

River Salinity and Climate Change

Evidence from Coastal Bangladesh

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Abstract

In a changing climate, saltwater intrusion is expected to worsen in low-lying coastal areas around the world. Understanding the physical and economic effects of salinity ingress, and planning adaptation, are key to the long-term development of countries for which sea level rise has been identified as a major risk from climate change. This paper presents a study conducted in Bangladesh, which quantifies the prospective relationship between climate-induced changes in sea level, temperature, rainfall, and altered riverine flows from the Himalayas, and the spread and intensity of salinization on river water in the coastal zone for 2050. The research takes into account the projected land subsidence of the Ganges Delta, as well as alternative scenarios of upstream withdrawal of freshwater. The findings indicate that

climate change will cause significant changes in river salinity in the southwest coastal area of Bangladesh by 2050. These changes are likely to lead to significant shortages of drinking water in the coastal urban areas, scarcity of water for irrigation for dry-season agriculture, and significant changes in the coastal aquatic ecosystems. Changes in the availability of freshwater fish will likely affect the composition of capture fishery, although the increase in brackish water will enhance opportunities for brackish water aquaculture. Assessment of location-specific economic impacts of the changes in river salinity, identification of suitable adaptation alternatives, and costing of adaptation are high priorities for further analysis.

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River Salinity and Climate Change: Evidence from Coastal Bangladesh*

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1. Introduction

Coastal areas are densely populated and often the most developed stretches of land in many parts of the world.⁶ It is estimated that 50 percent of the world's population lives within 100km of a coastline (World Bank 2009) and expectations are that this figure will grow in the next half century. Climate change is a serious threat to countries with high concentrations of population and economic activity in coastal regions.

The potential impacts of climate change on coastal areas include progressive inundation from sea level rise, heightened storm damage, loss of wetlands, and increased salinity from saltwater intrusion. Most research has focused on the long-run effects of inundation as the sea level rises, along with associated losses from heightened storm surges (for example, Agarwala et al. 2003; Ali 1996, 2003; Ali and Chowdhury 1997; Dasgupta et al. 2009; Dasgupta et al. 2010; Dasgupta et al. 2011; Kabir et al. 2006; Nicholls 2003, 2006; Hanson et al. 2011). The implications of climate change for saltwater intrusion and its impact on livelihoods and adaptation alternatives have not been investigated in great detail (World Bank 2009). However, sporadic measurement of soil and water salinity along coastal areas indicates intrusion of saline waterfront landward in many areas (Mohal et al. 2006). Anecdotal evidence also indicates that increased salinity from saltwater intrusion poses an imminent threat to livelihoods and public health through its impacts on agriculture, aquaculture, infrastructure, coastal ecosystems, and the availability of freshwater for household and commercial use (DFID 2007; Hussain 2008). The problem of saltwater intrusion is expected to become more severe in low-lying coastal areas throughout the world, with increased sea level caused by climate change (Bates et al. 2008; Akhter 2012). Hence, understanding the socioeconomic impacts of salinity ingress and adaptation alternatives is a key requirement for long-term development and are subjects of our ongoing research.

Understanding socioeconomic impacts of salinity ingress in turn calls for the modeling of spatio-temporal diffusion of salinity in a changing climate and an analysis of the physical impacts. As a prerequisite for upcoming analyses of the socioeconomic impacts and adaptation to salinity, this paper presents a study undertaken for Bangladesh to quantify the relationship between climate-induced changes in sea level, temperature, rainfall, altered riverine flows from the Himalayas, and the spread and intensity of the effects of salinization on river water in the coastal zone for

⁶ In the majority of cases, the term "coastal" is defined as a sea-land surface.

2050. The research takes into account the projected land subsidence of the Ganges Delta as well as alternative scenarios of upstream withdrawal of freshwater.

The remainder of the paper is organized as follows: Section 2 describes the study area, the coastal zone of Bangladesh, and provides background information. Section 3 describes the modeling of climate change and other factors to determine the expected impacts on the salinity of river water in the coastal zone. Section 4 presents salinity maps, estimated isohalines (contours of equal salinity), and location-specific salinity projections for various climate-change scenarios. Section 5 concludes the paper.

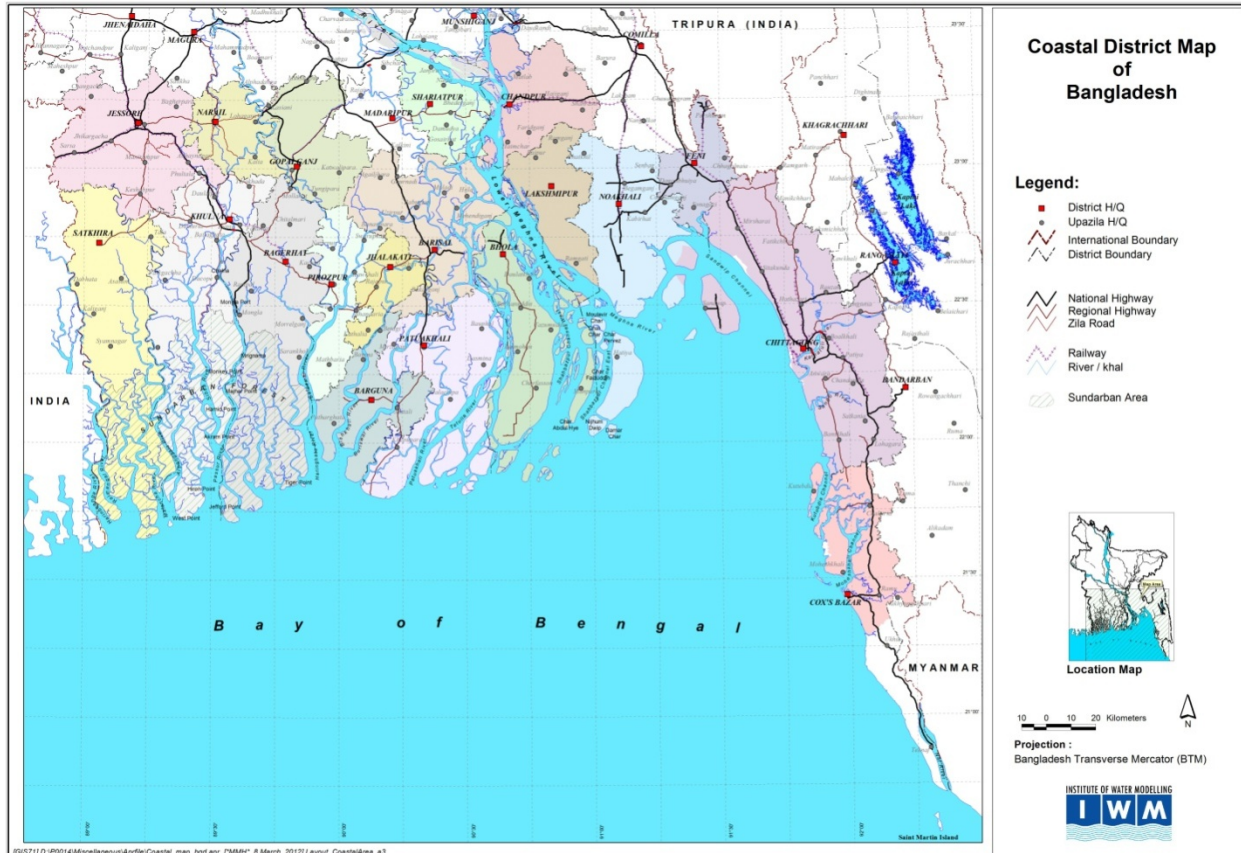
2. Coastal Bangladesh

The coastal area of Bangladesh (see Figure 1) covers 19 districts⁷ facing or near the Bay of Bengal, encompassing 148 subdistricts and the Exclusive Economic Zone, accounting for 32 percent of the land area and 25.7 percent of the population of Bangladesh (BBS 2011). It has been estimated that the coastal area sustains the livelihoods of more than 37 million people.⁸ The area's diverse natural resources include critical ecosystems such as Sundarban mangrove forests, fisheries, shrimp farms, agriculture, and deposits of minerals and salt (GoB 2006). Export promotion sites, harbors, airports, ports, tourism, and other industries are also located in the coastal area. Yet, poverty in the coastal area is high: 14 of the 19 coastal districts have poverty rates greater than the national average. High vulnerabilities in terms of insecurity of food, income, water, health, and poverty are prominent in Bagerhat, Bhola, Noakhali, and Satkhira Districts (BBS et al. 2009; GoB 2006). Twelve of the coastal districts, comprising 51 subdistricts (covering 50 percent of the land area of the coastal zone), already face a combination of cyclone risk, salinity, and tidal water movement above critical levels.

⁷ The 19 coastal districts are Jessore, Narail, Gopalganj, Shariatpur, Chandpur, Satkhira, Khulna, Bagerhat, Pirozpur, Jhalakati, Barguna, Barisal, Patuakhali, Bhola, Lakshmipur, Noakhali, Feni, Chittagong, and Cox's Bazar.

⁸ Initial projections indicate that population may grow to about 60 million by 2050 (World Bank 2009).

Figure 1 Coastal Area of Bangladesh



River Salinity in Coastal Bangladesh

River water salinity in coastal Bangladesh depends on the volume of freshwater discharges from the upstream river systems, the salinity of the Bay of Bengal near the coast, and the circulation pattern of the coastal waters induced by the ocean currents and the strong tidal currents in the coastal waters. A reduction in freshwater inflows from the trans-boundary Ganges River, siltation of the tributaries of the Ganges, and siltation of other rivers following the construction of the polder system⁹ has resulted in a significant increase in river salinity in

⁹ In the 1960s and 1970s, 123 polders (49 of which are sea-facing) were constructed to protect low-lying coastal areas in Bangladesh against tidal floods and salinity intrusion. Regulators and other structures to control water intake and drainage of the poldered area were put in place with the primary goal of improving agricultural productivity. Today 1.2 million hectares of land (15 percent of the country's total arable land) under agriculture is within the coastal embankment system.

coastal Bangladesh during the dry season. For example, salinity increased from 2ppt to 20ppt at Mongla in the Pussur River from 1962 to 2008.¹⁰

A map displaying the distribution of maximum river salinity from field measurements during the 2010-2011 dry season (October 2010 to May 2011) is shown in Table 1.

¹⁰ Salinity is measured in parts per thousand (ppt), grams of salt per 1,000 grams of water.

