's Numbers of different mangrove species for different water levels were then estimated first for their root systems (see Table 4, Column 3) and then combining with that of the trunk systems for alternative spacing between trees (see Table 4, Columns 4-6).

Table 4: Bed resistance (Manning Roughness) for root and trunk system of selected mangrove species

Water Depth (m)		Manning's Number, M			
		Root System	Root+Trunk System		
			5m Spacing	7.5m Spacing	10m Spacing
10	*Sonneratia apetala*	18.24	6.27	8.78	10.78
5		16.4	8.91	11.42	12.98
2.5		13.9	10.7	12.15	12.81
			4m Spacing	6m Spacing	8m Spacing
10	*Avicennia officinalis*	26.1	6.53	9.44	11.99
5		25.3	9.86	13.56	16.34
2.5		23.8	13.83	17.4	19.49
			5m Spacing	7m Spacing	10m Spacing
10	*Heritiera fomes*	25.10	6.52	9.39	11.89
5		24.11	9.79	13.37	16.01
2.5		22.50	13.56	16.87	18.76
10	*Excoecaria agallocha*	24.24	7.97	11.22	13.85
5		23.14	11.59	15.17	17.51
2.5		21.41	15.08	17.78	19.12
10	*Ceriops decandra*	24.70	8.22	11.55	14.25
5		23.70	11.94	15.61	18.00
2.5		22.00	15.55	18.32	19.70

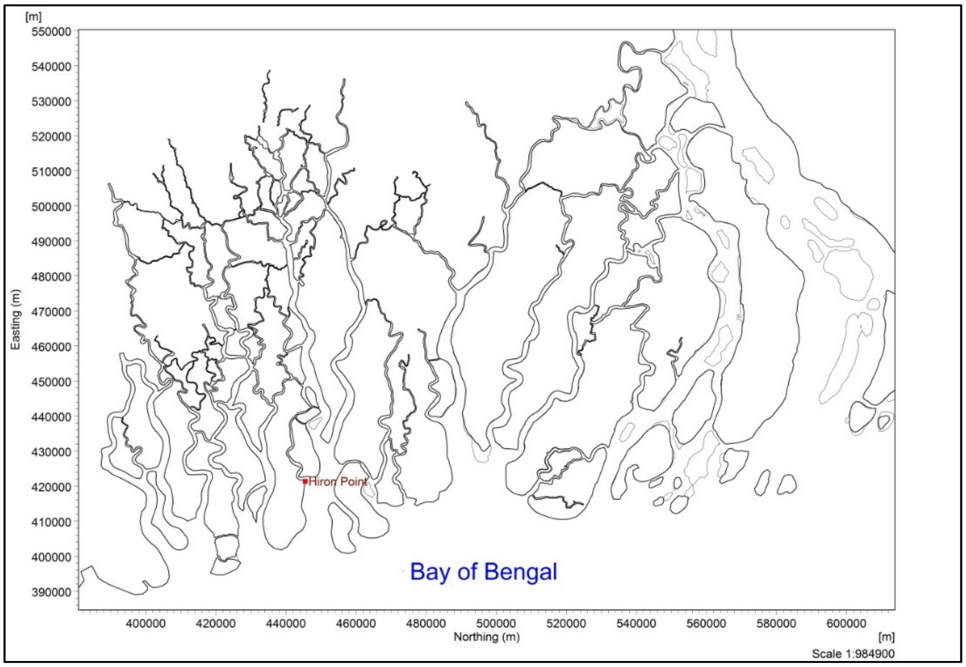
Table 4 documents changes in Manning's coefficients with changes in density of planting of different mangrove species for different water depths. As expected, the estimates confirm that resistance to water flowing through mangroves varies with mangrove species, density of trees, as well as depth of water. Once again, our estimates of the Manning's coefficients confirm that resistance to water flow by mangroves decreases with increase in the depth of water. Among the mangrove species short-listed for this analysis, irrespective of water depth, *Sonneratia apetala* causes maximum hindrance, followed by relatively similar resistance from *Avicennia officinalis* and *Heritiera fomes.* Estimates further indicate that resistance from *Excoecaria agallocha* exceeds that of *Ceriops decandra* for all water depths considered in our analysis. As expected, resistance to water flow increases with increase in density of planting. However, density of planting or the minimum spacing between trees depends on the trunk/branch structures of the mangrove species. Field observations considering minimum distance between mature trees conclude that planting of *Sonneratia apetala* at 5m spacing, *Avicennia officinalis* at 4m spacing and *Heritiera fomes, Excoecaria agallocha, Ceriops decandra* at 5m spacing in the study regions are feasible and will yield the best resistance to water flow through the mangroves.

4. Simulations of Cyclones and Findings

Mangrove creates resistance and reduces the surge height and flow velocity of water by providing drag force against the incoming tidal energy. The passage of surge was modeled numerically with the upgraded Bay of Bengal model for estimation of the surge height and water flow velocity in our analysis. To start, cyclone Sidr[16] with a maximum wind speed of 248 kph, maximum wind radius of 64km, central pressure of 928 hPa, normal pressure of 1009 hPa was simulated without mangroves with only the already existing polders to capture the current condition. For investigation of the impacts of mangroves on surge height and water flow velocity, potential mangrove afforestation areas were then defined and overlaid along the river/ sea-facing shoreline of the study areas. The model was calibrated at Hiron Point where there is an automated water level gauge maintained by Bangladesh Inland Water Transport Authority. Figure 5 presents the calibration plot. Cyclone Sidr was then simulated again with the mangrove forest. For each location, the storm surge model for cyclone Sidr was carried out for a range of width and density of afforestation of different short-listed mangrove species, recording the resulting surge height, and water flow velocity. Finally, the optimum set of afforestation parameters: species, width and density based on the simulation results were reported.