Table 1: Maximum River Salinity in Coastal Bangladesh

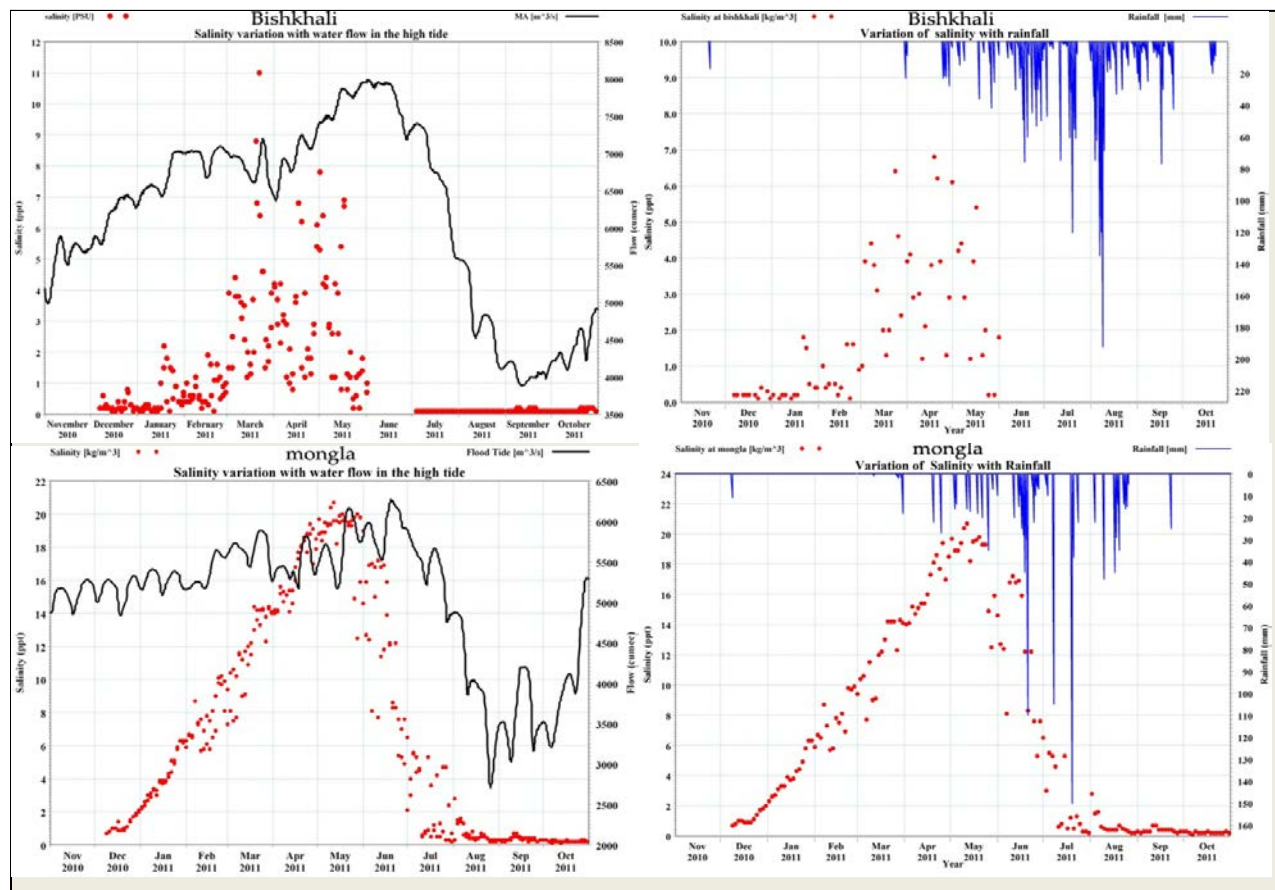
River salinity displays temporal and spatial variation in coastal Bangladesh.

Temporal Variation of Salinity

Location	River	Maximum measured Salinity (ppt)
Amtali	Burisuar	0.9
Badurgasa	Darunmollik	22.9
Bamni/ Char Elahi	Meghna	19.8
Bardia/ Nabaganga	Noboganga	9.8
Bashantapur	Ichamoti	22.6
Bhairab	Hospital ghat/fulbari ghat	16.9
Bishkhali DS	Bishkhali River	11
Burhanuddin	Tetulia	3.5
Chapailghat	Modhumati	5.3
Chandpur	Meghna	0.1
Char Doani	Baleswar	8.5
Daulatkhan	Meghna	6
Gangrail	Shundor mohol	23.2
Habour Khali	Darunmollik Miega Ghat	9.9
Haridashpur	Madaripur Beel Route	2.1
Hilsha	Ganeshpura	4.6
Hiron Point	Pussur	27.3
Kaikhali	Modan Gauga	28.2
Khepupara Kolapara	Adhanmanik	19.8
Khulna	Rupsha	16.8
Kobadak	Kobadak	27.3
Madaripur	Arialkha	0.2
Madhupara	Andharmanik	13.9
Mohipur	Shibbaria Khal	22.8
Moju Chowdhury Hat	Meghna	1.5
Mongla	Pusure	20.7
Musapur	Little Feni	21.2
Nalian	Shibsha	23.4
Patgati	Modhumati	3.9
Pirojpur	Baleswar	0.6
Ramgati Jarirdona Regulator	Meghna	12.7
Shalta	thanibuina	20.3
Sharankhola	Vola	5.3
Swarupkathi	Swarupkathi	0.2

Average salinity concentrations of the rivers in the coastal area are higher in the dry season than in the monsoon because of lack of freshwater flow from upstream.¹¹ Salinity generally increases almost linearly from October (post-monsoon) to late May (pre-monsoon), with the gradual reduction in the freshwater flow (See Figure 3). At the end of May, the salinity level drops sharply because of rainfall and increased upstream flow of freshwater through the river system. The salinity levels are at the minimum in the wet season, usually during September or early October.¹²

Figure 3. Salinity, Rainfall and High Tide Flow in Coastal Bangladesh



Spatial Variation of Salinity

¹¹ Freshwater flow from upstream river and tidal effects jointly determine the extent of salinity.

¹² As the tides in the Bay of Bengal are semi-diurnal, peak daily salinity generally coincides with the arrival of high water at the coast. The daily range of salinity concentrations at the river entrances varies with the spring or neap tide as well as with the season. Tidal amplitudes during spring tides are around 2.5 to three times higher than the neap tides. The higher water levels at the coastal boundaries during spring tides result in greater volume of saline water entering inland. The dilution effect of any freshwater flows in the inland rivers is consequently weaker during spring tides in the dry season. As a result, salinities in coastal inland surface water during spring tides are generally higher.

In addition to temporal variation, there is pronounced spatial variation in river salinity. The entire coastal area of Bangladesh can be divided broadly into four distinct geo-morphological zones.

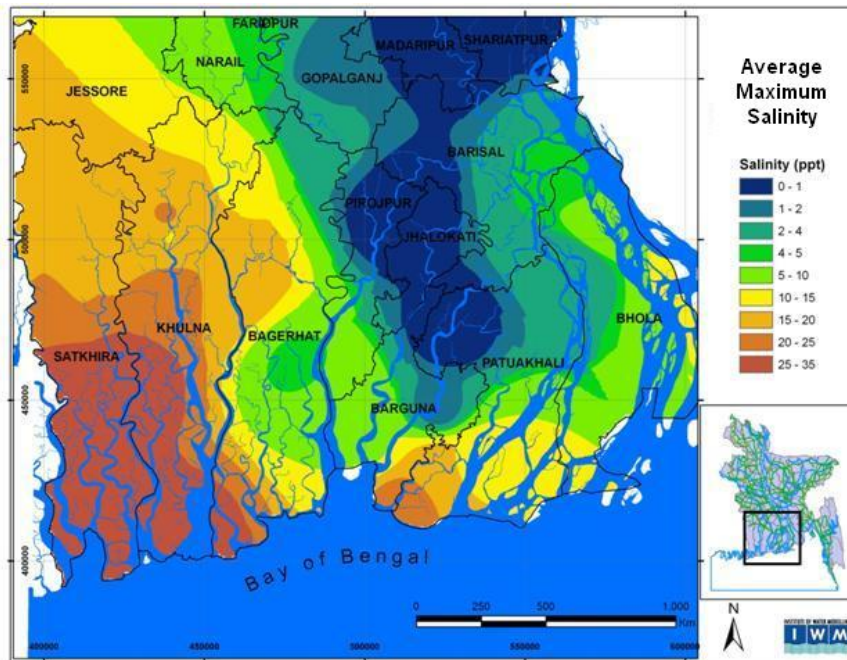
- i. The southwest zone contains the Sundarbans, which is bounded by Baleswar River in the east, Raimongal River, and the border with India in the west. The Gorai River, a distributary of the Ganges, is the main source of freshwater for this zone. This area is part of the Ganges Delta and therefore dependent on the tributaries of the Ganges River.
- ii. The south-central zone is situated between the southeast zone and southwest zone of the coastal area. This part of the coastal area receives considerable freshwater from the Padma River and the Lower Meghna rivers.
- iii. The southeast zone extends from the Feni River to Badarmokam, the southern tip of the mainland. The Lower Meghna River is the western boundary of this region. As most of the combined flow of the Ganges-Brahmaputra-Meghna system is discharged through the Lower Meghna River, heavy sediment inputs from the rivers result in a morphologically dynamic coastal zone. The Lower Meghna River is highly influenced by tidal interactions and consequential backwater effects.
- iv. The Eastern-Hill zone is characterized by flat beaches comprised of clay and sand. In this region, the Karnaphuli, Matamuhuri, Sangu, and Naf Rivers discharge freshwater through the plain. This region is in the Chittagong and Cox's Bazar Districts.

At present, the rivers of the southwest zone and the eastern-hill zone suffer from salinity intrusion among the four coastal zones.

The water from the Ganges River, which flows through its tributary, the Gorai River, is the only major source of freshwater to the southwest zone. The offtake of the Gorai is almost dry during the dry season (December to May). The salinity level at the Bay of Bengal during the dry season is also comparatively high; and saline water intrudes through the major rivers, namely the Baleswar, Jamuna, lower Meghna, Malancha, Pussur, Sibsa, and Tnetulia, through tidal effects. The land topography of the region is very flat; strong tidal effects at times travel up to 200km upstream of the coast. Consequently, the region is severely affected by salinity intrusion. Spatial variation of river salinity within the southwest region, however, depends on tidal amplitude, the extent of landward penetration of tides, and the volume of freshwater flow from

the upstream rivers. Figure 2 presents the spatial variation of the maximum river salinity level during 2011–2012 in the southwest zone.

Figure 2 Map of Average Maximum River Salinity in the Southwest Region of Bangladesh



By contrast, the levels of river salinity in the adjacent south-central and southeastern coastal zones remain low. The low salinity level in the south-central zone (less than 2ppt) throughout the year results from the considerable volume of freshwater discharge from the Padma River and the Lower Meghna River, which is diverted into the region through the Arialkhan, Buriswar, and Bishkhali Rivers. The Feni, Little Feni, and Bamni Rivers flow in the southeast and are controlled by regulators at the outfalls to prevent landward movement of saline water during high tides.

In the eastern-hill zone, the water stretching from Chittagong to Cox's Bazar is always saline near the sea; it is saline in the downstream stretches of the Karnaphuli and Sangu Rivers throughout the wet season; and, with the onset of the dry season, the salinity diffuses northward. The water in the Sandwip Channel between Sandwip and the mainland becomes saline as the tidal flow outweighs the freshwater flow from the rivers and the runoff through the Naf River is not adequate to reduce the level of salinity at Teknaf.