[16] During Sidr (2007), radius of maximum wind 64km, maximum wind speed 248 kph, central pressure 928 hPa, normal pressure 1009 hPa were recorded.

Figure 5: Location and Storm Surge (cyclone SIDR, 2007) calibration at Hiron Point



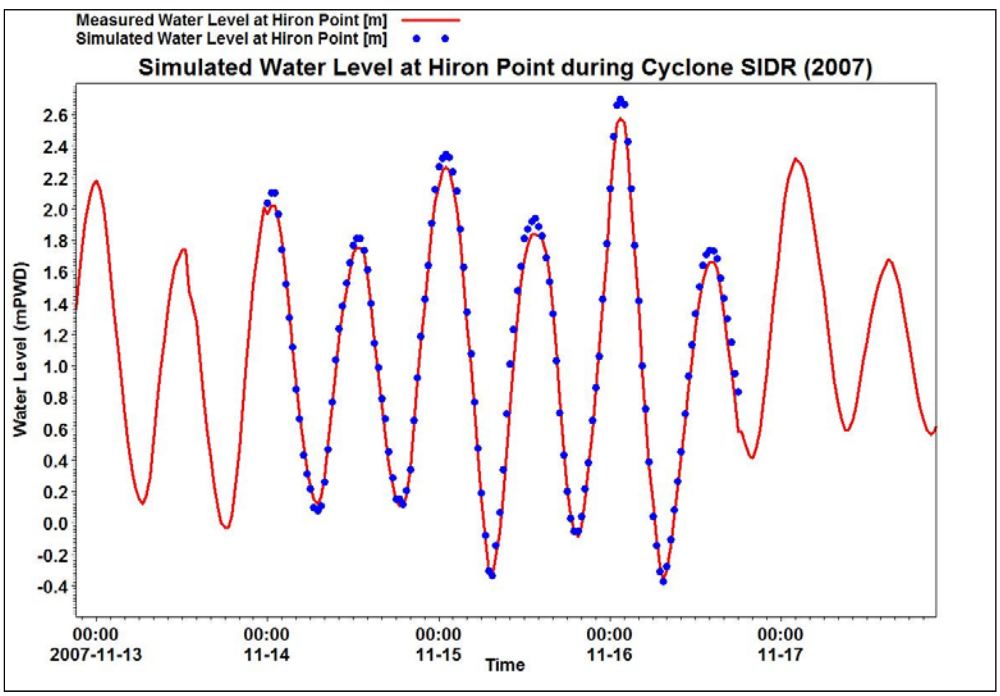
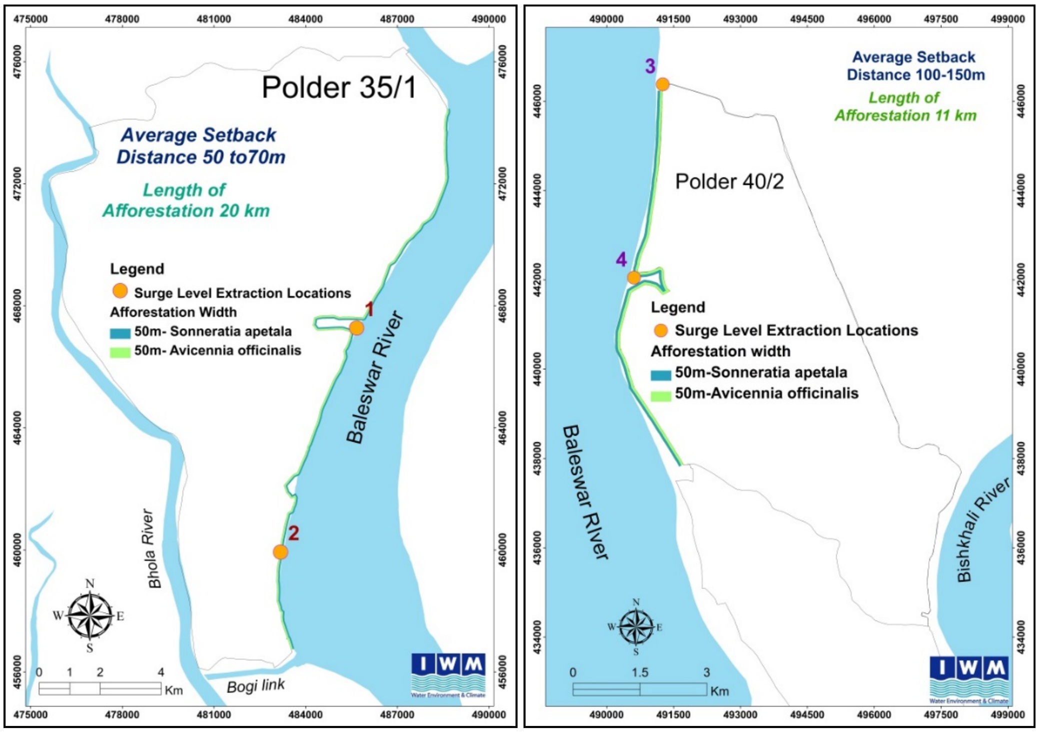
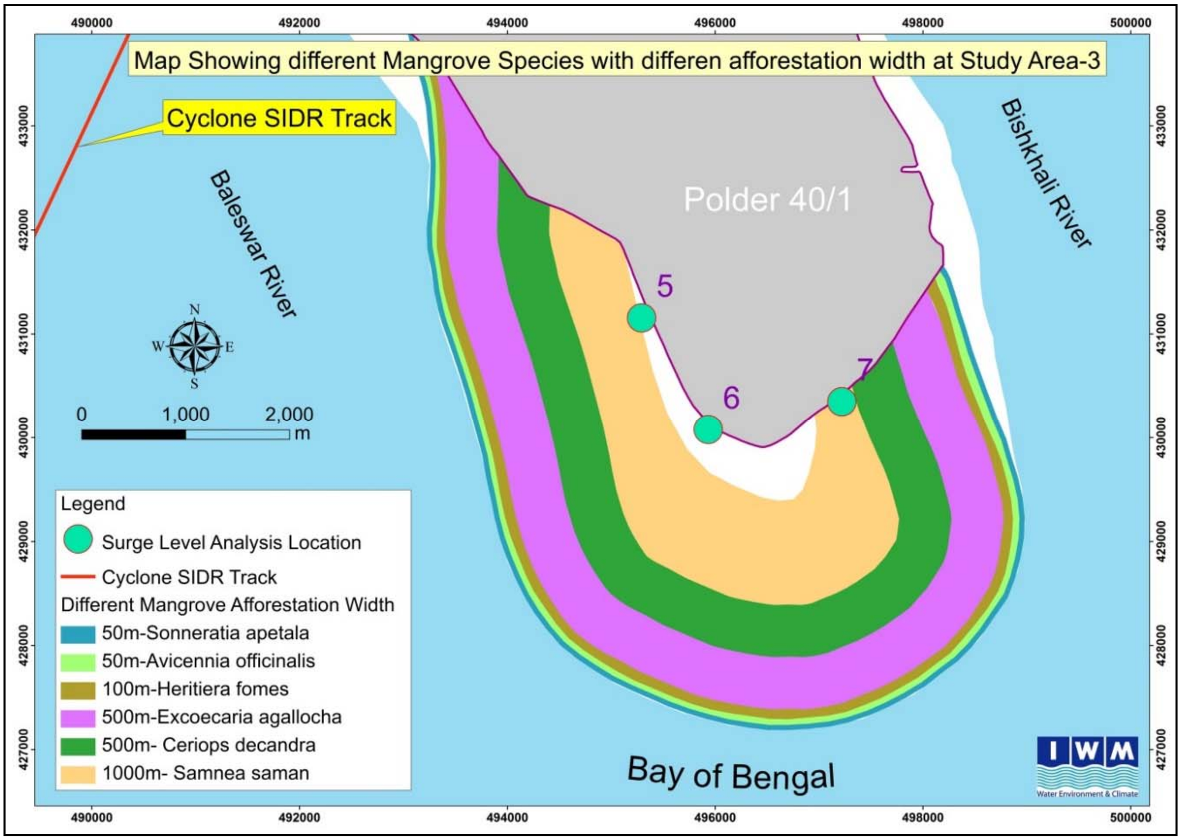