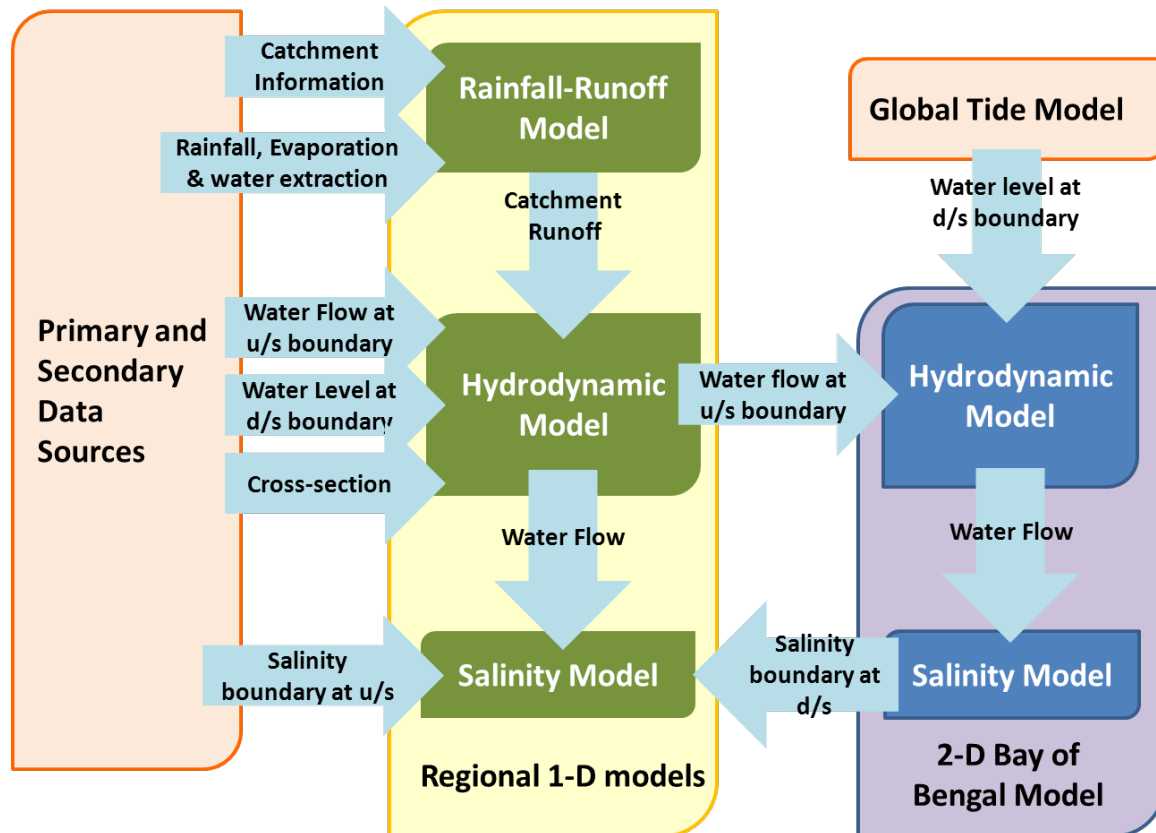
The problem of river salinity is most severe in the southwest zone. The water resource system of the southwest zone has degraded considerably over time, primarily because of the reduction in freshwater inflows from the Ganges (see Appendix 1 for details), cutoff of the Ganges distributaries, and increased salinity intrusion from the Bay of Bengal. Several studies in Bangladesh indicate that coastal zone vulnerability will become more acute in a changing climate from the combined effects of sea level rise (SLR), changes in upstream river discharge, and increased frequency of more intense cyclones (Cruz et al. 2007; CEGIS 2006; IWM 2005). Hence, the focus of this study is on the southwest coastal region of Bangladesh.

3. Modeling Salinity Intrusion

River salinity in coastal Bangladesh depends on the freshwater flow upstream, surface water runoff from rainfall events, and the tidal dynamics of the coastal river system. Tidal waves from the Indian Ocean travel through the deeper part of the Bay of Bengal and approach the coast of Bangladesh from the south. The process of mixing freshwater from the upstream river system and saline water from the Bay of Bengal in the coastal water occurs as turbulence is generated by wind and tidal currents. We used four models—Rainfall-Runoff, Hydrodynamic, Bay of Bengal, and Salinity models—to capture the effects of all the factors that affect salinity in the southwest coastal zone of Bangladesh (see Figure 4).¹³

¹³ A literature review conducted prior to modeling salinity in coastal Bangladesh identified nine available options for modeling water flow: the MIKE series of models by the Danish Hydraulic Institute; ISIS by Halcrow Ltd.; SOBEK by Deltares; HEC-RAS by the U.S. Army Corps of Engineers; RiverWare by the Center for Advanced Decision Support for Water and Environmental Systems; WEAP by the U.S. Center of the Stockholm Environment Institute; MODSIM by Colorado State University; RIBASIM by Deltares; and WaterWare by Austrian Environmental Software and Services. Among these, four—MIKE, ISIS, SOBEK, and HEC-RAS—have water quality (advection-dispersion) modules to facilitate salinity modeling. Upon consultation with experts from Bangladesh, the MIKE 11 modeling system was selected for this exercise as the Surface Water Modeling program of Bangladesh has been developed using MIKE 11 for the past 20 years.

Figure 4 Model Set-up



*u/s denotes the upstream boundary of a river and d/s denotes downstream boundary.

Model Steps

The modeling process is described in four steps.

Step 1. The Rainfall-Runoff model was applied to estimate the runoff from rainfall in various catchments (watersheds) of the model area. The Rainfall-Runoff model takes into account the catchment characteristics, rainfall, soil moisture, irrigation and water extraction from the surface or groundwater sources in the catchments, evaporation, percolation, and other losses. The model generated runoff or overland flow for the catchments.

Step 2. To develop the water flow and the water level in the river systems of the southwest region, the hydrodynamic module of the MIKE 11 model system (the Southwest Regional Model, SWRM) was used.¹⁴ Inputs for SWRM include the rainfall runoff estimates from the Rainfall-Runoff model, water flow data recorded by river gauges at the upstream end of the river (upstream boundary), water level data from the downstream end of the river (downstream boundary), and the cross-sectional river data. SWRM generated the water flow, water level, and flow velocity of the river systems. These estimates were used for the water flow boundary upstream in the Bay of Bengal model as well as for the river salinity model. Box 1 provides details on SWRM.

Step 3. Salinity of the Bay of Bengal was simulated by the Bay of Bengal (BoB) model based on the MIKE 21FM module of the Danish Hydraulic Institute (DHI). The BoB model domain extends from Chandpur on the lower Meghna River (23° N) in the north to 16° N latitude in the Bay of Bengal in the south. The BoB model used the water flow estimates from SWRM at the upstream boundary. The time-series water level data at the downstream boundary were generated from the DHI Global Tide model. Measured concentrations of salinity along the upstream boundary and constant 32ppt salinity at the downstream boundary were used as salinity inputs. For details on the BoB model, see Box 2.¹⁵

Step 4. A Salinity model (the advection-dispersion module of MIKE 11) is coupled with the hydrodynamic module to assess river water salinity in the southwest coastal zone. Measured concentrations of salinity along the upstream boundary and estimates of the salinity of the Bay of Bengal generated by the BoB model for the downstream boundary were used as inputs.

The BoB model and SWRM were run under the assumption that the polders in the coastal zone were all functioning well and would not be overtopped even in the future.

¹⁴ The MIKE 11 hydrodynamic module solves an implicit, finite difference scheme to compute unsteady flows in rivers and estuaries. A detailed description of the model is available at <http://www.dhigroup.com>.

¹⁵ The downstream boundary of this model is far from the coast. The maximum depth along the open downstream boundary is more than 2,000m. Salinity at this location does not vary over time and space.

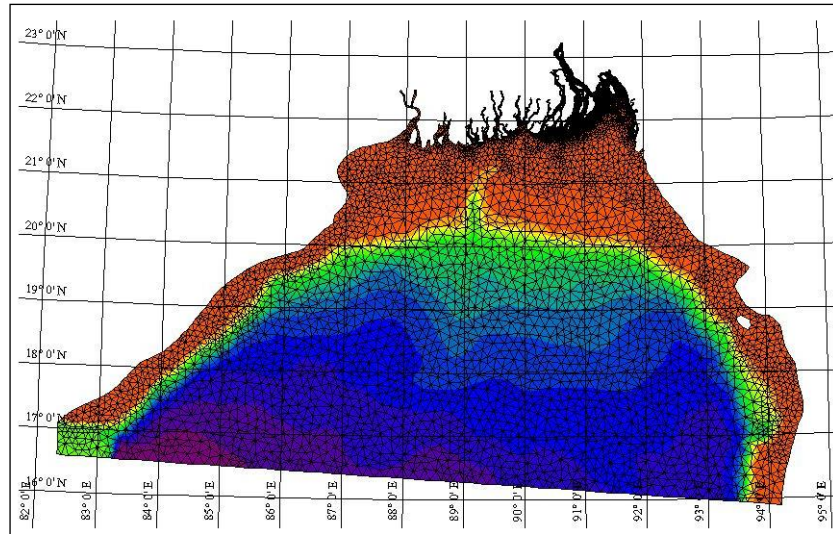
Box 1 Southwest Regional Model

The Southwest Regional Model (SWRM) covers an area of 37,300km² in Bangladesh. The area is surrounded by the Ganges River to the north, the Bay of Bengal to the south, Meghna Estuary to the east, and the international border with India to the west. The total length of the rivers and channels in this region is approximately 5,600km. Major nontidal rivers, the Gorai, Arial Khan, Jayanti, and upper Meghna, are located in the northern part of the area. The southern rivers mostly comprise the tidal estuary systems—the major rivers being the Baleswar, Jamuna, Lower Meghna, Malancha, Pussur-Sibsa, and Tnetulia. A dense network of tidal channels interconnects these major rivers; the channel network located in the Sunderban Forest is particularly complex.

The cross-sections of most of the river branches were updated with data surveyed in 2009–2012. Among the upstream boundaries, Gorai Railway Bridge on the Gorai River, Baruria on the Padma River, and Bhairabbazar on the Upper Meghna River are the major entry points for freshwater flow from the Ganges-Brahmaputra-Meghna basins. It is ideal to use discharge data from the upstream boundaries for the hydrodynamic model. Rating curves (for the statistical relationship between water level and discharge) were updated and used to generate discharge data. Data from Gorai Railway Bridge were used for the Gorai boundary and data from Baruria were used for the Padma boundary. No reliable discharge estimates were available for Bhairabbazar. Scattered data and tidal influence during the dry season prevented generation of satisfactory rating curves at Bhairabbazar. Time-series water level data were used for the upstream boundary of the Upper Meghna River. Observed data and results from the Bay of Bengal model were used to generate the water level and salinity at the downstream boundaries.

Box 2 Bay of Bengal Model

The Bay of Bengal (BoB) model is based on the MIKE 21FM module of the Danish Hydraulic Institute (DHI). MIKE 21 FM modeling, in turn, is based on an unstructured, flexible mesh that consists of linear triangular elements. The BoB model domain extends from Chandpur on the lower Meghna River in the north to 16° N latitude in the Bay of Bengal in the south. The grid or mesh size of the BoB model decreases from 200km² in the deep ocean to 0.1km² near the coastlines and islands.



Computational Mesh of the Bay of Bengal Model

The model applies the Public Works Datum of Bangladesh mean sea level 0.46 m. In the model, intertidal areas are flooded and dried to mimic the diurnal tidal cycle.

The time-series water level data for the downstream boundary were generated from the DHI Global Tide model. Constant 32ppt salinity was used for the downstream boundary. The time-series salinity data for the upstream boundaries were from the measurements at Nailan (Sibsa River), Mongla (Pussur River), Arpangasia (Kobadak River), Pirozpur (Baleswar River), and Swarupkathi (Kaliganga River). Estimates of the water flows of the river systems were generated by the MIKE 11 hydrodynamic module for the southwest region and were used as inputs for the upstream boundaries.

Model Calibration and Validation

The models were calibrated and validated with historical observed data at various locations. The water flow model was calibrated with hourly data on water level time series from November 2011 to June 2012 and hourly data on water discharge time series for one spring and one neap tidal cycle during February 2012 and March 2012. The salinity model was calibrated with the salinity time series (data were monitored twice a day on alternate days during high and low tides) from November 2011 to June 2012. The models were validated against the corresponding time series of measured data from November 2010 to April 2011. The match between the model-generated estimates and the measured data was reasonably good (see Table 2).

Table 2 Degree of Agreement between Model-Generated Results and Measured Data

Location	R ²
<i>Comparison of water flow</i>	
Baleswar River at Char Doani	0.95
Buriswar River at Amtali	0.87
Pussur River at Akram Point	0.94
Pussur River at Mongla	0.91
<i>Comparison of water level</i>	
Marichbunia River	0.84
Pussur-Kazibacha River	0.95
<i>Comparison of salinity</i>	
Baleswar River at Char Duani	0.73
Pussur River at Mongla	0.99
Rupsa River at Khulna	0.83
Sibsa River at Nalian	0.97

Likely Effects of Climate Change

The effects of climate change on river salinity in the coastal area of Bangladesh are expected to manifest in several ways. Changes in rainfall, temperature, freshwater flow from rivers in the

Himalayas, cyclone-induced surge intensification,¹⁶ and SLR are likely to be the most significant effects of climate change. In particular, salinity ingress is likely to be more severe in the future for two reasons: a) freshwater flows from rivers in the Himalayas are predicted to decrease during the dry season and b) the sea level will gradually rise. In the following, we present a model and simulation results for river salinity during the dry season (December to May) in the southwest coastal region of Bangladesh for 2050.

Modeling Scenarios

Baseline: In order to model the impact of climate change on salinity, we defined the baseline scenario (current conditions) of salinity using historical (measured) data on the maximum river salinity for the dry season of 2011–2012 (December 2011 to May 2012). The data are from the database of the Institute of Water Modeling in Bangladesh.

Climate Change: Overall, climate change uncertainties in the Ganges basin are extreme. Regarding the greater Himalayan region, the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR4) pointed out that available data were insufficient to support a credible analysis (IPCC 2007a). Uncertainties are compounded by the inability so far to construct a credible methodology for modeling predictions of how monsoon patterns might change, in particular with regard to the relationship between climate and hydrology (World Bank 2013).

In recent years, attempts have been made to downscale temperature, rainfall, and runoff for the Ganges Basin using all the Global Circulation Models (GCMs) recognized by IPCC AR4. A number of studies have been conducted on glacier melt, snow accumulation in the Himalayas, SLR, and the possibility of cyclone intensification in the Bay of Bengal. Our study draws on the existing literature to outline the climate change scenarios for coastal Bangladesh.

¹⁶ Although Bangladesh is a global tropical cyclone hotspot, storm surge-induced river salinity is less of a concern. Cyclone-induced river salinity in coastal Bangladesh is generally short-term and washed away with the advent of monsoon.

Projections for Temperature and Rainfall

Inputs for temperature and rainfall for the climate change scenarios were based on analysis of a subset of nine GCMs¹⁷ and three emission scenarios (SRES A2, A1b, and B1)¹⁸ used for IPCC AR4. In order to synthesize the myriad of climate projections, which often have conflicting messages,¹⁹ a step-by-step process was followed. First, pattern downscaling (daily timescale Bias-Corrected Spatial Disaggregation) was applied to project maximum monthly temperature and total monthly rainfall for each GCM and emission scenario for 2050.²⁰ Second, we ranked the models from low to high based on their median projections. Finally, to capture the uncertainty of the extent of climate change, three GCMs (IPS-CM4L, MIROC3.2, and ECHO-G) with the highest, medium, and lowest ranks and the corresponding projections were selected.

The scenario projections include a temperature increase in Bangladesh of about 2.6 to 8 percent for the A2 scenario, 3.3 to 8.2 percent for the A1b scenario, and 3.3 to 7.1 percent for the B1 scenario by 2050. The rainfall projections for 2050 are the following ranges: 30.9 percent decrease to 26.4 percent increase for the A2 scenario, 6.9 percent decrease to 21.9 percent increase for the A1b scenario, and 23.4 percent decrease to 21.2 percent increase for the B1 scenario (see Table 3).²¹

¹⁷CCCMA-GCM3.1 is the Canadian Centre for Climate Modeling and Analysis; CNRM-CM3 is the Centre National de Recherches Météorologiques, Météo France, France; ECHAM5/MPI-OM is the Max Planck Institute for Meteorology, Germany; ECHO-G is the Meteorological Institute of the University of Bonn (Germany) and the Institute of KMA (Republic of Korea) and Model and Data Group; GFDL-CM2.0 and CM2.1 are the Geophysical Fluid Dynamics Laboratory, NOAA, USA; IPS-CM4L is the Institut Pierre Simon Laplace, France; MIROC-MIROC3.2 is the CCSR/NIES/FRCGC, Japan; and MRI-CGCM2.3.2 is the Meteorological Research Institute, Japan.

¹⁸The A1b scenarios are characterized by rapid economic growth, global population that reaches nine billion in 2050 and then gradually declines, quick spread of new and efficient technologies, a convergent world (income and way of life converge between regions), extensive social and cultural interactions worldwide, and balanced emphasis on all energy sources. The A2 scenarios are characterized by a world of independently operating, self-reliant nations; continuously increasing population; and regionally oriented economic development. The B1 scenarios are characterized by rapid economic growth as in A1, but with rapid changes toward a service and information economy; population rising to nine billion in 2050 and then declining as in A1; reductions in material intensity and the introduction of clean and resource efficient technologies; and emphasis on global solutions to economic, social, and environmental stability.

¹⁹For the Ganges basin, although climate models somewhat agree that temperatures will increase significantly, there is wide variation in the direction and magnitude of rainfall predictions.

²⁰Provided by the climatewizard.org website <http://climateknowledgeportal.climatewizard.org/> and the World Bank Group's Climate Change Knowledge Portal, <http://climateknowledgeportal.worldbank.org>.

²¹It should be noted that for the Ganges basin, predictions regarding rainfall vary widely; and different GCMs point to the possibility of either increasing or decreasing rainfall (World Bank 2013).

Table 3 Projections of Percentage Change in Temperature and Rainfall for the Southwest Region in 2050

Emission Scenario	2050 Temperature			2050 Rainfall		
	IPS-CM4L	MIROC 3.2	ECHO-G	IPS-CM4L	MIROC 3.2	ECHO-G
A2	8.03	2.61	3.33	-30.91	26.42	4.88
A1b	8.16	3.32	4.16	-6.96	11.72	21.86
B1	7.11	3.34	3.04	-23.37	21.18	17.7

Projections for Freshwater Flow from Himalayan Rivers

The rate at which glaciers will melt in the Hindu Kush Himalayan region with climate change is uncertain (Cogley et al. 2010; Immerzeel et al. 2010; Bolch et al. 2012; Miller et al. 2013). However, since glacier melt contributes only about 2 percent of the annual flow of the Ganges (Alford and Armstrong 2010), the Ganges system as a whole is unlikely to be significantly affected by glacier melt even if it increases in the future (World Bank 2013). However, it should be noted that the schedule of accumulation and melting of snow in the Himalayas could change and lead to key changes in the Ganges basin hydrology with climate change.²²

Bangladesh has a signed treaty with upper riparian country India on sharing the water of the Ganges under different river flow regimes. In light of the uncertainty of the effects of climate change on the Ganges basin hydrology, we have assumed strict adherence to the existing Ganges water treaty between Bangladesh and India for the Ganges water flow from India in this analysis.²³ An average of the measured Ganges water flow from India over past 16 years was

²² “Temperatures during the monsoons are expected to be warmer and the zero-degree isotherm is expected to rise to a higher altitude, some of the precipitation that falls as snow today will then become rain, resulting in lower snow accumulation and higher runoff. Consequently, during the spring thaw, there will be less snow to melt, resulting in lower water flow in the pre-monsoon low-flow (dry) season and can have a significant impact in some catchments where snowmelt is a major input.” (World Bank 2013)

²³ See Dinar et al. (2010) on trans-boundary river treaties and climate change.

used to approximate the Ganges water flow from India in 2050 (see Annex 1). The water flow for the Brahmaputra in 2050 was approximated by its dry season water flow in 2012.²⁴

Projections for Sea Level Rise

IPCC AR4 projected increased global SLR between 0.18m and 0.59m across various emission scenarios over the next 100 years.²⁵ However, these projections were calculated from projections of SLR caused by thermal expansion and melting of glaciers—with the Greenland and Antarctic ice sheets calculated as being *close to mass balance*—and *excluded* rapid dynamic changes in ice flow (IPCC 2007b). Hence, it should be noted that the SLR estimates by IPCC AR4 are conservative.

The most recent evidence suggests that global SLR could reach one meter or more during this century (Hansen and Sato 2011; Vermeer and Rahmstorf 2009; Pfeffer et al. 2008; Hansen 2006, 2007; Rahmstorf 2007; Overpeck et al. 2006). These results focus on the dynamic implications of ice sheet instability and produce estimates significantly beyond the upper limit of the range cited by IPCC AR4 (IPCC 2007a): a 90 percent confidence interval of 18 to 59cm based principally on thermal expansion, with an additional 10 to 20cm allowed for a potential dynamic response from the Arctic and Antarctic ice sheets.²⁶

At present, regional estimates of SLR are scarce. In the absence of a scientific SLR estimate for the Bay of Bengal near the coast of Bangladesh, upon consultation with experts in Bangladesh, we use an estimate of between 27 and 32cm global SLR by 2050. This range was derived from various climate change scenarios as reported in Rahmstorf (2007).²⁷

²⁴ Brahmaputra is a trans-boundary river and one of the major rivers of Asia. The water of the Brahmaputra is currently shared by China, India, and Bangladesh. Predicting the water flow of the Brahmaputra is complex and should be a subject of future research.

²⁵IPCC AR3 suggested an SLR of 0.09 to 0.88m by the year 2100 unless greenhouse gas emissions are reduced substantially (IPCC 2001).

²⁶For a review of the scientific literature on sea level rise, see Dasgupta and Meisner (2009).

²⁷This 27 to 32cm SLR is also the interval estimate of “medium sea level rise” by 2050 from a study by the World Bank (2011). See Neumann (2009) for details.

Other Determinants of Future Water Level and Water Flow

Projections for Land Subsidence

The Ganges Delta in Bangladesh is still in an active, dynamic state. Therefore, it is critical to include in the analysis land subsidence of the lower Bengal delta (the Ganges Delta in Bangladesh) in simulating future climate scenarios. Physical impacts of relative mean SLR (RMSLR) are caused by a combination of SLR scenarios associated with global warming and vertical land movement (subsidence or accretion). Experts agree that land subsidence in the lower Bengal delta is mainly caused by tectonic subsidence and isostatic adjustments, the rate of sediment loading or delta aggradation, compaction of Holocene sediments, compaction of peat layers, water withdrawal, and surface water drainage and management. However, the available estimates of land subsidence in the lower Bengal delta vary widely, from a fraction of a millimeter to a few centimeters per year (Pethick 2012; ADB 2011; Akhter et al. 2012; Syvitski et al. 2009; Nicholls and Goodbred 2004; Brammer 1996; Emery and Aubrey 1991). At present there is an intense controversy in Bangladesh regarding the estimates and projections of land subsidence in the coastal region. In light of the widely varying estimates, the hydrological modeling for our analysis was run for three alternative scenarios of land subsidence: 2mm per year, 5mm per year, and 9mm per year.