Figure: Storm Surge calibration at Hiron Point (cyclone SIDR, 2007)

Figure 6 presents the afforestation area in each study area.

Figure 6: Afforestation areas





Storm Surge Reduction by Mangroves

Table 5A: Attenuation of surge heights from afforestation of mangrove species in Study Area 1

Scenario	Site 1		Site 2	
	Surge Level (m PWD)	Attenuation of surge height from the baseline (cm)	Surge Level (m PWD)	Attenuation of surge height from the baseline (cm)
Baseline: without mangroves	**4.054**		**4.211**	
Only 50m *Sonneratia apetala* at 5m spacing	4.011	4.223	4.168	4.367
Only 50m *Sonneratia apetala* at 7.5m spacing	4.013	4.033	4.169	4.204
Only 50m *with Avicennia officinalis* at 4m spacing	4.012	4.164	4.168	4.304
Only 50m *with Avicennia officinalis* at 6m spacing	4.013	4.014	4.170	4.184
50m *Sonneratia apetala* at 5m spacing followed by 50m *Avicennia officinalis* at 4m spacing	4.001	5.233	4.159	5.245

Scenario	Site 1		Site 2	
	Surge Level (m PWD)	Attenuation of surge height from the baseline (cm)	Surge Level (m PWD)	Attenuation of surge height from the baseline (cm)
50m *Sonneratia apetala* at 5m spacing followed by 50m *Avicennia officinalis* at 6m spacing	4.002	5.151	4.159	5.219
50m *Sonneratia apetala* at 7.5m spacing followed by 50m *Avicennia officinalis* at 4m spacing	4.002	5.140	4.160	5.177
50m *Sonneratia apetala* at 7.5m spacing followed by 50m *Avicennia officinalis* at 6m spacing	4.003	5.100	4.160	5.150

Table 5A: Attenuation of surge heights from afforestation of mangrove species in Study Area 2

Scenarios	Site 3		Site 4	
	Surge Level (m PWD)	Attenuation of surge height from the baseline (cm)	Surge Level (m PWD)	Attenuation of surge height from the baseline (cm)
Baseline: without mangroves	**4.223**		**4.238**	
Only 50m *Sonneratia apetala* at 5m spacing	4.176	4.677	4.188	4.981
Only 50m *Sonneratia apetala* at 7.5m spacing	4.177	4.603	4.189	4.889
Only 50m *with Avicennia officinalis* at 4m spacing	4.177	4.619	4.189	4.912
Only 50m *with Avicennia officinalis* at 6m spacing	4.177	4.589	4.191	4.739

Scenarios	Site 3		Site 4	
	Surge Level (m PWD)	Attenuation of surge height from the baseline (cm)	Surge Level (m PWD)	Attenuation of surge height from the baseline (cm)
50m *Sonneratia apeta* at 5m spacing followed by 50m *Avicennia officinalis* at 4m spacing	4.168	5.484	4.181	5.696
50m *Sonneratia apetala* at 5m spacing followed by 50m *Avicennia officinalis* at 6m spacing	4.169	5.359	4.182	5.652
50m *Sonneratia apetala* at 7.5m spacing followed by 50m *Avicennia officinalis* at 4m spacing	4.170	5.330	4.182	5.624
50m *Sonneratia apetala* at 7.5m spacing followed by 50m *Avicennia officinalis* at 6m spacing	4.170	5.320	4.182	5.584