Projections for Water Abstraction

Although Bangladesh has abundant water in the wet season, the supply of water is limited in the dry season. River water is abstracted for the production of *boro*²⁸ rice and for the supply of water to Khulna City.²⁹ Therefore, it is important to take into account the expected change in river-water abstraction in the future for the projections of water flow and water level in the hydrological modeling.

Bangladesh does not maintain a database on water abstraction for irrigation. The analysis uses secondary data on low-lift irrigation pumps³⁰ from the subdistrict level annual Irrigation Reports

²⁸Rice grown in winter.

²⁹ Other municipalities use groundwater. Khulna Water Supply and Sewerage Authority currently extracts 123,000m³ per day of groundwater.

³⁰ The capacity of these pumps varies from one to five cusec and they operate from six to ten hours per day.

published by the Bangladesh Agricultural Development Corporation. To estimate current water abstraction for *boro* production, estimates of evaporation and percolation losses were combined with annual data maintained by the Department of Agricultural Extension on area of irrigated *boro*. In order to assess the potential change in the future, Key Informant Interviews were conducted by the Institute of Water Management in Dhaka. In addition, several experts from the Bangladesh Agricultural Development Corporation and the International Rice Research Institute were consulted.

The expected change in surface water abstraction for Khulna City was estimated by combining projections of future population (IWM 2010) with the basic water requirement of 50 liters per person per day for domestic use and a water requirement of 15 liters per person per day for other uses, and an allowance of 20 percent loss in evaporation and leakage.

Simulations

We set up the Rainfall-Runoff model and estimated the runoffs from various catchments for the IPCC: A2, A1b, and B1 emission scenarios with each of the three GCMs for changing climate (temperature and rainfall) in 2050. We then used the nine sets³¹ of runoff estimates from the Rainfall-Runoff model, projections of water abstraction for 2050, the observed flow in the Ganges and Gorai Rivers over the past 16 years, and the dry season water flow of the Brahmaputra in 2012 as proxies for 2050 dry season water flow from major rivers upstream in the hydrodynamic module of the MIKE 11 model. We estimated various alternative time series of water flow and flow velocity along 230 river branches in the southwest region of Bangladesh. The water flow estimates from the hydrodynamic module of the MIKE 11 model were used as inputs for the upstream boundary of the BoB model. The Global Tide model was set up in parallel and was simulated to estimate the tides and the water level along the coast (the downstream boundary of the BoB model) for alternative scenarios of SLR and land subsidence in the Ganges Delta, in particular for 35cm, 40cm, 47cm, 52cm, 62cm, and 67cm RMSLR by 2050.³²

³¹ Three emission scenarios x three GCMs = nine scenarios.

³² The 35cm RMSLR is estimated from 27cm global SLR by 2050 + 2mm per year subsidence up to 2050; 40cm RMSLR is estimated from 32cm global SLR by 2050 + 2mm per year subsidence up to 2050; 47cm RMSLR is estimated from 27cm global SLR by 2050 + 5mm per year subsidence up to 2050; 52cm RMSLR is estimated from 32cm global SLR by 2050 + 5mm per year subsidence up to 2050; 62cm RMSLR is estimated from 27cm global SLR by 2050 + 9mm per year subsidence up to 2050; and 67cm RMSLR is estimated from 32cm global SLR by 2050 + 9mm per year subsidence up to 2050.

We used the estimated river flows, tidal effects, salinity of the river flows, and salinity of the tides to estimate location-specific river salinity for the southwest coastal region for December 2049 to March 2050. The model was estimated for 27 alternatives for the future: 40cm, 52cm, and 67cm RMSLR for nine scenarios of upstream water flows for the A2 scenario; 40cm, 52cm, and 67cm RMSLR for nine scenarios of upstream water flows for the A1b scenario; and 35cm, 47cm, and 62cm RMSLR for nine scenarios of upstream water flows for the B1 scenario. The BoB model and SWRM were run under the assumption that all 61 polders (of which 13 are sea-facing) in the coastal area are functioning well and will not be overtopped by 2050.

4. Results

The effects of climate change on river salinity in the southwest coastal region of Bangladesh show up in two ways: intrusion of the salinity frontier inland (see the isohalines displayed in Figure 5) and higher location-specific salinity. As expected, the estimates indicate that the extent of the intrusion of the salinity frontier is primarily determined by RMSLR. For each emission scenario, salinity differs marginally across GCMs.³³ The B1 emission scenario with 35cm RMSLR is the best future scenario (least increase in salinity from the baseline) and the A2 emission scenario with 67cm RMSLR is the worst future scenario (largest increase in salinity from the baseline).

Overall Effects in the Southwest Coastal Zone

Area estimates indicate the following changes from the baseline (March 2012) to the best and worst case future scenarios (March 2050):³⁴

- “Slight saline” river area is likely to decrease from 22 percent at the baseline to 16 and 13 percent in the best and worst case scenarios, respectively.
- “Slight to moderately saline” river area is likely to decrease from 35 percent at the baseline to 30 and 21 percent in the best and worst case scenarios, respectively.

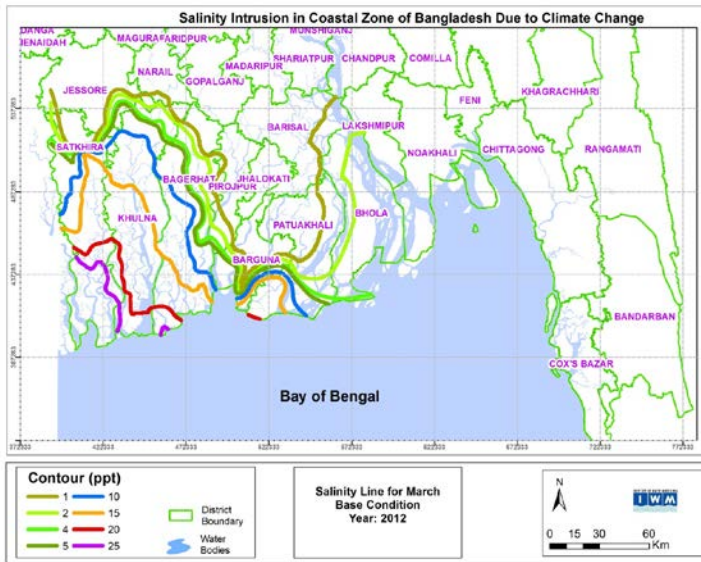
³³ GCMs agree about the change in future temperature, but do not agree on the direction of change in future rainfall in Bangladesh, much less on the magnitude in either direction. Hence, it is important to consider alternative GCMs in any analysis of changing climate. However, the problem of river salinity in coastal Bangladesh is a dry season phenomenon and therefore differences in future rainfall projections associated with differences in GCMs turned out to be insignificant in this case.

³⁴ Other monthly estimates are available from the authors upon request.

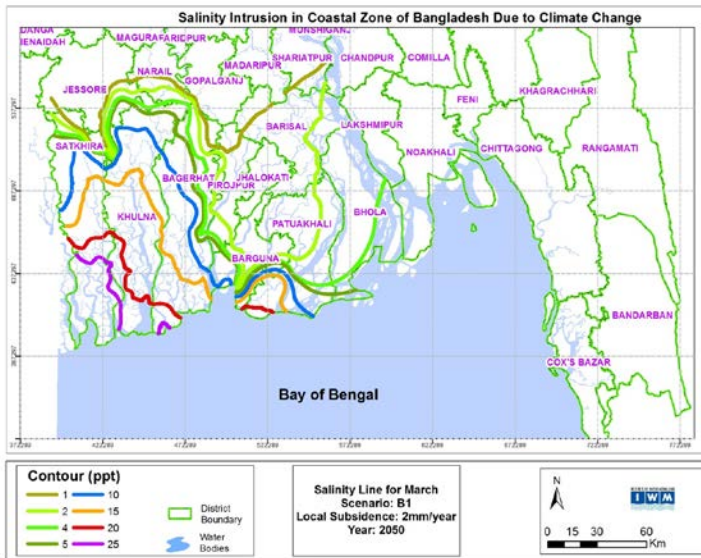
- “Moderate to high saline” river area is likely to increase from 8 percent at the baseline to 17 and 27 percent in the best and worst case scenarios, respectively.
- “Highly saline” river area is expected to increase from 35 percent at the baseline to 38 and 40 percent in the best and worst case scenarios, respectively.³⁵

³⁵ In the National Water Management Plan, the Water Resources Planning Organization in Bangladesh has categorized surface water salinity into the following groups: (i) <1dS/m: slightly saline; (ii) 1–5 dS/m: slightly to moderately saline; (iii) 5–10 dS/m: moderately to highly saline; and (iv) > 10dS/m: highly saline. This classification is for average dry season values (WARPO 2001). The conversion factor of dS to ppt depends on temperature. 1dS = 1.75 ppt has been used as a conversion factor in this analysis from the readings of salinity meters in coastal Bangladesh.

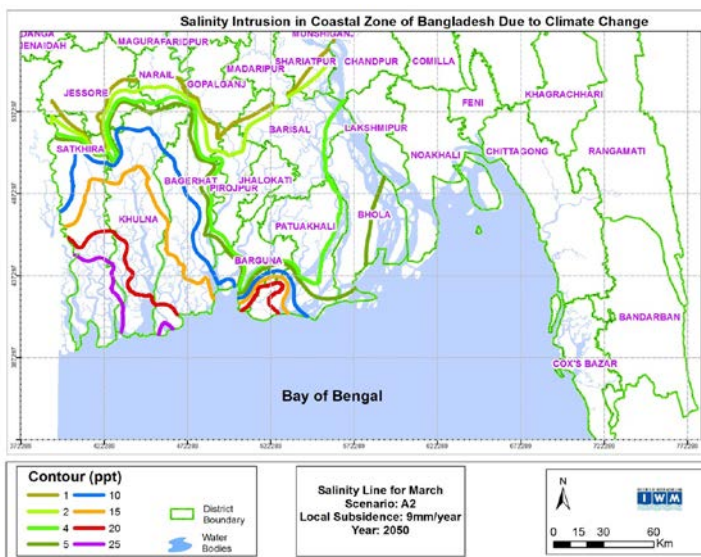
Figure 5 Isohalines in the Southwest Coastal Region



Panel a: Baseline (March 2012)



Panel b: Best Future Scenario (March 2050): B1 emission scenario with 35cm RMSLR



Panel c: Worst Future Scenario (March 2050): A2 emission scenario with 67cm RMSLR

In particular, freshwater river area (0–1ppt) is expected to decrease from 40.8 percent at the baseline to 19.7 and 17.1 percent in the best and worst case future scenarios, respectively (see Table 4). An immediate impact of this change would be on the supply of drinking water from rivers. There would be a shortage for the urban areas, with 1ppt being the critical level of salinity for drinking water.³⁶

Agriculture is the predominant economic activity in coastal Bangladesh. Approximately 70 percent of employment in the coastal area is dependent on agriculture (DFID 2007). The critical salinity level for agriculture is 2ppt.³⁷ Climate change is expected to have a significant impact on coastal agriculture, especially on the *boro* rice crop, through increased river salinity. Area with salinity less than 2ppt is expected to decrease by 11.1 percent in the best case future scenario and by 29.7 percent in the worst case future scenario.³⁸

Table 4 River Salinity in the Southwest Coastal Zone of Bangladesh in 2050 for Alternative Scenarios (Percentage of Area*)

Salinity (ppt)	Baseline, March 2012	B1 and 35cm RMSLR	B1 and 62cm RMSLR	A1b and 40cm RMSLR	A1b and 67cm RMSLR	A2 and 40cm RMSLR	A2 and 67 cm RMSLR
0–1	40.8	19.7	17.5	18.9	17.1	18.9	17.1
1–2	9.8	19.8	3.9	17.2	3.8	17.2	3.8
2–4	11.3	16.5	24.7	19.5	24.1	19.6	24.1
4–5	1.7	4.8	9.3	5.2	11.1	5.2	11.1
5–10	7.7	9.3	13.7	9.2	13.1	9.2	13.1
10–15	9.4	9.9	10.0	9.8	9.7	9.8	9.7
15–20	12.4	12.2	12.1	12.1	12.1	12.1	12.1
20–25	3.3	4.0	4.7	4.1	4.8	4.1	4.8
25–30	3.5	3.8	4.1	3.9	4.2	3.9	4.2

*Total area is 30,056 square kilometers.