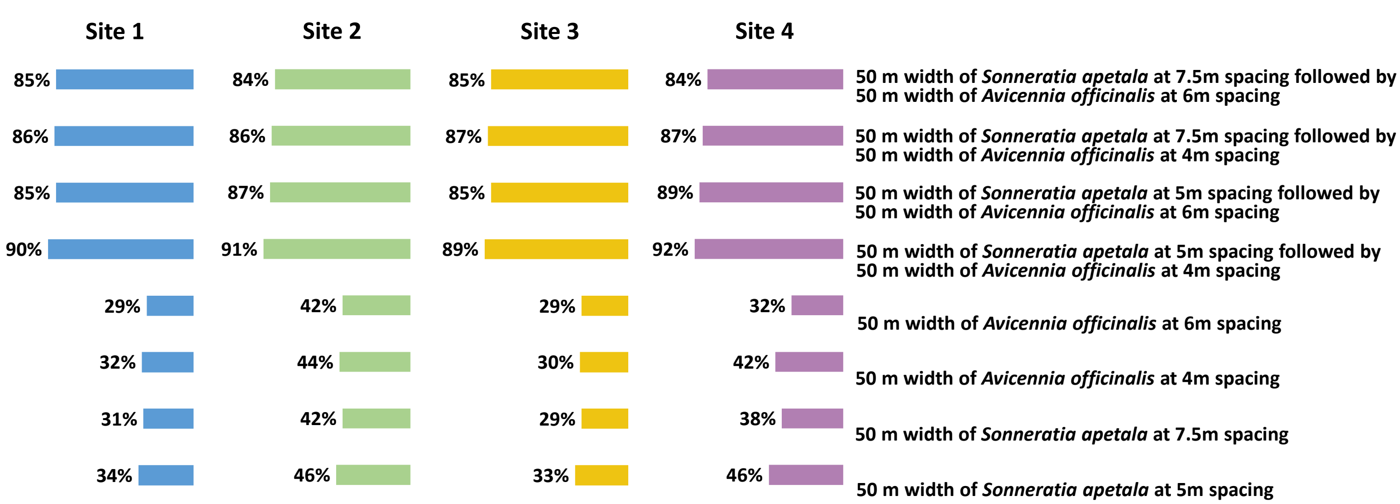
Table 5C: Attenuation of surge heights from afforestation of mangrove species at 5m spacing in Study Area 3

Scenario	Site 5		Site 6		Site 7	
	Surge Level (m PWD)	Attenuation of surge height from the baseline (cm)	Surge Level (m PWD)	Attenuation of surge height from the baseline (cm)	Surge Level (m PWD)	Attenuation of surge height from the baseline (cm)
Baseline: without mangroves	**4.440**		**4.527**		**4.646**	
Only 50m *Sonneratia apetala*	4.384	5.588	4.471	5.620	4.583	6.347
50m *Sonneratia apetala* +50m *Avicennia officinalis*	4.367	7.282	4.454	7.308	4.574	7.214
50m *Sonneratia apetala* +50m *Avicennia officinalis* +100m *Heritiera fomes*	4.358	8.203	4.440	8.776	4.564	8.260
50m *Sonneratia apetala* +50m *Avicennia officinalis* +100m *Excoecaria agallocha*	4.358	8.188	4.440	8.759	4.564	8.250
50m *Sonneratia apetala* +50m *Avicennia officinalis* +100m *Ceriops decandra*	4.359	8.127	4.440	8.746	4.565	8.146

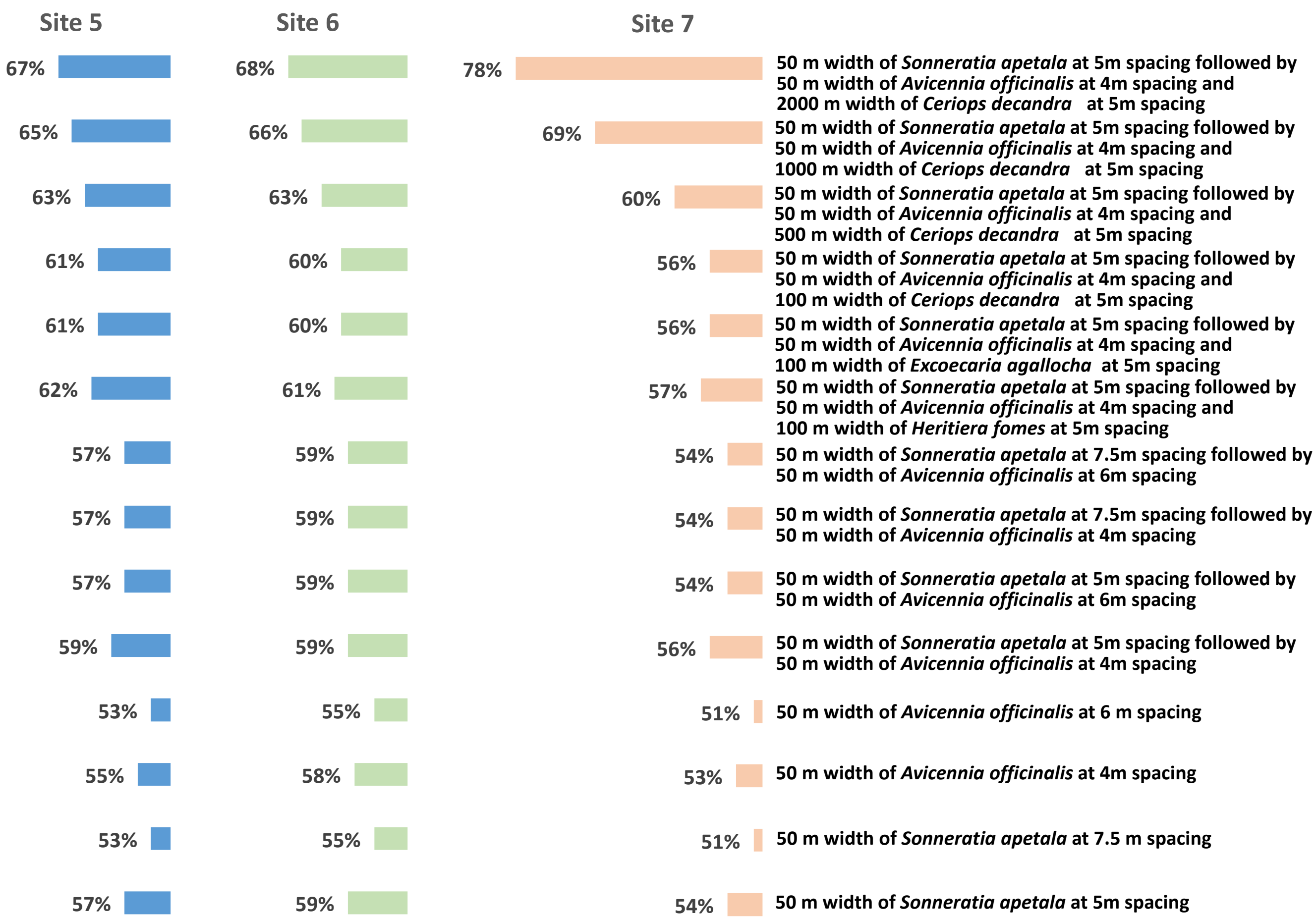
Scenario	Site 5		Site 6		Site 7	
	Surge Level (m PWD)	Attenuation of surge height from the baseline (cm)	Surge Level (m PWD)	Attenuation of surge height from the baseline (cm)	Surge Level (m PWD)	Attenuation of surge height from the baseline (cm)
50m *Sonneratia apetala* +50m *Avicennia officinalis* +500m *Ceriops decandra*	4.339	10.130	4.398	12.948	4.541	10.527
50m *Sonneratia apetala* +50m *Avicennia officinalis* +1000m *Ceriops decandra*	4.325	11.483	4.377	15.000	4.546	10.056
50m *Sonneratia apetala* +50m *Avicennia officinalis* +2000m *Ceriops decandra*	4.297	14.329	4.350	17.752	4.481	16.476