³⁶ The official salt concentration limit for drinking water in the United States is 1,000parts per million. http://www.engineeringtoolbox.com/water-salinity-d_1251.html.

³⁷ The typical limit for agricultural irrigation is 2,000ppm. http://www.engineeringtoolbox.com/water-salinity-d_1251.html

³⁸ Implications on yield is a subject of ongoing research at the World Bank.

Expected increase in river salinity is likely to change the aquatic ecosystems of coastal Bangladesh. There are approximately 500,000 fishing households in the coastal area of the country (DFID 2007). Saline intrusion into freshwater habitats of fish is likely to change the composition of capture fishery during the dry season. Habitats of freshwater large fish, for example Catla (*Catla catla*), Rui (*Labeo rohita*), and Mrigal (*Cirrhina mrigala*), are likely to decline in the wild.³⁹ Reductions in the wild are also expected for small indigenous freshwater fish species, for example Bacha (*Eutropiichthys vacha*), Bata (*Mugil parsia*), Batashi (*Pseudeutropicus atherinoides*), Chela (*Salmostoma argentea*, *Salmostoma phulo*, *Salmostoma bacaila*), Darkina (*Esomus danricas*, *Rasbora daniconius*, *Rasbora rasbora*), Kajuli, Baspata (*Ailia coila*, *Ailichthys punctate*), Kash Khaira (*Chela laubuca*), Kholisha (*Colisa fasciatus*), and Tengra (*Mystus tengra*). The optimum level of surface water salinity is less than 4ppt for Golda/giant freshwater prawn (*Macrobrachium rosenbergii*) and ten to 20ppt for brackish water Bagda/Black Tiger shrimp (*Penaeus monodon*). Golda production in the wild⁴⁰ is expected to decrease and Bagda production on monoculture farms is expected to increase.⁴¹

Expected increase in river salinity is likely to trigger changes in the ecosystems of the Sunderbans⁴² mangrove forest, the UNESCO Heritage site. The most commonly found trees in Sunderbans are Sundari (*Heritiera fomes*), Gurjan (*Dipterocarpus turbinatus*), Gewa (*Excoecaria agallocha*), Guran (*Ceriops decandra*), Keora (*Sonneratia apetala*), and Kankra (*Bruguiera sexangula*).⁴³ Among these, Sundari is the single most dominant and important species of Sunderbans, with the highest market value. The diameter of the trunk of the Sundari

³⁹ Although these fish species can tolerate salinity up to 10–11ppt, they grow better around 5ppt. Estimates indicate that river water area with a level of salinity <5ppt would decline by 4 to 12 percent from the baseline by 2050 with climate change. See Pillay and Kutty (2005).

⁴⁰ Spawning grounds for Golda prawn are likely to move upstream as freshwater is essential for Golda juveniles.

⁴¹ In 2010, estimated combined production of shrimp and prawn was around 98,000 tonnes, Shrimp and prawn are major exports of Bangladesh and generated US\$412 million in 2009–2010. See Belton et al. (2011) for details.

⁴² The Bangladesh Sundarbans merges with the Sundarbans forest of West Bengal in India and together they make up the largest continuous tidal mangrove forest area of the world. Sundarbans is a UNESCO site. It is a unique ecosystem and a rich wildlife habitat with 334 recorded plant species, 270 species of birds, 42 species of mammals, 35 reptiles, eight amphibian species, and at least 150 species of commercially important fishes. The name Sunderbans is coined from Sundari trees. The Bengali word “ban” (pronounced as “bon”) means forests.

⁴³ Tolerance for salinity varies across species. For example, Sundari and Kankra are freshwater-loving species with lower ecological amplitude. Guran, Gewa, and Keora are moderately salt tolerant with wider ecological amplitude. See Islam and Gnauck (2007).

decreases steadily with salinity and shows a dramatic decline when salinity is more than 25ppt. Guran grows better with increasing salinity. Increase in salinity with climate change is likely to induce an overall shift from Sundari to lower value species (Gewa and Guran) in Sunderbans (Water Science and Technology Library 2004).

Expected Effects by District

An overlay of isohalines on administrative areas of the coastal districts indicates that Barguna, Barisal, Bagerhat, Bhola, Khulna, Jhalokati, Patuakhali, and Pirojpur Districts will be affected severely by the increase in river salinity with climate change by 2050. Areas affected by expected change in river salinity, by district, for the best and the worst case future scenarios are summarized in Table 5.

The estimates indicate that even in the best case future scenario, freshwater (0–1ppt) zones will be lost entirely in Barguna, Jhalokati, Khulna, and Patuakhali Districts. In the best case scenario, freshwater zones are expected to be reduced in Barisal, Pirojpur, and Bagerhat Districts by 85, 81, and 71 percent, respectively. In the worst case scenario, 100 percent of fresh river water in Pirojpur, 93 percent in Bagerhat, and 91 percent in Barisal will be at risk.

In addition, a serious shortage of water for dry season agriculture (water with salinity <2ppt) is envisioned with climate change. River water will no longer be utilizable for agriculture in Barguna, Bhola, Jhalokati, Khulna, and Patuakhali Districts in the worst case future scenario.

Table 5 River Salinity by District (Area in square kilometers)

Panel a: Baseline (March 2012)

District	Baseline (March 2012)								
	0–1ppt	1–2ppt	2–4ppt	4–5ppt	5–10ppt	10–15ppt	15–20ppt	20–25ppt	Over 25ppt
BAGERHAT	455	303	478	136	816	975	659	216	0
BARGUNA	737	123	138	52	325	72	73	0	0
BARISAL	2113	429	0	0	0	0	0	0	0
BHOLA	0	747	2045	43	0	0	0	0	0
GOPALGANJ	1456	0	0	0	0	0	0	0	0
JESSORE	2054	167	108	34	78	0	0	0	0
JHALOKATI	742	0	0	0	0	0	0	0	0
KHULNA	96	49	241	82	383	1136	1737	419	51
NARAIL	930	48	0	0	0	0	0	0	0
PATUAKHALI	1113	833	218	76	266	171	408	3	0
PIROJPUR	960	179	85	28	12	0	0	0	0
SATKHIRA	353	88	101	60	436	473	848	359	1006
SHARIATPUR	1233	0	0	0	0	0	0	0	0

Panel b: Best Future (March 2025) Scenario

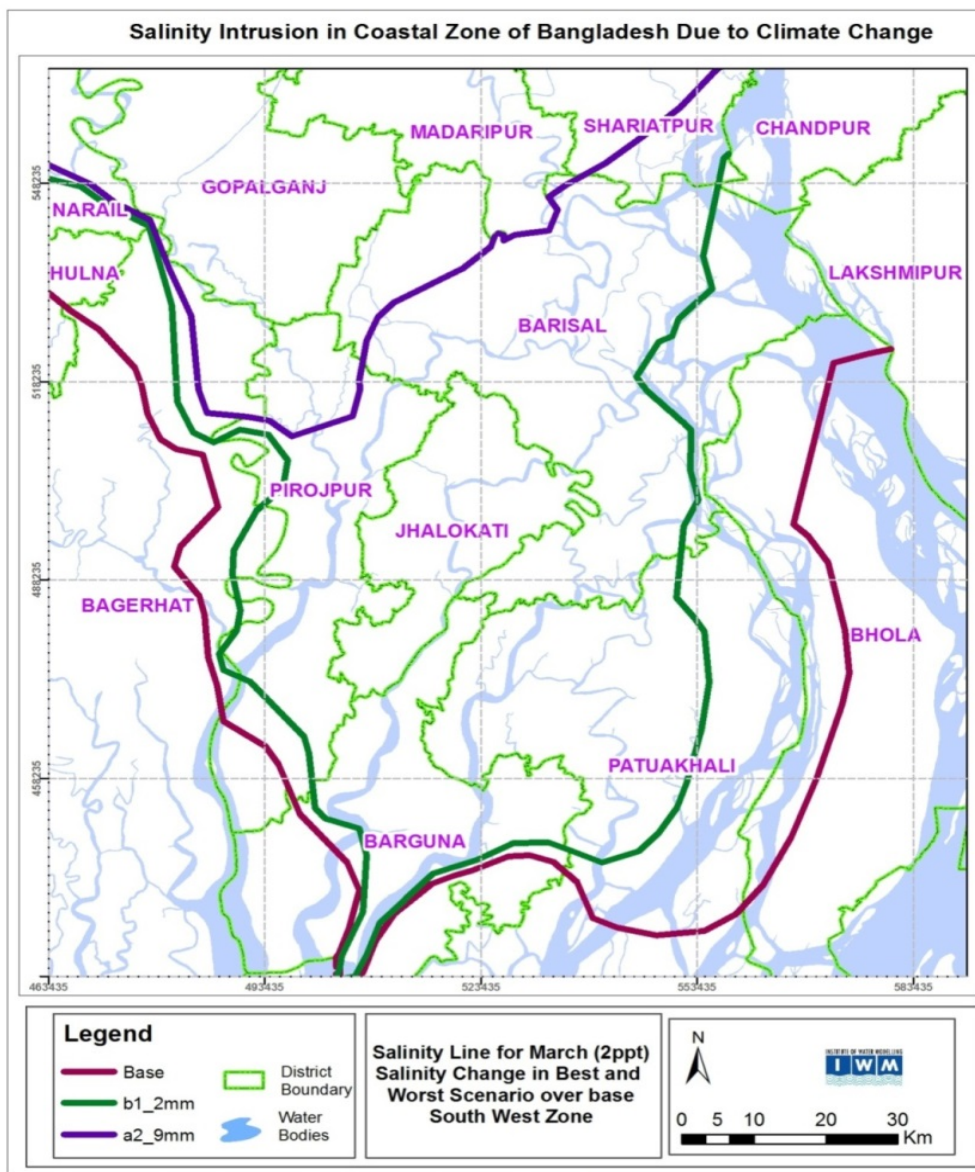
District	Best Future Scenario: B1 emission scenario and 35 RMSLR								
	0–1ppt	1–2ppt	2–4ppt	4–5ppt	5–10ppt	10–15ppt	15–20ppt	20–25ppt	Over 25ppt
BAGERHAT	136	199	469	292	777	1166	768	232	0
BARGUNA	0	755	191	56	334	102	77	4	0
BARISAL	322	1690	530	0	0	0	0	0	0
BHOLA	19	0	2082	635	99	0	0	0	0
GOPALGANJ	1454	2	0	0	0	0	0	0	0
JESSORE	1921	166	189	48	115	3	0	0	0
JHALOKATI	0	742	0	0	0	0	0	0	0
KHULNA	0	3	44	190	558	994	1795	542	68
NARAIL	605	191	168	15	0	0	0	0	0
PATUAKHALI	0	1081	964	106	309	193	376	59	0
PIROJPUR	183	812	201	34	33	0	0	0	0
SATKHIRA	224	109	133	48	486	482	812	354	1076
SHARIATPUR	1023	202	8	0	0	0	0	0	0

Panel c: Worst Future (March 2025) Scenario

District	Worst Future Scenario: A2 emission scenario and 67 RMSLR								
	0–1ppt	1–2ppt	2–4ppt	4–5ppt	5–10ppt	10–15ppt	15–20ppt	20–25ppt	Over 25ppt
BAGERHAT	34	143	353	227	964	1216	857	212	33
BARGUNA	0	0	863	81	357	126	80	13	0
BARISAL	188	134	1970	249	0	0	0	0	0
BHOLA	19	0	8	1963	845	0	0	0	0
GOPALGANJ	1438	18	0	0	0	0	0	0	0
JESSORE	1864	169	171	85	144	8	0	0	0
JHALOKATI	0	0	742	0	0	0	0	0	0
KHULNA	0	0	12	42	659	891	1838	669	83
NARAIL	509	207	179	69	15	0	0	0	0
PATUAKHALI	0	0	1663	519	333	150	275	149	0
PIROJPUR	3	200	943	53	64	0	0	0	0
SATKHIRA	161	92	149	49	500	535	718	391	1130
SHARIATPUR	847	177	210	0	0	0	0	0	0

Tentulia River, which currently provides water to the Bhola Irrigation Project, will be nonoperational, with estimated salinity exceeding 2ppt. Scarcity will be severe even in the best case future scenario. For example, 98 percent of the rivers in Khulna and 97 percent of the rivers in Bhola will be adversely affected. However, Bishkhali River, Buriswar River, and the upstream stretch of the Baleswar River, with estimated salinity lower than 2ppt, are expected to remain functional for irrigation in the best case future scenario (see Figure 6).

Figure 6 Isohaline (2ppt) in March 2050 under Baseline and Alternative Climate Change Scenarios, Barisal Division*



*Barisal division includes Barguna, Barisal, Bhola, Jhalokati, Patuakhali, and Pirojpur Districts.

Increase in river salinity will inevitably generate significant changes in the ecosystems in the coastal districts. Even in the best case future scenario, optimum river area for Catla, Rui, and Mrigal is likely to decrease in Khulna, Bagerhat, and Satkhira Districts by 49, 20, and 15 percent, respectively. Wild habitats ideal for Golda prawn are expected to decrease by 88 percent in Khulna, 35 percent in Bagerhat, 25 percent in Gopalganj, and 14 percent in Satkhira Districts. In the worst case future scenario, expected reductions in the prime habitats for Catla, Rui, and Mrigal will be 100 percent in Khulna, 81 percent in Bagerhat, 43 percent in Bhola, and 34 percent in Satkhira; and that for Golda prawn will be 99 percent in Gopalganj, 97 percent in Khulna, 57 percent in Bagerhat, 26 percent in Satkhira, 23 percent in Patuakhali, and 14 percent in Barguna. Significant changes in the freshwater small fish species in the wild are also probable. Changes in the availability of freshwater fish will likely affect the composition of capture fishery. However, an increase in brackish water will enhance opportunities for brackish water aquaculture, for example, farming of *Tilapia Nilotica* and Bagda.

The incidence of poverty is very high in Bagerhat, Barguna, Bhola, Khulna, Patuakhali, and Satkhira Districts. A poverty mapping exercise conducted by the Bureau of Statistics in Bangladesh, the World Bank, and the World Food Programme in 2009 identified many *upzilas* in Bagerhat, Barguna, Barisal, Bhola, Khulna, Patuakhali, and Satkhira Districts with high poverty headcount ratios⁴⁴ (BBS et al. 2009). Hence, it is important to assess the probable impacts of increase in river salinity on the wellbeing of the poor. Data from rural areas in Bangladesh suggest that low-value, wild, small freshwater fish are the most common fish consumed in rural areas and the most important source of dietary protein (Belton et al. 2011; Thilsted 2010, 2012).⁴⁵ Small fish are generally sold in rural markets and can be purchased in affordable quantities by the rural poor and shared more equitably among household members, including women and children (Roos et al. 2007). Hence, probable decline in the biodiversity of freshwater, low-value, wild fish species with increased river salinity may have significant implications for the nutrition of the rural poor. It is also likely that intrusion of salinity into freshwater will adversely impact the livelihoods and incomes of fishing communities that currently rely on freshwater capture fisheries. However, expansion of brackish water aquaculture and the shrimp sector may offer numerous lower-value livelihood opportunities for

⁴⁴ The proportion of the population with food expenditure at the level of the food poverty line using the Cost of Basic Needs by the Government of Bangladesh.

⁴⁵ The nutritional contribution of small fish species is generally high. And, as many small fish species are consumed whole, they provide a significant percentage of recommended intakes of calcium, vitamin A, iron, and some minerals (Thilsted 2010, 2012).

the rural poor in the future. Therefore, the impact of increase in river salinity on the livelihoods of the poor is difficult to assess and warrants location-specific analysis of economic impacts.⁴⁶

5. Conclusion

Even if greenhouse gas emissions were to be stabilized today, it is virtually certain that SLR will continue beyond 2100. Therefore, understanding the potential impacts of SLR and planning adaptation to increased climate risks is essential for the development of countries for which SLR has been identified as a major risk of climate change. With climate change, rising sea levels threaten inundation and extreme weather events in coastal areas of developing countries. These threats have already received some attention in the literature. At present, systematic studies of the implications of climate change for saltwater intrusion and its impacts on livelihoods and adaptation alternatives are scarce. This paper is an attempt to narrow the knowledge gap with a case study of coastal Bangladesh.

In this paper, we have provided an analysis that integrates information on climate change, hydrological models, and geographic overlays to assess the vulnerability of the southwest coastal region of Bangladesh to saltwater intrusion by 2050. In the absence of agreement among scientists about the time and spatial profile of climate change, our paper estimated potential location-specific impacts on river salinity in the southwest coastal region in Bangladesh for 27 alternative scenarios of climate change.

Our study method adopted a five-step process. First, climate in 2050 was approximated by statistical downscaling (daily timescale Bias-Corrected Spatial Disaggregation technique) of temperature and rainfall for the territory of Bangladesh from nine GCMs for three emission scenarios: B1, A1b, and A2. Projections from three GCMs (IPS-CM4L, MIROC3.2, and ECHO-G) were selected in order to capture the uncertainty of the extent of climate change. Second, alternative probable estimates of RMSLR for the Bay of Bengal near the coastline of Bangladesh by 2050 were compiled from the available literature on global SLR and land subsidence in the lower Bengal Delta. Third, the Rainfall-Runoff model, the MIKE 11

⁴⁶ This research also developed a River Salinity Information System on location-specific river salinity estimates from December 2049 to May 2050 for user-defined alternative values of climate change parameters over a predefined range. Annex 2 summarizes expected changes in river salinity by *thana*-level as an illustrative example.

hydrodynamic module, the DHI Global Tide model, the Bay of Bengal model, and the MIKE 11 advection-dispersion module were used to estimate the freshwater flows from upstream, surface water runoff from rainfall events, and tidal dynamics in the coastal river system. The models were also used to predict location-specific river salinity for 27 alternative scenarios of climate change⁴⁷ by December 2049 to May 2050. Fourth, predictions of location-specific concentrations of the salinity of the coastal river systems for alternative scenarios of climate change were compared with concentrations at the baseline (measured river salinity in 2012). Fifth, estimated geo-coded changes in river salinity were overlaid with district boundaries to quantify the expected changes by administrative boundaries.

Our findings indicate that climate change will cause *significant* changes in river salinity in the southwest coastal area of Bangladesh by 2050. Overall, a probable reduction in slight saline (<1dS/m) river area from 22 to 13 percent, a reduction in slight to moderately saline (1–5dS/m) river area from 35 to 21 percent, an increase in moderate to high saline (5–10dS/m) river area from 8 to 27 percent, and an increase in highly saline (> 10dS/m) river area from 35 to 40 percent is expected.⁴⁸ These changes are likely to lead to significant shortages of drinking water in the coastal urban areas; scarcity of water for irrigation for dry-season agriculture, especially for the *boro* crop; and significant changes in the coastal aquatic ecosystems as well as in the World Heritage Sunderbans mangrove forest. In particular, our estimates indicate that freshwater river area (0–1ppt) may decrease from 40.8 to 17.1 percent and river area suitable for agricultural irrigation (with salinity less than 2ppt) may decrease by 29.7 percent. Changes in the availability of freshwater fish will likely affect the composition of capture fishery. Wild habitats of freshwater fish (including small indigenous species) and giant freshwater prawn (Golda) will be affected adversely. But the increase in brackish water will enhance opportunities for brackish water aquaculture, for example, farming of *Tilapia Nilotica* and Black Tiger Shrimp (Bagda) in coastal districts. Climate change is projected to cause an increase in water salinity that is also likely to induce an overall shift from Sundari (the species with the highest market value) to Gewa and Guran in Sunderbans.

⁴⁷ Approximated by combinations of three emission scenarios (B1, A1b, and A2), temperature and rainfall projections from three GCMs (IPS-CM4L, MIROC3.2, and ECHO-G), and alternative estimates of RMSLR.

⁴⁸ Water with 1.15 deciSiemens per water (dS/m) contains approximately 2,000 pounds of salt for every acre foot of water.

Our estimates further indicate that Bagerhat, Barguna, Barisal, Bhola, Khulna, Jhalokati, Pirojpur, and Satkhira Districts will be the most adversely affected by the increase in river salinity caused by climate change. In light of the fact that the incidence of poverty is also very high in Bagerhat, Barguna, Barisal, Khulna, and Satkhira Districts, an assessment of location-specific economic impacts of the changes in river salinity, identification of suitable adaptation alternatives, and costing of adaptation remain subjects for immediate future analysis.

We acknowledge several limitations of the present analysis. First, this paper presents a modeling process for changes in river salinity caused by climate change; probable changes in the salinity of soil have not been assessed.⁴⁹ Second, predictions of the future water flows of the trans-boundary Brahmaputra River were not attempted because of geopolitical complications. Third, the analysis assumed that the Ganges Water Treaty will hold between Bangladesh and India in the future. Fourth, our analysis assumes away potential overtopping and breaches of polders and embankments in the coastal area. An enormous amount of saline water from cyclone-induced storm surges could become trapped in the surface water for a long period of time if polders and embankments become breached or overtopped. Fifth, our analysis of impacts is restricted to exposure to salinity and does not take into account the extent to which adaptive capacity exists in the affected areas to encounter potential changes.