<u>Reductions in water flow velocity from afforestation of mangrove species</u>

Study Area 1: <u>Site 1</u> Water flow velocity of Sidr (2007): 0.624 m/s
Study Area 1: <u>Site 2</u> Water flow velocity of Sidr (2007): 0.593m/s
Study Area 2: <u>Site 3</u> Water flow velocity of Sidr (2007): 0.687m/s
Study Area 2: <u>Site 4</u> Water flow velocity of Sidr (2007): 0.651m/s



Study Area 3: Site 5 Water flow velocity of Sidr (2007): 0.618m/s
Site 6 Water flow velocity of Sidr (2007): 0.987m/s
Site 7 Water flow velocity of Sidr (2007): 0.709m/s



Our estimates confirm the protective role of mangroves during cyclones and highlight that the extent of attenuation of surge height and surge flow velocity from mangroves is location-specific and depends on mangrove species, width of mangrove area as well as the density of planting. Among the three study areas considered in our analysis, attenuation of surge height is relatively higher in study area 3, which is sea-facing and shallower compared to the other study areas on river banks.[17] Among the seven sites considered in our analysis, the reduction of surge

[17] The variation in bed level of study area 1, study area 2 and study area 3 are from -6mPWD to -10mPWD, -10mPWD to -12mPWD and 0mPWD to -3mPWD respectively (Reference: Figure A1 in the appendix).

height is 4cm to 16.5cm, with a median reduction of 5.5cm. The least reduction (4cm) in surge height was recorded from a 50m wide belt of *Sonneratia apetala* at 7.5m spacing or from a 50m wide belt of *Avicennia officinalis* at 6m spacing in Site 1. The most reduction (16.5cm) was from a 50m wide belt of *Sonneratia apetala* at 5m spacing followed by a 50m wide belt of *Avicennia officinalis* at 4m spacing and 2000m wide belt of *Ceriops decandra* at 5m spacing in Site 7. The reduction in surge flow velocity is in the range of 29 percent (from a 50m wide belt of *Avicennia officinalis* at 6m spacing in Site 1) to 92 percent (from 50m width of *Sonneratia apetala* at 5m spacing followed by 50m width of *Avicennia officinalis* at 4m spacing in Site 4). The median reduction in water flow velocity is 59 percent recorded from a 50m width of *Sonneratia apetala* at 5m spacing in site 6.

Our estimates of surge height attenuation from mangroves are in centimeters. Therefore, for densely populated cyclone-prone Bangladesh, where surge heights typically range from 1.5m to 9m <u>mangroves alone will not be sufficient to protect</u> assets and activities at risk, but <u>must be used along with built infrastructure</u>, such as embankments. However, since mangroves attenuate surge height, embankments with mangroves in foreshore areas can be lower in height as compared to the ones without mangroves. This may result in a significant savings in construction cost of embankments due to potential cost savings in land reclamation and earthwork. Design parameters of embankments with foreshore areas consequently should also take into consideration potential mangrove protection. In the long run, mangroves also help in reducing land erosion and in the accretion of the foreshore area by trapping sediment.

As mentioned earlier, our estimates reveal significant reduction of water flow velocity from mangroves. Reduction in water flow velocity is likely to protect the embankments from “toe erosion,” breaching and other damages. Thus, the presence of healthy mangroves in the foreshore area is also likely to contribute to savings in the maintenance cost of embankments. One should also keep in mind that in addition to coastal protection services as highlighted in this paper, mangroves provide many benefits that include the provision of food, timber, wood fuel, medicine, habitat and nurseries for fish and other wildlife. Mangroves also trap nutrients and contaminants to maintain water quality and store a much higher amount of carbon per equivalent area than terrestrial forests (Herr et al. 2012, Murray et al., 2011). It is important to consider all the multiple benefits of mangroves for an appropriate benefit evaluation of mangrove afforestation programs.

Bangladesh has a long-standing mangrove afforestation program. The country initiated its mangrove afforestation programs in 1966. By 2013, approximately 60km of sea-facing polders had mangrove forests in their foreshore area. Although various mangrove species, such as *Avicennia officinalis*, *Bruguiera sexangula*, *Ceriops decandra, Exoecaria agallocha* and *Sonneratia apetala* were planted, a review by Siddiqi and Khan in 2004 pointed out that *Sonneratia apetala* accounted for 94.4% and *Avicennia officinalis* accounted for 4.8% of successful mangrove plantings and *Sonneratia apetala* performed particularly well all along the coastline of Bangladesh,[18] This historical evidence is promising as among the five mangrove species considered in our analysis, *Sonneratia apetala* showed maximum potential for attenuation of storm surge and water velocity. A full grown *Sonneratia apetala* plant can grow up to 20m and is also effective in blocking erosion and in quickening the accretion of land.

However, experience suggests that areas afforested only with *Sonneratia apetala* are susceptible to pest attacks[19] and a combination of diverse mangrove species would reduce the risk of pest contamination. Since *Sonneratia apetala* colonize only on mud-flats in newly emergent areas where sedimentation is still ongoing, the only other candidate mangrove species for companion planting are *Avicennia officinalis* and *Bruguiera gymnorhiza*. It should also be noted that the survival rates of both *Sonneratia apetala* and *Avicennia officinalis* are less than 50% after five years and replacement planting should be planned after three years. With vertical accretion, the land will be unsuitable for replanting of *Sonneratia apetala* after three years and during replacement planting *Ceriops decandra, Exoecaria agallocha* and *Heritiera fomes* are suitable species for a permanent forest cover.

[18] Success of *Avicennia officinalis* is mostly limited to the Eastern coastal zone of Bangladesh (Islam, 2015).

[19] For example, *Zeuzera conferta*stem and Streblote siva are common in coastal Bangladesh.

5. Conclusion

Scientific literature to date emphasizes that mangroves can substantially reduce the vulnerability of adjacent coastal lands from storm surges as the flow of water through the mangrove forest is obstructed by the matrix of roots/trunks and leaves of the mangrove trees. As a result, the protective role of mangroves and other coastal forests and trees against cyclonic storm surges has received considerable attention in disaster management in recent years. Even though experts and scientists agree that coastal forest belts, if well designed and managed, have the potential to act as bioshields for the protection of people and other assets against storm surges, most of the studies conclude that additional location-specific information is needed to define the specific details and limits of this protective function (FAO, 2007; Das and Vincent, 2009; Arkema et al. 2013).

This paper evaluates the effects of different species of mangroves, different widths of mangrove forests and densities of planting on the cyclone-induced surge height and water flow velocity for seven sites in cyclone-prone coastal region of Bangladesh. For each study site, suitable mangrove species were short-listed upon consultation with ecologists considering the survival potential of the tree species in the local environment, and taking into account the familiarity and interest of the local inhabitants in preserving the species. During field visits, roots, trunk systems and optimal spacing between trees were recorded. For understanding the resistance of water flow from mangroves, Manning's coefficients were then estimated from field measurements of the root and trunk systems of mangrove species.

A hydrodynamic model for the Bay of Bengal based on the MIKE21FM modeling system was set up, calibrated and run multiple times to simulate the surge of cyclone Sidr that made landfall in Bangladesh in 2007 with a maximum wind speed of 248 kph, maximum wind radius of 64km, central pressure of 928 hPa and normal pressure of 1009 hPa. Estimates of surge height and water flow velocity were first recorded without mangroves and then with different widths of mangrove forests under different densities of planting using specific information on local topography, bathymetry and Manning coefficients estimated from the root and trunk systems of relevant mangrove species.

Our findings confirm the protective role of mangroves during cyclones, and highlight that the extent of attenuation of surge height and water flow velocity from mangroves is location-specific. Among the species considered in our analysis, *Sonneratia apetala* causes maximum friction and hindrance to water flow. Estimates indicate that likely surge height reduction is from 4cm to 16.5cm from a 50m to 2km wide mangrove strip. Therefore, for densely populated cyclone-prone Bangladesh, where surge heights typically range from 1.5m to 9m mangroves alone will not be sufficient to protect assets and activities at risk, but must be used along with built infrastructure, such as embankments. Despite modest attenuation of surge heights, our estimates also indicate significant reduction of water flow velocity from mangroves. The expected reduction in water flow velocity is 29% to 91% from a 50m or 100m wide mangrove forest of *Sonneratia apetala* and *Avicennia officinalis*. Reduction in water flow velocity is likely to contribute to savings in the maintenance cost of embankments by protecting the embankments from "toe erosion," breaching and other damages. Consequently, design parameters of embankments with foreshore areas[20] should take into account potential mangrove protection.

It should be noted that economic assessment of the location-specific benefits of mangrove protection from flooding during cyclones, potential cost savings in rehabilitation of the embankments and in the cost of operation and maintenance of embankments, as well as the costs of afforestation could not be computed at this stage due to resource constraints and should be addressed in future analysis. We also have not estimated the extent of attenuation of wind waves from mangroves during cyclones in this paper; modeling of wind waves should also be a subject of future analysis.

[20] Many embankments do not have adequate foreshore areas, especially in active deltas where land erosion is taking place.

References

Arkema, K.K., G. Guannel, G Verutes, S. A. Wood, A. Guerry, M. Ruckelshaus, P. Kareiva, M. Lacayo, and J.M. Silver. 2013. "Coastal habitats shield people and property from sea-level rise and storms." Nature Climate Change 3, 913–918.