Despite the noted limitations, the paper presents information on an analytical framework that the Government of the People's Republic of Bangladesh can use to develop location-specific coastal adaptation plans at this time to prepare for future changes. We believe the analysis in this paper also will be of interest to other developing countries and to those experts and organizations concerned with the impacts of climate change on coastal areas in developing countries. Given the general lack of such studies in the developing world, we hope our analysis will raise awareness and will prompt countries (at least the countries for which inundation from SLR has been identified as a major problem associated with climate change) to initiate detailed, country-level assessments of potential impacts of climate change on salinity in coastal areas, including analysis of the socioeconomic impacts of the resulting salinity changes. Such estimates may then trigger various actions aimed at protecting or facilitating increased resilience of coastal assets and activities to imminent climate risks.

⁴⁹ For implications of climate change on coastal aquifers in Bangladesh, see World Bank (2009).

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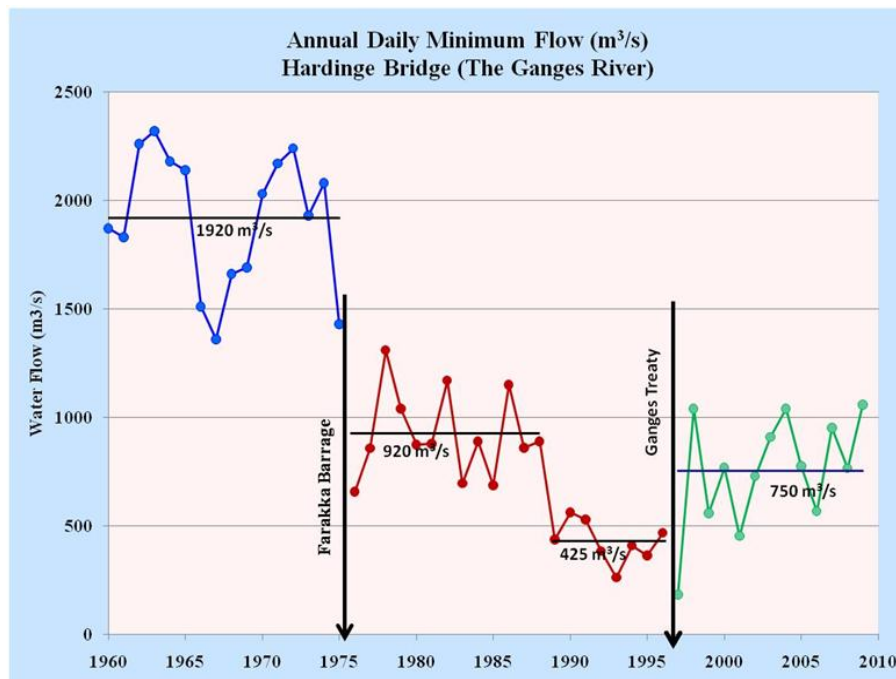
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Annex 1 Effect of Trans-Boundary Flow on Salinity

The level of river salinity and its temporal and spatial variation in the southwest coastal zone of Bangladesh are largely affected by the trans-boundary flow in the Ganges River and its distributaries. The average minimum flow in the Ganges River at Harding Bridge (inside Bangladesh) was $1,920\text{m}^3/\text{s}$ prior to 1975. After the construction of the Farrakka Barrage in 1975, water was diverted to Hooghly River in India and the average minimum water flow in the Ganges River near Harding Bridge was $400\text{m}^3/\text{s}$ during 1988–1996. The average minimum flow at Harding Bridge increased to $619\text{m}^3/\text{s}$ after the Ganges Water Treaty was signed by India and Bangladesh in 1996.

FigureA1 Change in Trans-Boundary Flow over the Years in the Ganges River at Harding Bridge, Bangladesh



An immediate impact of the change in the Ganges River flow was observed in the level of river salinity in Khulna in the southwest coastal zone of Bangladesh. The level of river salinity was below 1ppt at Khulna and could be used for drinking, agriculture, and industrial purposes prior to

1975. At present, the level of river salinity at Khulna remains above 12ppt during the dry season, restricting the multipurpose use of river water.

In order to understand the impact of the flow of the Ganges River on river salinity in the southwest coastal region, SWRM was calibrated and run for various scenarios of Ganges water flow through its major tributary, Gorai River.⁵⁰ The findings indicate that a reduction of the freshwater flow from 150m³/s to 15m³/s in the Gorai River results in an intrusion of the 2ppt isohaline landward by 45km, significantly reducing the availability of freshwater for agricultural and other uses. The eastern and central parts of Sunderbans become highly saline, with major implications for the biodiversity of Sunderbans.

⁵⁰ The Gorai River, with a total length of 200km and an average annual discharge of 1200m³/s between 1964 and 2009, is a major distributary of the Ganges River.

Annex 2 River Salinity in Thanas of the Southwest Coastal Region of Bangladesh

District	Thana	Level of River Salinity		
		Baseline: March2012	Best Future (March 2050) Scenario	Worst Future (March2050) Scenario
JESSORE	ABHAYNAGAR	1.0	2.6	3.2
BARISAL	AGAILJHARA	0.2	0.5	0.7
BARGUNA	AMTALI	4.4	5.5	6.3
SATKHIRA	ASSASUNI	16.5	16.5	16.5
BARISAL	BABUGANJ	0.8	1.8	3.4
BAGERHAT	BAGERHAT SADAR	2.9	4.8	5.9
JESSORE	BAGHER PARA	0.0	0.5	0.6
BARISAL	BAKERGANJ	1.0	1.9	3.6
BARGUNA	BAMNA	1.0	2.0	3.1
BARISAL	BANARI PARA	0.7	1.2	2.6
BARGUNA	BARGUNA SADAR	1.0	2.0	3.9
BARISAL	BARISAL SADAR (KOTWALI)	1.0	1.9	3.7
KHULNA	BATIAGHATA	9.9	11.8	12.6
PATUAKHALI	BAUPHAL	1.0	2.1	3.9
BARGUNA	BETAGI	1.0	2.0	3.2
PIROJPUR	BHANDARIA	1.0	2.0	3.0
SHARIATPUR	BHEDARGANJ	0.3	0.7	1.2
BHOLA	BHOLA SADAR	2.0	3.3	4.4
BHOLA	BURHANUDDIN	2.1	3.3	4.6
BHOLA	CHAR FASSON	2.4	3.8	4.7
JESSORE	CHAUGACHHA	0.0	0.0	0.0
BAGERHAT	CHITALMARI	0.9	1.0	1.6
KHULNA	DACOPE	14.6	15.8	16.2
SHARIATPUR	DAMUDYA	0.4	0.7	1.1
PATUAKHALI	DASHMINA	1.2	2.4	4.0
KHULNA	DAULATPUR	3.9	6.0	7.0
SATKHIRA	DEBHATA	8.9	9.4	9.5
KHULNA	DIGHALIA	2.8	4.9	5.8
KHULNA	DUMURIA	10.3	12.0	12.6
BAGERHAT	FAKIRHAT	5.0	7.1	8.0
PATUAKHALI	GALACHIPA	1.6	2.7	4.0
BARISAL	GAURNADI	0.2	1.0	1.8
GOPALGANJ	GOPALGANJ SADAR	0.2	0.2	0.2
SHARIATPUR	GOSAIRHAT	0.6	1.4	2.3

BARISAL	HIZLA	1.0	2.0	3.6
JHALOKATI	JHALOKATI SADAR	1.0	1.4	3.1
JESSORE	JHIKARGACHHA	0.1	0.1	0.1
BAGERHAT	KACHUA_B	2.0	4.0	5.1
PATUAKHALI	KALA PARA	18.7	19.0	20.0
SATKHIRA	KALAROA	0.3	1.0	1.2
NARAIL	KALIA	1.0	3.1	4.0
SATKHIRA	KALIGANJ	11.9	11.9	11.9
JHALOKATI	KANTHALIA	1.0	2.0	3.0
GOPALGANJ	KASHIANI	0.0	0.3	0.4
PIROJPUR	KAWKHALI	1.0	2.0	3.0
JESSORE	KESHABPUR	0.4	1.0	1.5
KHULNA	KHALISHPUR	5.3	7.8	8.6
KHULNA	KHAN JAHAN ALI	3.6	5.7	6.6
KHULNA	KHULNA SADAR	5.6	8.5	9.4
GOPALGANJ	KOTALI PARA	0.2	0.2	0.2
JESSORE	KOTWALI	0.0	0.6	0.7
KHULNA	KOYRA	18.2	19.1	19.5
BHOLA	LALMOHAN	2.2	3.6	4.8
NARAIL	LOHAGARA_N	0.1	0.4	0.5
JESSORE	MANIRAMPUR	0.0	0.0	0.0
BHOLA	MANPURA	3.1	4.7	5.7
PIROJPUR	MATHBARIA	1.6	2.5	3.5
BARISAL	MEHENDIGANJ	1.7	2.9	4.0
PATUAKHALI	MIRZAGANJ	1.0	2.0	3.3
BAGERHAT	MOLLAHAT	0.9	3.6	4.5
BAGERHAT	MONGLA	13.8	15.0	15.8
BAGERHAT	MORRELGANJ	2.0	3.7	4.8
GOPALGANJ	MUKSUDPUR	0.0	0.0	0.0
BARISAL	MULADI	0.5	2.0	3.3
JHALOKATI	NALCHITY	1.0	1.6	3.3
NARAIL	NARAIL SADAR	0.4	0.7	0.9
SHARIATPUR	NARIA	0.0	0.1	0.3
PIROJPUR	NAZIRPUR	0.8	1.0	1.6
PIROJPUR	NESARABAD (SWARUPKATI)	1.0	1.1	2.4
KHULNA	PAIKGACHHA	14.3	14.3	14.3
SHARIATPUR	PALONG	0.0	0.0	0.0
BARGUNA	PATHARGHATA	6.3	7.2	8.3
PATUAKHALI	PATUAKHALI SADAR	1.0	2.0	3.5
KHULNA	PHULTALA	3.1	4.8	5.6
PIROJPUR	PIROJPUR SADAR	1.0	2.0	3.0

JHALOKATI	RAJAPUR	1.0	2.0	3.0
BAGERHAT	RAMPAL	7.8	10.1	10.9
KHULNA	RUPSA	3.8	5.9	6.9
BAGERHAT	SARANKHOLA	9.1	10.2	11.2
SATKHIRA	SATKHIRA SADAR	2.2	7.7	7.9
JESSORE	SHARSHA	0.9	0.9	0.9
SATKHIRA	SHYAMNAGAR	25.2	26.0	26.6
KHULNA	SONADANGA	6.3	8.9	9.7
SATKHIRA	TALA	4.6	4.6	4.6
BHOLA	TAZUMUDDIN	2.9	4.0	5.2
KHULNA	TEROKHADA	1.0	5.0	6.0
GOPALGANJ	TUNGI PARA	0.6	0.6	0.6
BARISAL	WAZIRPUR	0.5	1.2	2.5
SHARIATPUR	ZANJIRA	0.0	0.0	0.0