Barbier, E.B., E.W. Koch, B.R. Silliman, S. Hackaer, E. Wolanski, J. Primavera, E.F. Granek, S. Polasky, S. Aswani, L. A. Cramer, D.M. Stoms, C.J. kennedy, D. Bael, C.V. Kappel, G.M.E. Perillo, D. J. Reed. 2008. "Coastal Ecosystem-Based Management with Nonlinear Ecological Functions and Values". Science 319, 321.

Brinkman, R.M., Massel, S.R., Ridd, P.V.,Furukawa, K. 1997. "Surface wave attenuation in mangrove forests". Proceedings of 13th Australasian Coastal and Ocean Engineering Conference 2, 941-949.

Chapman, V.J. 1976. Mangrove Vegetation. Cramer, Vaduz, 447 pp.

Chatenoux B., Peduzzi p. 2007. Impacts from the 2004 Indian Tsunami: analyzing the potential protecting role of environmental features. Natural hazards 40: 289-304.

Das, S. and J. R. Vincent. 2009. "Mangroves protected villages and reduced death toll during Indian super cyclone". PNAS 18: 7357-7360

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).

Doney, S.C., Ruckelshaus, M., Duffy, J.E., Barry, J.P., Chan, F., English, C.A., Galindo, H.M., Grebmeier, J.M., Hollowed, A.B., Knowlton, N., Polovina, J.J., Rabalais, N.N., Sydeman, W.J., Talley, L.D., 2012. Climate change impacts on marine ecosystems. Annu. Rev. Mar. Sci. 4, 11–37

Duke, N.C. 1992. Mangrove Floristics and Biogeography. In Tropical mangrove Ecosystems, A.I. Robertson and D.M. Alongi, Eds. American Geophysical Union, Washington DC, USA.

Ellison, J.C. and D.R. Stoddart, 1991. Mangrove Ecosystem Collapse during Predicted Sea-level Rise; Holocene Analogues and Implications. Journal of Coastal Research 7: 151-165.

FAO (2007) The World's Mangroves 1980-2005, FAO Forest Strategy Paper 153.

Gedan, K.B., M.L.Kirwan, E. Wolanski, E.B. Barbier and B. R. Silliman. 2011. "The present and future role of coastal wetland vegetation in protecting shorelines: answering recent challenges to the paradigm". *Climatic Change*. 106:7-29.

GoB (2008), Cyclone sidr in Bangladesh: damage, loss, and needs assessment for disaster recovery and reconstruction. A report prepared by the government of Bangladesh assisted by the international development community with financial support from the European commission.

Herr, D., E. Pidgeon, D. Laffoley (eds). 2012. Blue Carbon Policy Framework. Gland Switzerland: IUCN and Arlington, VA: Conservation International.

Holland, G. 1980. An Analytic Model of the Wind and Pressure Profiles in Hurricanes. Monthly Weather Review. 108, 1212-1218.

IPCC (2007), A report by Working Group I of the Intergovernmental Panel on Climate Change, Chapter 10, Chapter 11 and Technical Summary

Islam, S. A., Miah, M. A. Q. and Habib, M. A. (2015). Performance of Mangrove Species Planted inside *Sonneratia apetala* Buch.-Ham. Plantations in the Coastal Belt of Bangladesh. *Journal of Bioscience and Agriculture Research* 03(01), 38-44.

IWM (2009), Use Existing Data on Available Digital Elevation Models to Prepare Useable Tsunami and Storm Surge Inundation Risk Maps for the Entire Coastal Region, Final Report, Volume-I: Tsunami and Strom Surge Inundation of the Coastal Area of Bangladesh

IWM (2013), Coastal Embankment Improvement Project, Phase-I, (CEIP-I), Final Report ,Volume III: Modelling And Survey Reports, Dhaka, Bangladesh

Kerr, A.M., Baird A.H.2007. Natural Barriers to Natural Disasters, BioScience 57: 102-103.

Liu, H., Zhang,K., Li, Y., and Xie, L., 2013. Numerical study of the sensitivity of mangroves in reducing storm surge and flooding to hurricane characteristics in southern Florida. Continental Shelf Research. 64, 51-65

Massel S.R., Furukawa, K. Brinkman R.M. 1999. “Surface wave propagation in mangrove forests”. Fluid Dyn. Res 24: 219-249.

Mazda Y., Magi M, Kogo M., Hong PN. 1997. “Mangroves as a coastal protection from waves in the Tong King Delta, Vietnam”. Mangroves and Salt Marshes 1: 127-135.

McIvor, A., T. Spencer, I. Möller, and M. Spalding. (2012a): Storm Surge Reduction by Mangroves. Natural Coastal Protection Series: Report 2. Cambridge Coastal Research Unit Working Paper 41. Published by The Nature Conservancy and Wetlands International. ISSN 2050-7941.

McIvor, A.L., Möller, I., Spencer, T. and Spalding. M. (2012b) Reduction of wind and swell waves by mangroves. Natural Coastal Protection Series: Report 1. Cambridge Coastal Research Unit Working Paper 40. Published by The Nature Conservancy and Wetlands International. 27 pages. ISSN 2050-7941.

Murray, B., L. Pendleton, W. A. Jenkins, and S. Sifleet. 2011. "Green Payments for Blue Carbon: Economic Incentives for Protecting Threatened Coastal Habitats." Nicholas Institute for Environmental Policy Solutions Report NI R 11-04

Pinsky, M. L., G. Guannel, and K. K. Arkema, 2013. Quantifying wave attenuation to inform coastal habitat conservation, *Ecosphere*, *4*(8), art95.

Quartel, S., Kroon, A., Augustinus, P.G.E.F., Van Santen, P., Tri, N.H., 2007. "Wave attenuation in coastal mangroves in the Red River Delta, Vietnam". Journal of Asian Earth Sciences 29, 576-584.

Siddiqi, N. A. and M. A. S. Khan. 2004. "Human-induced Succession of Vegetation on New Accretions in the Coastal Areas of Bangladesh". Journal of Tropical Forest Science, Vol. 16, No. 2, 187-198.

SMRC, 1998.The impact of tropical cyclones on the coastal regions of SAAR Countries and their influence in the region. SAARC Meteorological Research Centre No. 1, 329 pp.

Tomlinson, P.B. 1986. The botany of mangroves. Cambridge, UK, Cambridge University Press.

UNDP (2004), A Global Report. Reducing Disaster Risk. A Challenge for Development

UNEP-WCMC, 2006. In the Front Line: Shoreline protection and Other Ecosystem Services from Mangroves and Coral Reefs, UNEP-WCMC. Cambridge, 33 pp.

Waite, R, L. Burke, and E. Gray. 2014. "Coastal Capital: Ecosystem Valuation for Decision Making on the Coastal Caribbean." World Resources Institute, Washington, DC 78 pp.

World Bank. 2014a. Bangladesh Poverty Map 2010-Technical Report. Dhaka: World Bank, Bangladesh Bureau of Statistics, World Food Programme http://www-wds.worldbank.org/external/default/WDSContentServer/WDSP/IB/2014/11/11/000442464_20141111221335/Rendered/PDF/904870v20Bangl0LIC000Sept004020140.pdf , Accessed September 2017

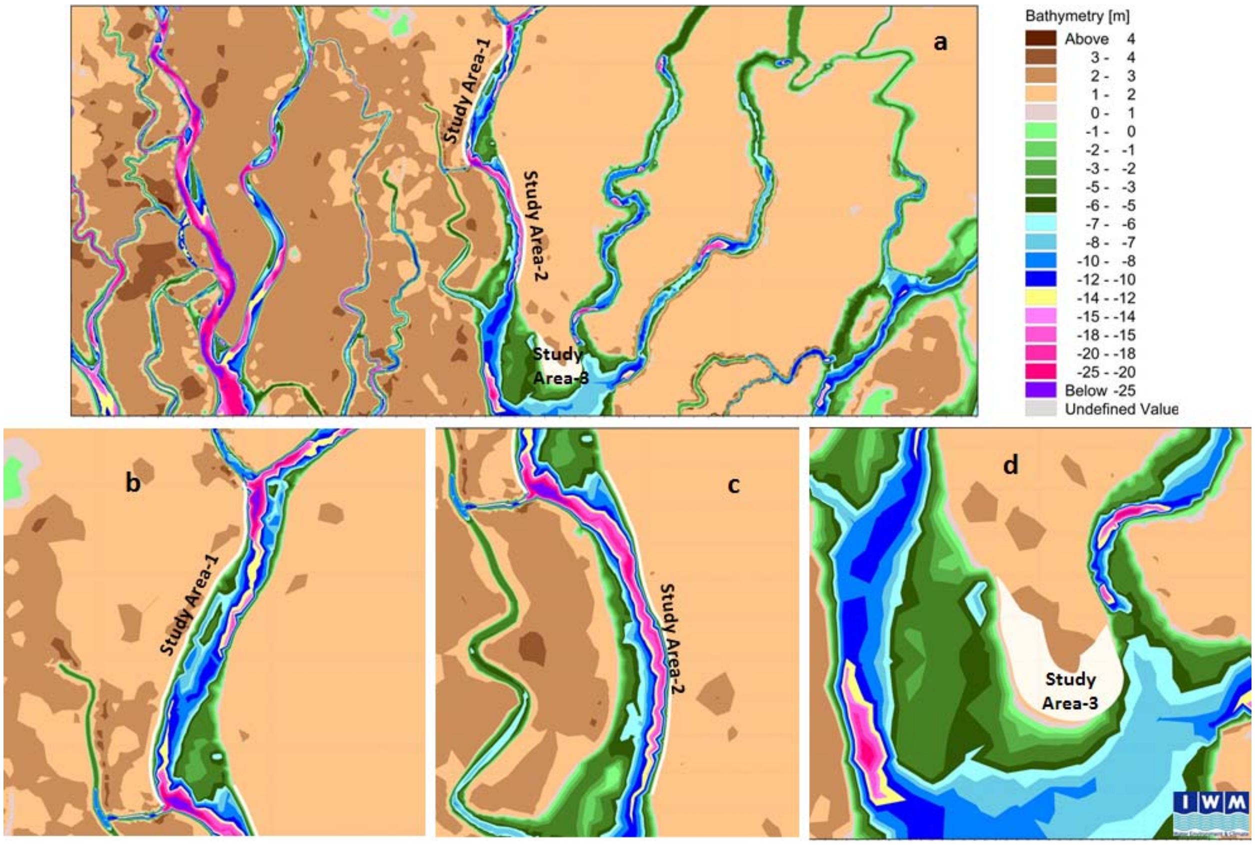
World Bank. 2014b. Bangladesh Poverty Map 2010. Dhaka: World Bank, Bangladesh Bureau of Statistics, World Food Programme

http://www-wds.worldbank.org/external/default/WDSContentServer/WDSP/IB/2014/09/10/000442464_20140910105709/Rendered/PDF/904870WP0WB0Po00Box385319B00PUBLIC0.pdf, Accessed September 2017.

Zhang K, Liu H, Li Y, Xu H, Shen J, Rhome J, Smith TJ. 2012. The role of mangroves in attenuating storm surges. Estuary Coast Shelf Sci. 102–103:11–23.

Appendix

Figure A1: Bathymetry of the Study Areas



a. Study area bathymetry
b. Study area-1 bathymetry
c. Study area-2 bathymetry
d. Study area-3 bathymetry